Da dove vengono i designer (se non si insegna il design)? Torino dagli anni Trenta ai Sessanta

Sustainable Development

WILEY

Sustainable Development

RESEARCH ARTICLE OPEN ACCESS

Enhancing Sustainability and Resilience Against Natural Hazard of the Built Environment—State of the Art and Development of a Novel Framework

Roberta Di Bari[1] | Raffaele Cucuzza[2,3,4] | Marco Domaneschi[3,5] | Stergios Aristoteles Mitoulis[6,7]

[1]Department of Civil Engineering, University of Birmingham, Birmingham, UK | [2]College of Civil Engineering, Henan University of Technology, Zhengzhou, China | [3]Department of Structural, Geotechnical and Building Engineering, Politecnico di Torino, Turin, Italy | [4]School of Civil Engineering, Southeast University, Nanjing, China | [5]International Institute for Urban Systems Engineering, Southeast University, Nanjing, China | [6]The Bartlett School of Sustainable Construction, University College London, London, UK | [7]MetaInfrastructure.Org, London, UK

Correspondence: Roberta Di Bari (r.dibari@bham.ac.uk) | Stergios Aristoteles Mitoulis (s.mitoulis@ucl.ac.uk)

Received: 5 November 2024 | **Revised:** 26 July 2025 | **Accepted:** 2 August 2025

Funding: This work was supported by HORIZON EUROPE Marie Sklodowska-Curie Actions, 101086413.

Keywords: life cycle analyses | resilience | risk assessment | sustainability | systematic literature review

ABSTRACT

As climate change poses increasing challenges, it is vital to create climate-resilient cities and promote sustainable practices for responsible resource management. This paper aims to develop integrative methodologies combining resilience and sustainability assessments for built systems, both new and existing. It classifies published research by the frameworks used for these assessments and identifies gaps in understanding specific aspects of sustainability and resilience, as well as their interdependencies. The analysis highlights that current methodologies lack comprehensive integrated assessments; they often rely on structural verifications according to design codes and predominantly assess losses from shock events without considering broader social impacts throughout the life cycle. Furthermore, existing approaches generally focus on repair after events, neglecting the evolutionary performance of built systems—whether through upgrades, like refurbishments, or downgrades due to factors such as corrosion. To address these gaps, the paper proposes a novel two-step framework for assessment. The initial assessment phase aims to identify optimal design solutions, while the final assessment phase incorporates dynamic analyses to evaluate the performance changes of systems over time. This approach will help determine the best times to implement proactive measures, ultimately reducing the risks of unforeseen losses resulting from natural hazards and enhancing the structural resilience and sustainability of the built environment.

1 | Introduction

As greenhouse gas emissions continue to climb, climate change is progressing faster than expected, exacerbating natural disasters such as floods, hurricanes, and wildfires. The consequences are serious for cities and communities. Despite the sheer necessity of decarbonisation, the process is progressing slowly, and the last few years have led to further difficulties due to the pandemic and the energy crisis (International Energy Agency (IEA) 2022). The United Nations Environmental Programme (UNEP) reported that only about 5% of the carbon budget is available for the 1.5°C global warming limit target (United Nations Environmental Programm 2022; International Energy Agency (IEA) 2022), increasing uncertainties about the decarbonisation

Abbreviations: LCA, life cycle assessment; LCC, life cycle cost; PRA, probabilistic risk assessment; QRA, quantitative risk assessment; RA, risk assessment; SDGs, Sustainable Development Goals; S-LCA, social life cycle assessment; SLR, systematic literature review.

process. While 195 nations still pledge to keep warming within the safe limit of 1.5°C set out in the Paris Agreement, recent studies warn that limiting the temperature increase to below 1.5°C is no longer possible with even a moderate likelihood. Cities and communities need to be prepared for the possibility of more frequent extreme events and an overshoot of the 1.5°C limit (McKay et al. 2022; Gernaat et al. 2021; Fawzy et al. 2020).

The construction sector can be deemed a *culprit and a victim*. In fact, the construction industry is responsible for 40% of worldwide greenhouse gas (GHG) emissions. On the other hand, unpredictable weather conditions impact construction industry schedules and budgets by delaying construction projects worldwide (estimated at 45%); costing builders and contractors billions of dollars in additional expenses and lost revenue each year (Schuldt et al. 2021). Maintaining a competitive advantage and ensuring operational environmental, economic, and social sustainability requires collaboration between different types of stakeholders to trade off different requirements (Frost et al. 2022). Under these uncertain conditions, it is also advisable for stakeholders to proactively identify, assess, and mitigate these risks while enhancing the resilience of built systems (Bocchini et al. 2014).

To this end, methods are needed to assess the sustainability and resilience of built systems under the uncertainties arising from climate change and overall natural hazards (e.g., earthquakes, volcanism) (Murtagh et al. 2020). Such methods must enable the identification of optimal solutions for built systems and trade off different needs by identifying the interdependencies between resilience and environmental, economic, and social sustainability aspects (Sajjad et al. 2021). As a result, stakeholders will have the information they need to plan comprehensive and ambitious measures to make the built environment resilient to climate change and other natural hazards, with the lowest harm to the environment and the best impact on society and the economy (Abbass et al. 2022).

This paper explores the state-of-the-art methodologies for an integrated assessment of sustainability and resilience metrics based on a Systematic Literature Review (SLR). This paper is organized as follows: Section 2 clearly defines the dimensions of sustainability and resilience and describes the interdependencies that are fundamental to the development of integrated hazard defense methods. In Sections 3 and 4, the missing knowledge and the organization of the work are presented. Section 5 presents the search methodology and the results of the bibliometric analysis, while Section 6 provides a critical review of the state of the art with a summary of the most recent concerns uncovered by the literature review. In Section 7, a novel framework is presented that aims to overcome the limitations not yet addressed by the scientific community.

2 | Sustainability and Resilience as Two Different and Complementary Concepts

The concept of sustainability has a recognised definition from the Brundtland Report of 1987 (Commission, U.U.N.W. and Development 1987) "meeting the needs of the present without compromising the ability of future generations to meet their own needs". This definition was further articulated by the Sustainable Development Goals (SDGs) (United Nations, Department of Economic and Social Affairs Sustainable Development 2015), a framework that contains a list of 17 points covering three main domains (also called *the three pillars*) of sustainability: *(1) environmental protection; (2) economic development and (3) social well-being*.

Resilience is meanwhile a widely used concept across various disciplines, including environmental studies, materials science, engineering, psychology, sociology, and economics?. In the field of the built environment, the definition of resilience can be clarified. It refers to the ability of a (built) system to recover its original functionality in the undamaged configuration in the shortest possible time Jennings et al. (2013). This paper focuses on the level of building and infrastructure asset level. Therefore, the authors will relate resilience to the notion of *structural resilience*, which is defined as "the ability of a system to reduce the chances of a shock, to absorb such a shock when it occurs, and to recover quickly after the shock" (Bruneau et al. 2003; Bruneau and Reinhorn 2007).

In view of the above, it can be argued that sustainability and resilience are two different concepts and that their assessment is carried out using different methods and standards. However, as Elmqvist (2017) emphasizes, this difference is not yet consistently taken into account in studies and strategies at the international level. There, sustainability and resilience are often used interchangeably, leading to disagreement among researchers. This could be due to the fact that sustainability and resilience are both broad definitions (Elmqvist et al. 2019). Furthermore, this can be justified by the existence of *interdependencies* between the two concepts, which allow for a complementary use of assessment methods for sustainability and resilience (Redman 2014).

2.1 | Sustainability Assessment and Life Cycle Analyses Under Natural Hazard

The Sustainable Development Goals (SDGs) are an essential milestone for (i) the assessment of sustainability and (ii) a clear definition of sustainability metrics (Backes and Traverso 2022; Wulf et al. 2018). In terms of methodologies, they have recognized the Life Cycle Thinking (LCT) and Life Cycle Sustainability Assessment (LCSA) methodologies (Finkbeiner et al. 2010) to compare competing technical solutions based on the three pillars of sustainability and to assess the environmental, social, and economic impacts and benefits of the life cycle (Guinée 2016). LCSA is based on the three main life cycle analyses: Life Cycle Assessment (LCA) for the evaluation of the environmental impact according to the international standards (International Standardisation Organisation 2006a, 2006b), Life Cycle Cost (LCC) for the economic evaluation according to (International Standardisation Organisation 2017), and Social Life Cycle Assessment (S-LCA) for the evaluation of the social quality (Benoît et al. 2010; International Standardisation Organisation 2024).

Life cycle analyses can be valuable tools for quantifying the impact of hazardous events. For this purpose, Risk

Assessment (RA) can be integrated into life cycle analyses (Spreafico 2021; Plumblee and Klotz 2014; Sauve and Van Acker 2021). For *built systems*, such as buildings and infrastructures, their vulnerability and the magnitude of a shock event determine the occurrence of damage and the resulting repair measures. A "what-if" scenario analysis according to Höjer et al. (2008) can be performed, and decision trees can be modelled (Gantner et al. 2018), which determine the assumed activities after an event. In this way, the Life Cycle Inventory (LCI) and the Life Cycle Impact Assessment (LCIA) are created. Within the LCIA, RA tools can be used to propagate uncertainties (Huijbregts 1998, 2002). The choice of the right method depends on several factors, such as the type of hazard to be assessed, the intended purpose of the assessment, and the available skills, resources, and data (Linkov et al. 2009). These can be divided into tools for Quantitative Risk Assessment (QRA), which include Bayesian networks and Monte Carlo Simulation (MCS), Qualitative Risk Assessment, including SWIFT analysis DELPHI technique, and Semiquantitative Risk Assessment (SQRA), which is generated by a combination of quantitative and qualitative RA tools, such as Multi Criteria Decision Analysis (MCDA).

The calculated sustainability metrics measure potential effects and losses due to natural hazards Sangha et al. (2020). Examples of economic metrics are, for example, Net Present Value (NPV) and Repair costs. There are also non-marketable metrics that reinforce positive aspects (Streatfield and Markless 2009), such as Profitability Index, Internal rate of return, Payback time, and Dynamic payback time (Wulf et al. 2018). The indicators for environmental sustainability are usually selected from the recommendations of the International Life Cycle Data (ILCD) and the midpoint indicators of the Society of Environmental Toxicology and Chemistry (SETAC) (e.g., Resource depletion—Abiotic resources, Climate change, Land Use), which are also core environmental indicators for building products. When these values are negative, they refer to impact savings (European Committee for Standardisation 2022). The S-LCA guidelines include indicators for social sustainability (Benoît et al. 2010), such as Accident rate at the workplace, Fatal accidents, Presence of sufficient safety measures, Social security expenditure, corruption index, and Employment creation) (see Table 1). These can also represent positive and negative effects.

TABLE 1 | Methods and examples of sustainability metrics to be investigated.

Method	Sustainability metrics	Unit
LCA	Climate Change Total (CC_{tot})	kg CO_2 eq.
	Resource depletion—Abiotic resources fossil (ADPF)	MJ
	Primary energy demand total (PE_{tot})	MJ
	Water use (WDP)	m^3
LCC	Levelised cost of energy	€
	Net Present Value (NPV) [including indirect costs due to disruptions]	€
	Profitability Index	[–]
	Internal rate of return	%
	Payback time (PB)	A
S-LCA	Accident rate	%
	Fatal accidents	number
	Presence of sufficient safety measures	[–]
	Social security expenditure	€
	Corruption Index or country	%

2.2 | Structural Resilience Assessment

The structural resilience of built systems can be assessed through four main metrics. These are robustness, resourcefulness, redundancy, and rapidity. These indicators have also been referred to as the four resilience dimensions (*4R Framework*) (Bruneau et al. 2003; Bruneau and Reinhorn 2007). *Robustness* is the ability of a structure or one of its elements to endure a certain load or requirement (e.g., damage) while maintaining its characteristic functionality. It can also be described as the damage tolerance of the system. *Redundancy*, as in load-bearing elements, refers to the ability to create alternative ways of supporting loads when degradation affects the primary elements, essentially replacing the original elements. *Resourcefulness* entails the ability to identify challenges, prioritize tasks, and mobilize resources in situations where the structure or its components may be disrupted. This includes the use of normalized indicators to address identified priorities and achieve objectives during the recovery process: financial, physical, technological, informational, and human resources during the recovery process to address identified priorities and achieve objectives. *Rapidity* refers to the capability to prioritize and swiftly execute tasks to minimize losses, restore functionality, and prevent further disruptions.

Based on these metrics, a resilience variable can be defined as the normalized shaded area under the system's function curve, denoted $Q(t)$, expressed as a dimensionless percentage function of time, as described by Opabola and Galasso (2024). The following Equation (1) defines the resilience quantitatively (Cimellaro et al. 2010):

$$R = \int_{t_{r0}}^{t_{r0}-t_{LC}} \frac{Q(t)}{T_{\mathrm{LC}}} dt \tag{1}$$

where $Q(t)$ is the functionality (dimensionless, expressed as a percentage), t_{r0} is the time for the start of recovery, t_{d0} is the time for the start of degradation (which starts at day zero for built systems), t_{LC} is the controlled time, that is a time set by the stakeholders for the recovery of system functionality. In Figure 1 the region is marked in blue, t_{o-o-o} is the out-of-service time, that is the time interval in which Q(t) is below a certain threshold, t_{re} is the time to complete the recovery, $\left(t_{o-o-o} - t_{r0}\right)$ is the residual service life at time t_{r0}, $T_{\mathrm{RE}} = \left(t_{re} - t_{r0}\right)$ is the time to restore functionality.

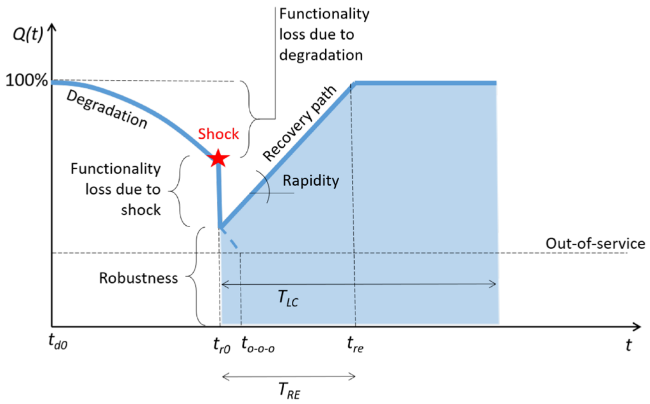


FIGURE 1 | Graphical representation of the functionality, resilience, and some properties (Domaneschi and Cucuzza 2023; Domaneschi, Cucuzza, Di Bari, et al. 2024).

With regard to the existing methods and tools for assessing the resilience of the built environment, two main approaches can be mentioned that relate specifically to the prediction of earthquake response and structural damage: statistical methods such as the damage probability matrix (Whitman 1973; Eleftheriadou and Karabinis 2013; Dolce et al. 2006; Rojahn et al. 1986) and deterministic methods such as N2 and the capacity spectrum method (Freeman 2004; Fajfar and Gašperšič 1996).

2.3 | Integrated Sustainability and Resilience Assessment

The definitions outlined above enabled a limited understanding of sustainability and the assessment of structural resilience in the case of natural hazards. The possibility of using sustainability and resilience assessment in a complementary way has been analysed in several works (Domaneschi, Cucuzza, Martinelli, et al. 2024; Fahimnia et al. 2019), highlighting some obstacles related to their implementation and the complexity of the analysis (Leal Msc et al. 2024). Depending on the objective of the analysis and the interactions analysed between sustainability and resilience, it is possible to couple the assessment of sustainability and resilience (*integrate*). In this paper, the authors refer to the typology described in Marchese et al. (2018) and propose an interpretation based on the possible interdependencies between resilience and sustainability metrics. This interpretation is also shown in Figure 2.

The first framework is based on the idea that increasing the resilience of a system makes that system more sustainable (Marchese et al. 2018; Weber 2023). It therefore considers a limited set of resilience metrics that interact with one or more of the three domains of sustainability. In Figure 2a, these are represented by the area that overlaps sustainability with the resilience areas. For example, if the repair and downtime of infrastructure is reduced, the indirect impact of traffic detours (i.e., the impact on the environment) is reduced. In this case, a resilience metric (M_{res}) influences the environmental sustainability (M_{env}) (see Figure 2a). The interdependency is unidirectional and always directed from resilience to sustainability (see arrow in Figure 2a).

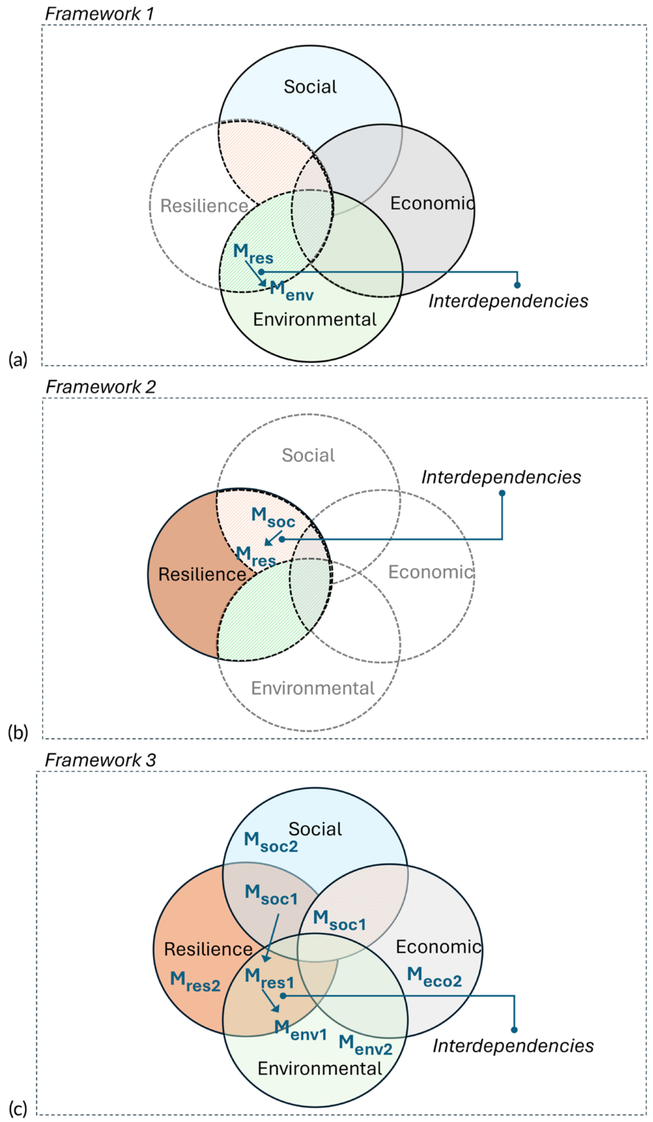


FIGURE 2 | Resilience and sustainability analyses. A graphic representation of (a) Framework 1; (b) Framework 2; (c) Framework 3 with interdependencies based on the definitions of Marchese et al. (2018).

The second framework considers sustainability as a component of resilience and works under the paradigm that increasing the sustainability of a system makes it more resilient. Ensuring the functionality and performance of a system is the primary goal during and after disruptions. Subordinate to this primary requirement, increased economic, environmental and social well-being Narjabadifam et al. (2025) enables better critical functionality (Marchese et al. 2018; Fiksel 2015). Therefore, in Figure 2b, these are represented by sustainability metrics that intersect the resilience domain. The interdependencies are also unidirectional and directed from sustainability to the resilience metrics (see arrow in Figure 2b). For example, the existence of sufficient public investment in safety measures for critical infrastructure (metric of social sustainability, M_{soc}) enables a rapid recovery time (resilience metric M_{res}).

The last framework describes resilience and sustainability as different concepts and separate objectives without establishing a hierarchy. Works that use Framework 3 argue that neither resilience necessarily contributes to sustainability, nor does sustainability fundamentally contribute to resilience (Marchese et al. 2018; Lew et al. 2016). These frameworks consider a broader range of metrics and not only those that show interdependencies and belong to the overlapping domains (see e.g., M_{soc2}, M_{env2}, M_{res2} in Figure 2c). The interdependencies are not necessarily directed from sustainability to resilience or vice versa (see arrows in Figure 2c). For example, repair times and robustness are necessary for the assessment of resilience. Repair time can have an impact on the environment and can be influenced by public investment in safety measures. In contrast, robustness may not have a direct impact on the environment, as robust structures can be designed with sustainability in mind. Planners can opt for an optimised design and/or prefer low-emission building materials. Furthermore, a higher environmental impact of a particular repair measure does not directly imply that this measure has a better structural capacity and robustness. Nevertheless, structural capacity has an impact on the robustness of the systems and can be achieved by using more construction materials, thereby maintaining redundancy and increasing the environmental impact. To summarise, investigating these dependencies between different metrics can be a valuable tool to understand synergies and conflicts between different aspects that contribute to the final overall performance of a system.

3 | Lack of Knowledge and Purpose of Review

The previous section has shown how an integrated use of methods for assessing sustainability and resilience can be conceptualised. Several papers provide an overview of sustainability and resilience, including specifically for buildings and structures. Probably due to the disagreements on the definitions of sustainability and resilience as outlined in Section 2, some of them focus only on environmental sustainability (Tanguay and Amor 2024; Ahern 2013; Simon et al. 2023; Xue et al. 2024; Sesana and Dell'Oro 2024) and do not consider economic and social dimensions. Furthermore, in Tanguay and Amor (2024), Sánchez-Silva et al. (2024), and De Genaro Chiroli et al. (2023), resilience is not analysed as a different area with different metrics. This leads to a lack of knowledge about the interdependencies between resilience and sustainability and a potential lack of integrated assessments. Therefore, a literature review should be conducted to examine the status of the development of methodologies that address sustainability and resilience. This will allow for the identification of the frameworks that are most commonly used for integrated assessment and the interdependencies that are more often considered. In addition, further potential gaps in methodology and applicability for the development of novel integrated methodologies will be identified.

4 | Organisation of Literature Review

This literature review analyses scientific contributions and proposes comprehensive frameworks for assessing sustainability and resilience that encompass aspects of the four domains (i.e., environmental, economic, social sustainability and resilience). Resilience and sustainability are two distinct yet interdependent domains. With this in mind, the status of the development of frameworks that can be categorised under Framework 3 and the investigation of the interdependencies between sustainability and resilience metrics are examined. The work is categorised according to the following criteria:

1. Methodology
   - Sustainability assessment: analyses and metrics, integration of Risk Assessment (RA) tools
   - Resilience assessment: Analyses and metrics
   - Sustainability and Resilience integration frameworks
2. Applications in civil engineering works
   - Construction type (buildings, infrastructure systems)
   - Measures aiming at renovation works (maintenance, repair, refurbishment)

The selected research papers will be analyzed and clustered depending on the framework for the integrative assessment of resilience and sustainability (i.e., framework 1, 2 or 3). Second, the analyses and assessed metrics are identified. This allows one to understand whether the integration of RA tools and the type and number of metrics are a barrier to the development of frameworks categorized under Framework 3.

Analysing the applicability of the methodologies used in the selected research papers will help to understand which activities are included in the assessment and whether some of them are more relevant for certain types of construction (buildings or infrastructure). The measures considered will also provide an understanding of the system boundaries of life cycle analysis used for sustainability assessment.

A matrix (see Table 2) is developed and organised into two sections, corresponding to the areas of research interest highlighted in the Section 3, that is, (i) Methodology (ii) applicability.

The first field investigates the methodology developed for sustainability, resilience, and integrated assessment. To learn more about the life cycle analyses provided, the use of environmental, economic, and social analyses is marked along with the sustainability metrics assessed. It also examines the approaches used. This can be a deterministic or a non-deterministic approach. Finally, the methods used are specified. The integrated sustainability and resilience methods are classified according to their framework (see classification in Section 2.3). The second field is dedicated to the applicability of the methodology, which can be aimed at buildings or other civil engineering works (in the Table called "other"). Moreover, the system boundaries and the included renovation works are examined. These can be classified as maintenance, repair, or refurbishment measures. *Maintenance* (B2, according to European Committee for Standardisation 2023) combination of all planned cleaning and inspection proactive activities during the service life to maintain the product installed in a building in a state in which it can deliver its required functional and technical performance. No significant improvement in structural performance is reached while preserving functionality and alignment with the minimum requirement. The frequency of such activities depends on the current regulations of that specific country. *Repair measures* (B3, according to European Committee for Standardisation 2023) are corrective, responsive, or reactive

TABLE 2 | Matrix organisation for the Systematic Literature Review (SLR).

Level 1	Level 2	Level 3	Level 4	Examples
Methodology	Sustainability	Metrics	Environmental	CCtot
			Economic	NPV
			Social	Fatalities
		RA integration	Approach	Deterministic
			Tools	MCS
			Hazard	Climate Change
	Resilience	Merics	Structural resilience	Robustness
	Sustainability and Resilience Integration	Framework		1
Applicability	Construction type			Buildings
				Infrastructures
				Others
	Renovation works			Maintenance
				Repair
				Refurbishment

actions and treatments to restore the technical performance of a product after an unexpected event (e.g., extreme weather events, inappropriate use, or vandalism). The action aims to return a product or building part to an acceptable condition to perform its original required functional and technical performances, including local damage repair or overall broken building part replacement. *Refurbishment* (B5 according to European Committee for Standardisation 2023) is a complex action involving a significant part of a built system, for exmple, the whole structural frame. These can be carried out as a proactive measure to upgrade the performance of the building system, adapt it to different use destinations or loads, and extend its service life.

Different levels are defined depending on the complexity of the respective topic and the level of detail of the analysis. In the area of sustainability, for example, a distinction is made between environmental, economic and social analyses and metrics, resulting in four levels of analysis. With regard to resilience, the work focuses exclusively on structural resilience indicators. In the area of applicability, there are two levels of analysis.

5 | Search Method Procedure and Bibliometric Analysis

The literature review was conducted in June 2024 using the official Elsevier abstract and citation database *Scopus*. The following search queries were used with the following keyword combinations:

- Sustainability AND Resilience AND Natural hazard
- LCA (or LCC OR SLCA OR S-LCA) AND Resilience AND Natural hazard
- Risk Assessment AND LCA (OR LCC OR SLCA OR S-LCA)
- Risk Assessment integration AND LCA (OR LCC OR SLCA OR S-LCA)
- Risk Assessment AND Lifecycle AND Environmental impact (OR Costs OR Social impacts)
- LCA (OR LCC OR SLCA OR S-LCA) AND Natural hazard
- LCA (or LCC OR SLCA OR S-LCA) AND Hazard integration

5.1 | Bibliometric Analysis

The literature research aimed at journal or conference papers in the English language published over the last 15 years: this narrowed the search to more recent studies. Review articles were considered for bibliometric analysis but were not screened for the compilation of the SLR matrix and the following critical review. The literature search led to an initial sample of 4129 articles (see Figure 3) derived from a bibliometric search based on the aforementioned keywords. As a first step, duplicates were removed, and the new sample of papers consisted of 3578 publications. As a second step, a review of journals was performed: in particular, all journals that were not related to the fields of risk assessment, sustainability, project management, and civil engineering were excluded. This allowed for a reduction of the sample to 1589 publications. Afterwards, all titles were screened. This provided a further reduction of the database. Initially, with regard to sustainability assessment, the search aimed to select articles using Life Cycle Analyses for sustainability assessment, LCA according to International Standardisation Organisation (2006a) for environmental impact assessment, LCC according to International Standardisation Organisation (2017) for cost assessment, and S-LCA for the social domain. However, no papers applying S-LCA were found; therefore, the use of S-LCA was not considered a necessary criterion for the selection of the papers. 85 papers met all the selection criteria, and the paper

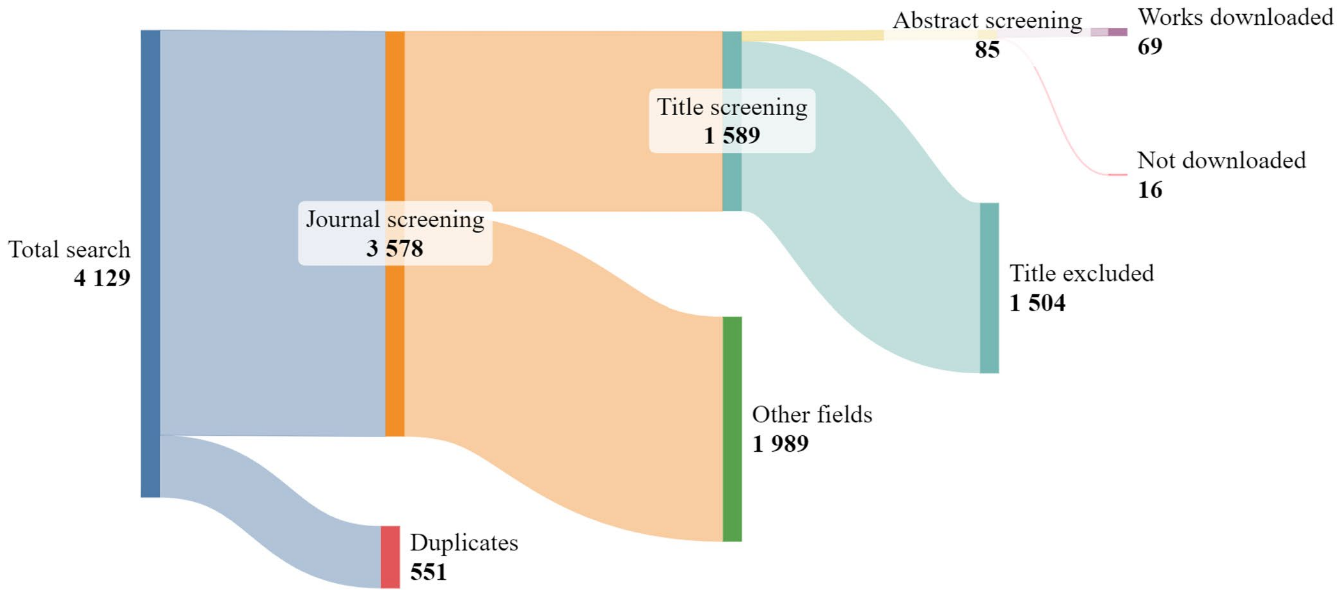


FIGURE 3 | Procedure for selection of final papers' sample for literature review.

download was performed. For 16 papers, due to access restrictions, a download was not possible. The final sample for the SLR therefore consisted of 69 scientific publications.

Bibliometric analysis was performed with the help of VOSviewer software, Centre for Science and Technology Studies, Leiden University (2023) to identify the relationship between different topics and show potential links between disciplines. A bibliometric analysis should highlight relationship trends based on the co-occurrence of keywords present in the selected database. Figure 4 shows the analysis of the co-occurrence of network visualisation, and Figure 5 shows the trend of keywords in recent years. The created maps collect and visualise *items*, which are, in this instance, authors' keywords.

In the network visualisation (see Figure 4), items are represented by their label (i.e., the caption) and a circle. The weight of the item determines the size of the label and the size of the circle of the item. The higher the weight of an item, the larger the label and the circle area containing it. Moreover, there can be only one link between any pair of items. A link is a connection or a relation between items. In this case, we are interested in detecting the keywords that occur together in the reviewed documents and, hence, finding the research topics that have a sort of relationship with each other.

A set of items is furthermore grouped into *clusters*, which in Figure 4 are represented using a common color for circles and networks and are automatically generated by the VOSviewer software. An item may belong to only one cluster. The distance between two items in the visualization approximately indicates the *relatedness* (or relationship) of the journals in terms of co-citation links. Generally, the closer two items are located, the stronger their relatedness is.

In the *network visualisation* provided by VOSviewer Centre for Science and Technology Studies, Leiden University (2023) and depicted in Figure 4, it is evident that "Sustainability" and "Resilience" are the most popular papers' keywords. This might also be due to the combination of selected keywords during the literature search. Four main clusters can be identified. The red cluster collects items primarily related to environmental sustainability (waste, life cycle assessment, greenhouse gas emissions). The blue cluster gathers items more related to sustainability and resilience (sustainable development, SDGs, urban resilience, urban sustainability, robustness). The green cluster presents keywords relating to the field of hazard and construction (bridge, damage, steel, risk analysis, extreme event). A yellow cluster can also be identified, but is not associated with a specific field. It is interesting to note that environmental sustainability has its own cluster. Therefore, this topic is highly relevant and prioritized compared to social and economic sustainability. Furthermore, urban systems and infrastructures, such as bridges, are relevant case studies for sustainability and resilience assessments.

In Figure 5, the so-called *Overlay visualisation* provided by VOSviewer Centre for Science and Technology Studies, Leiden University (2023) is shown. The overlay visualisation is identical to the network visualisation except that the items' colors depend on the selected item scores, which, in this case, are the year of the keyword's appearance. It is interesting to notice that while hazard and environmental impact assessments have been widely investigated over the years, resilience and sustainable development are more recent issues in the research community. This confirms that this field of research is still growing.

6 | Critical Review

This section is dedicated to a critical review of the selected works. A discussion of the frameworks used for integrated resilience and sustainability assessment is presented. The comprehensive matrix used for SLR can be found in Appendix A (Tables A1–A3).

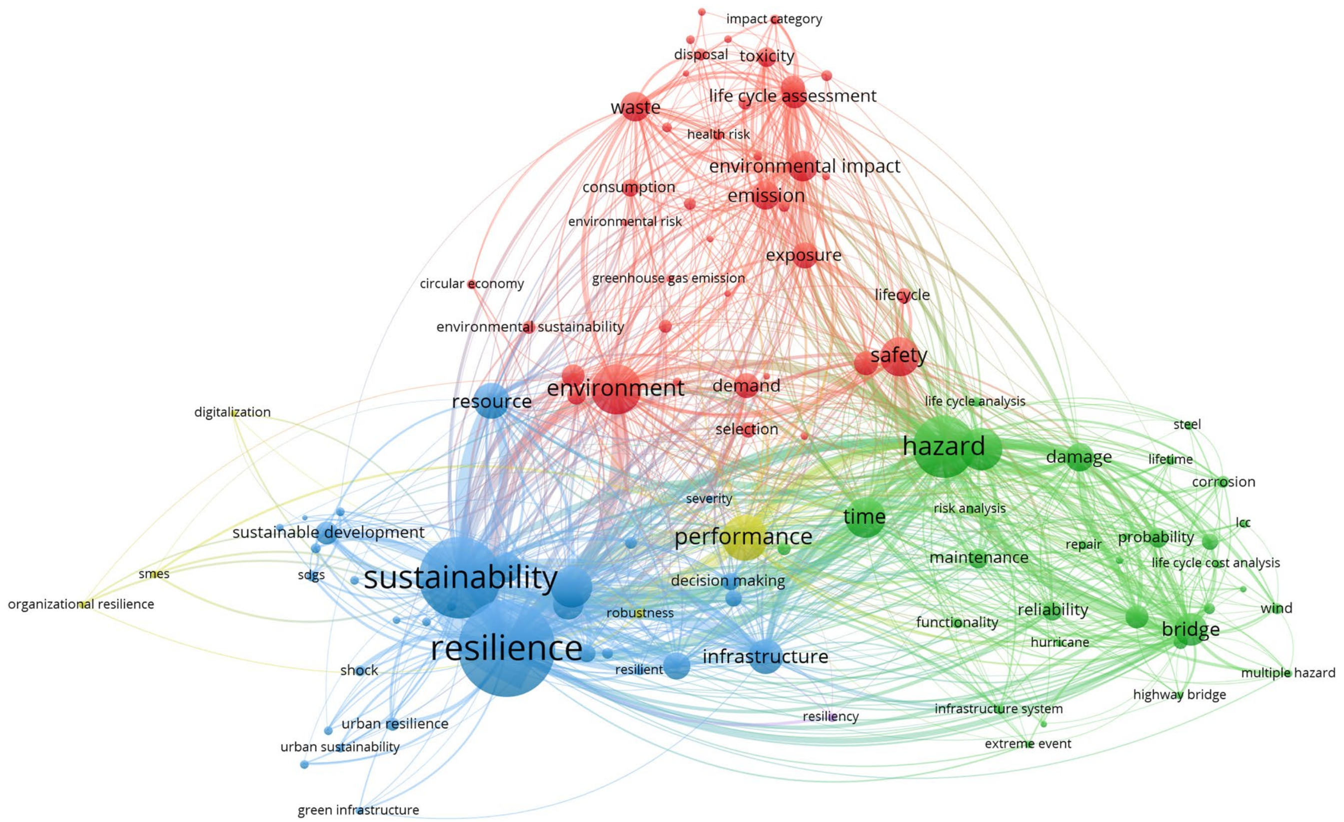


FIGURE 4 | Network visualisation of the co-occurrence of authors' keywords. The size of the captions and the circle is proportional to the items' weight. The size of links indicates the frequency of co-occurrence between two items. The distance between two items is proportional to their relatedness of the journals in terms of co-citation links. Colours of items and links are associated with a cluster (Red = cluster of environmental sustainability; blue = cluster of sustainability and resilience; green = cluster of hazard and construction).

6.1 | Methodology

The literature research did not identify works that can be associated with Framework 2. Therefore, in the following, a critical review of works attributable to none of the frameworks (Framework 0 in the SLR matrix in Appendix A), Framework 1, and Framework 3, is presented.

6.1.1 | Framework 0

The majority of the papers selected, even if they recognize the importance of an integrated assessment of resilience and sustainability, do not develop integrated methodologies. Therefore, these are marked as Framework 0 in the SLR matrix (in Appendix A).

There are works that carry out only cost analyses (NPV assessment). El-Khoury et al. (El-Khoury et al. 2018) demonstrated the economic benefits of control systems for risk-informed decision-making in seismic-prone areas. Furuta et al. (2011) provide relations among maximum earthquake acceleration, damage levels, and LCC. Jiang et al. (2020) perform cost-based seismic fragility analysis instead of performance-based seismic fragility analysis and develop a simple function describing the relationship between the LCC and structural parameters. The works of Kleingesinds et al. (2020, 2021, 2023) assess LCC related to the damage of components belonging to buildings due to hazardous events. They include life cycle costs in a multiobjective optimization problem. Mauro et al. (2017) provide an approach for selecting optimized retrofit solutions based on structural, energy, and cost analyses and investigate the relevance of location and seismic area for the measure selection. In Mirzaeefard et al. (2021), aging-dependent fragility curves with updating limit states are computed, followed by an LCC analysis due to failure. Noureldin and Kim (2020) formulate LCC based on damage probability for each limit state. In Padgett (2020), a risk-based LCC is provided, integrating probabilistic hazard models, the fragility of as-built and retrofitted bridges, and associated costs due to damage and retrofit. Venanzi et al. (2018) carry out an LCC, including the combined effects of earthquakes and winds, and a dynamic assessment depending on building height. This allowed for understanding cost variations based on the increased effect of wind loads in high buildings.

Some authors considered other contributions and different metrics for LCC analyses. Lagaros adds social costs to the life cycle cost (Lagaros (2010)) and provides dynamic analysis based on incident angles of seismic events. Nydahl et al. (2022) includes the social cost of carbon in total costs, trying to monetise social and environmental risks and opportunities due to climate change. Noshadravan et al. (2017) enlarges the analysis by including the payback period as an economic metric relevant for decision-making under different hazard scenarios and locations. Payback periods are also estimated in the Shen et al. (2021),

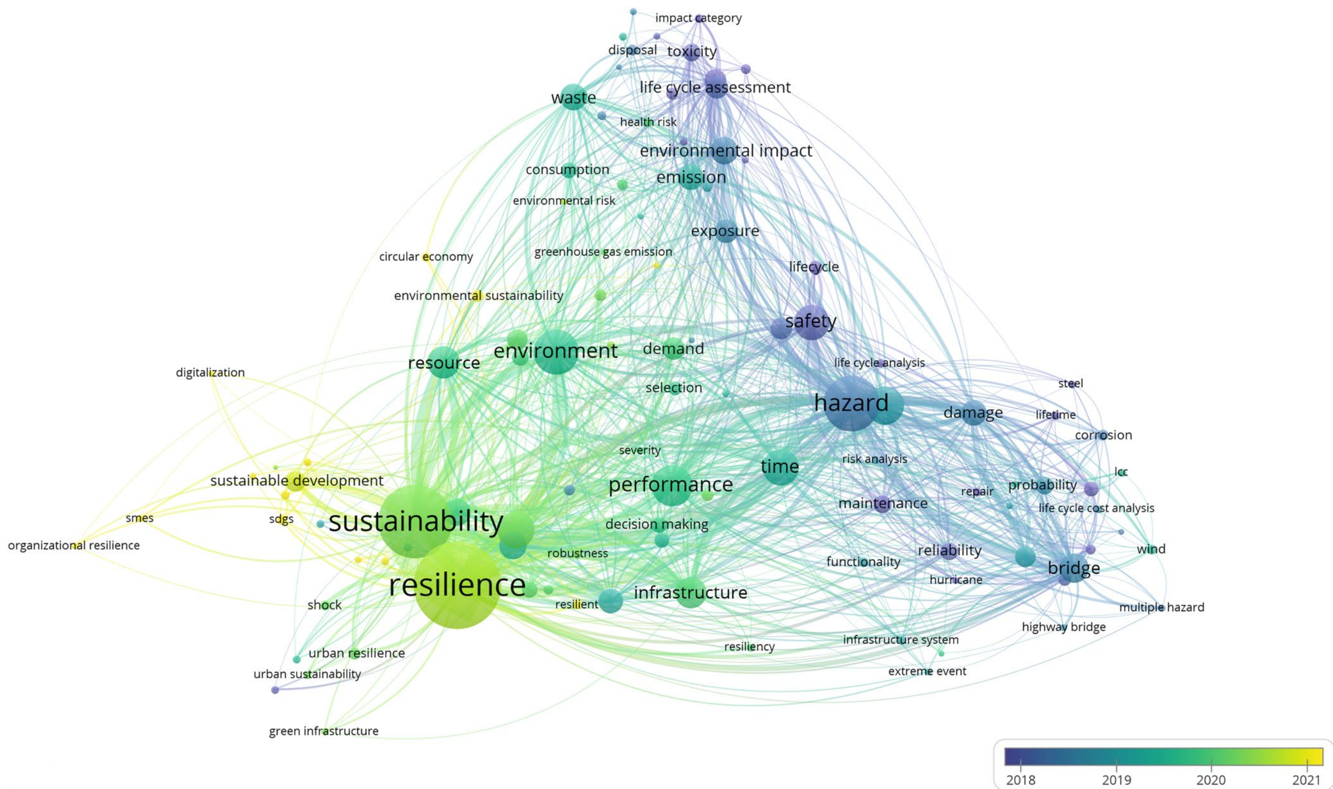


FIGURE 5 | Overlay visualization of the co-occurrence author's keywords of the last 15 years. The size of the captions and the circle is proportional to the items' weight. Links' size indicates the frequency of co-occurrence between two items. The distance between two items is proportional to their relatedness of the journals in terms of co-citation links. Colors represent the year of the keyword's first appearance.

which evaluates seismic losses with the help of the PACT tools. Payback periods due to energy-saving design and, therefore, show potential economic opportunities when structural and energy upgrades are performed in seismic-prone areas. Stewart and Deng (2015) assesses the cost/benefit ratio as an additional metric and applies risk-based approaches for enhancing climate adaptation strategies for built infrastructure. Cost assessments are carried out for all previously mentioned works, considering, at most, the variabilities due to discounting.

Meanwhile, effects due to uncertainties are explored in Babashamsi et al. (2022), which compares results obtained by dynamic and probabilistic + dynamic approaches. Probabilistic approaches can better explain the variability in the data quality or sources. Probabilistic approaches for cost assessment are also found in Ahmadie Amiri and Estekanchi (2023), Cadenazzi et al. (2021), Gong et al. (2019), Chhabra et al. (2018), Seo and Caracoglia (2013), which define the occurrence of a hazardous event (earthquake, wind, tsunami) as uncertainty and propagate the uncertainty through MCS. Decò and Frangopol (2013) apply probabilistic LCC analyses to quantify the effects due to multihazard (earthquake and traffic). This approach monetizes injuries and allows for assessing indirect costs due to traffic redistribution. Mahmoud and Cheng (2017) consider multihazard effects (due to earthquake and wind) and assess the cost losses based on first-order reliability techniques.

Studies that consider only environmental sustainability have also been conducted. Chhabra et al. (2018), Court et al. (2012), for example, carry out an environmental analysis (CCtot assessment) due to deterioration by performing a probabilistic LCA. In this study, impact increases of 42% are recorded when buildings are subjected to design-level earthquakes. Publications investigating environmental effects due to earthquakes and other natural hazards deterministically are found. In particular, they perform an LCA of hazard-resistant solutions. As a common aspect, these studies enlarge the sets of considered environmental impact categories. They do not consider only CCtot as a relevant impact category, but also ADP (Menna et al. (2012)), AP, EP, ODP (Salgado and Guner 2021; Ayoub et al. 2015) Embodied Energy—EE (Tapia et al. 2011). Probabilistic approaches exploiting MCS and enlarging the set of environmental indicators are developed by Matthews et al. (2016a) and (Hennequin, Sorup, et al. 2018). They account for CCtot, WDP, land use, and EE under flood hazard.

Adhikari et al. (2020), Angeles et al. (2021) and Francis et al. (2010) perform probabilistic environmental and cost analysis by using MCS for different hazards (tornadoes, earthquakes and climate change-induced hurricanes, respectively). In the work of Di Bari et al. (2020), an MCS is developed to perform dynamic and probabilistic LCA and LCC, which accounts for effects due to decarbonisation of building materials, price increase and discount rates. Belleri and Marini (2016) also provides a cost assessment with the help of the PACT tool and compares energy refurbishment solutions with structural retrofit in high-seismicity regions. MCS tools are also used in Cao et al. (2023) to simulate tornadoes due to climate change and consequently assess repair costs over the system life cycle. In Buggin et al. (2019), a general framework for assessing hazardous events, including other metrics (Energy savings, Investment Return Rate, Payback time), is provided. This work exploits the analytic hierarchy process (AHP), a multi-criteria decision analysis (MCDA) method (therefore SQRA tools).

In the works of Dong et al. (2013), Hossain and Gencturk (2016) and Padgett and Li (2016), the social domain is added to the sustainability assessment by evaluating downtimes, injuries, fatalities, and disturbance, which can in turn strongly affect economic metrics. In the work of Basu and Lee (2022), different social metrics are included in the sustainability assessment. These are aesthetics, employment, public safety, and land use patterns. This study recognizes the relevance of resilience and social metrics. However, the case study performs a multiobjective optimization accounting only for CCtot and project costs.

Unlike the previously mentioned works, Hasik et al. (2017) provide risk and resilience assessment by not evaluating sustainability metrics. Wuni (2024), meanwhile, uses fuzzy sets to derive risk assessment and final risk index (RI) that can quantify impacts due to various hazards and rank the magnitude of threat without providing distinguished economic, environmental, and social metrics.

6.1.2 | Framework 1

In total, seven studies applying methodologies attributable to framework 1 are found. Fereshtehnejad and Shafieezadeh (2018) and Fereshtehnejad and Shafieezadeh (2016) include in the cost analyses the contributions due to the initial construction cost, annual maintenance costs, and the hazard-induced repair costs considering the potential for the occurrence of multiple hazard incidents. Soleimani-Chamkhorami et al. (2024) present a tool for infrastructure managers to select the preferable solutions under climate change extreme events based on cost assessment and repair times. In both cases, indirect costs are not included in the calculation. Padgett (2020) presents a general framework where sustainability metrics are measured based on resilience. This work underlines the relevance of accounting for indirect consequences. To this purpose, loss of functionality and cumulative traffic delays while infrastructures are out of service must be derived. Zheng et al. (2018) assess repair costs solely, based on the evaluated resilience, to showcase the advantages of shape memory alloy (SMA) bridges. This work, in particular, prefers using first-order reliability methods instead of MCS to carry out the fragility analyses of a system. In Lanza et al. (2022), the robustness evaluation serves the environmental impact assessment (CCtot) due to earthquakes. In this work, environmental impacts are calculated through stochastic approaches and MCS. Navya Vishnu and Padgett (2023) consider travel time and distance as resilience metrics affecting the environmental, economic, and social domains. For sustainability and resilience metrics, linear correlation factors are determined. The authors confirm a strong correlation between indirect impacts and network resilience. Roostaie and Nawari (2022) investigated the effect of resilience on sustainability metrics. They defined resilience metrics as sustainability enhancers or detractors. Interdependencies are investigated only qualitatively with a score-based system.

6.1.3 | Framework 3

The remaining studies present wider frameworks that can be associated with framework 3. In particular, they consider a larger set of sustainability and resilience indicators, which might not necessarily be interdependent.

In the paper of Anwar et al. (2020), fast-track and slow-track repair strategies are considered, and probabilistic resilience is quantified along with their sustainability performance. Functionality losses are independently calculated with repair impacts. Omidian and Khaji (2023) provides a resilience index and direct life cycle costs due to earthquakes. These functions are included in a multiobjective optimisation problem to identify the optimal strategy. Hashemi et al. (2019) develops numerical models to quantify sustainability metrics, including repair cost, downtime and repair environmental impacts for consecutive hazards. Based on these, resilience metrics (loss of performance and recovery) are derived according to the probabilistic resilience-based earthquake engineering (PRBEE). Qiu et al. (2024) develops a multihazard resilience and sustainability analysis framework. CCtot is calculated based on Environmental Input Output (EIO-) LCA, accounting only for post-hazard repair measures. Repair costs and time are derived to assess resilience. Lounis and McAllister (2016) exploits resilience assessments to evaluate the loss of performance, recovery time and resilience index due to corrosion. They also provide environmental (CCtot and waste), cost (NPV) and social (accidents, disruptions) assessments, where indirect effects are also included. The analysis confirmed that using high-performance building materials could improve the sustainability and resilience of highway bridge decks. Briz and Gandini (2023) presents a methodology for resilience and sustainability assessment, considering the most common hazards and specific disaster-risk scenarios that target cultural and natural heritage. Domains and metrics are weighted to prioritise measures over others and support decision-making. The work is based on MCDA (AHP). Asadi et al. (2019) measures sustainability and resilience metrics as the basis for an MCDA, aiming at trading off impacts due to earthquakes with structural performance. environmental impacts are calculated with EIO-LCA. They demonstrate little impact on resilience metrics and a significant influence on environmental and economic metrics of reusing steel from diagrid structures. Lastly, the framework developed by Mitoulis et al. (2023) aims to quantify both ex-ante adaptation and ex-post recovery using three relevant metrics (CCtot, NPV including indirect effect, Resilience index). It further introduces a normalised metric based on a unique index (I_{SRC}), which enables the prioritisation of solutions over the others based on environmental sustainability, cost and resilience performance.

6.2 | Applicability

The developed frameworks aim to assess the impacts of repair activities, which are considered after the occurrence of shock events. Studies considering maintenance measures are not found frequently. Ten works assess maintenance measures and include them in the system boundaries. This interestingly occurs when the case study is an infrastructure (see Appendix A). In the studies of Adhikari et al. (2020), El-Khoury et al. (2018), Hasik et al. (2017) and Roostaie and Nawari (2022), maintenance measures of buildings are considered. In this work, the planned maintenance activities affect only life cycle costs.

Lastly, only seven studies assess refurbishment measures and consider performance upgrades. These methodologies are applied only to buildings. Buggin et al. (2019) and Mauro et al. (2017) consider an upgrade in building energy performance, wherein the first study focuses on roof insulation changes and the second one on energy retrofit in seismic-prone areas. Nydahl et al. (2022), Padgett and Li (2016), Shen et al. (2021) and Di Bari et al. (2020) assess measures aimed at service life extensions of buildings as an alternative to "do-nothing" or demolition and building new. In the last work, in particular, the enhancement of structural performance under seismic loads is considered over the whole building life cycle and not at a predefined point in time. Lastly, the framework of Stewart and Deng (2015) aims to assess the benefits (risk reduction) and costs of adaptation measures under climate change. Therefore, it entails innovative materials and design strategies.

6.3 | Final Remarks

Based on the literature review, integrated assessments of sustainability and resilience have been explored with some methodological disagreements.

Most works do not provide an integrated sustainability and resilience assessment. Resilience assessment might be lacking because most works rely on structural verification according to current design codes. In terms of sustainability assessment, the SLR confirmed that the majority of works focus on sustainability and in particular cost and environmental metrics. In this group of research papers, risk assessment tools are usually used to evaluate the impact of natural hazards in life cycle analyses. Among them, the MCS method is preferred, as it allows the propagation of parameter uncertainties. A limited number of studies still favor deterministic approaches and do not perform uncertainty analyses. In such cases, designed measures are assumed to have inherently higher resilience, and the assessment compares different options based on measured sustainability metrics. Integrated sustainability and resilience assessment use can be found only in eight works. The complexity of the analyses increases, affecting the choice of tool for carrying out a risk assessment and the metrics to be measured. For most of the reviewed works, risk-integrated impact assessments are performed using the MCS tool to produce fragility curves. Some authors, however, argue that this can lead to time-consuming computational tasks. Works that exploit probabilistic approaches strongly reduce the number of measured sustainability metrics. Environmental performance metrics that are prioritized are Climate Change total and Waste; differently from works exploiting deterministic approaches, other environmental indicators (e.g., Acidification Potential, Land Use) are not measured. Economic analyses are limited to the assessment of Net Present Value and effects due to indirect costs. When measured (one out of seven studies), social metrics refer to missed travels. The first-order reliability theory or multi-criteria decision analysis are alternatives to probabilistic approaches and the Monte Carlo Simulation tool.

Overall, it can be noted that in all studies, the social dimension is not assessed on the basis of the entire life cycle of the built system. While the environmental impact and cost analyses are based on metrics that are primarily to be evaluated over the entire life cycle (production, operation and end-of-life phase), the selected and evaluated social metrics refer exclusively to the occurrence of an unexpected event (deaths, injuries due to natural disasters). Therefore, no work is found that performs an S-LCA; the social analyses focus on *losses*. This represents a certain obstacle to the development of a rational risk-integrated LCSA methodology.

Besides the methodological disagreements, the literature research highlighted a significant lack in terms of applications. Ordinary maintenance and replacement measures are evaluated depending on their relevance for the study. When a building system is subjected to a shock event, a repair measure is assumed to reestablish the initial structural performance (see Figure 6, traditional LCA approach). As a simplification, state-of-the-art approaches consider a constant technical requirement of the asset throughout its life. This is reflected by a functional equivalent established in the goal and scope of the life cycle analysis, which is unchanged over the duration of the analysis. A decline of the overall performance due to ongoing aging, deterioration, and corrosion phenomena and performance improvements, which are possible with refurbishment measures, are not considered (Potrč Obrecht et al. (2019)). This assumption can lead to some limitations, especially for hazard-prone contexts. It restricts the range of alternatives to reactive strategies. Meanwhile, the proposed approach aims to address the effects of performance decline and enhancement, thus advancing the current state of the art of LCA analyses (see Figure 6, proposed approach). Moreover, since proactive refurbishment activities are included in life cycle analysis, it enables the development of a novel methodology and tools for life cycle management that can compare proactive with reactive strategies and suggest best practices in terms of sustainability and structural resilience.

7 | Development of a Novel Framework for Integrated Resilience and Sustainability Assessment

Based on these observations in the previous section, a proposal for a novel framework can be outlined (see Figure 7). The novel framework consists of a two-step assessment and aims to support stakeholders within the life cycle management while deciding *which construction work should be carried out* and *when the best point in time to perform it is.*

It consists of six main tasks, from Task 1a (T1a) to Task 5 (T5). Each task can have subtasks. Subtasks belonging to the same task are represented by square elements and have equal shape fill (see legend in Figure 7). The output of each task is represented by rectangles with rounded corners and shape outlines identical to the color assigned to the task. Input and final output are shown with red shape outlines. Sustainability and resilience experts are responsible for the tasks on the left side; meanwhile, designers carry out tasks on the right side of Figure 7. Task 1a (Model establishment) and Task 1b (Measures' preliminary design) can also be carried

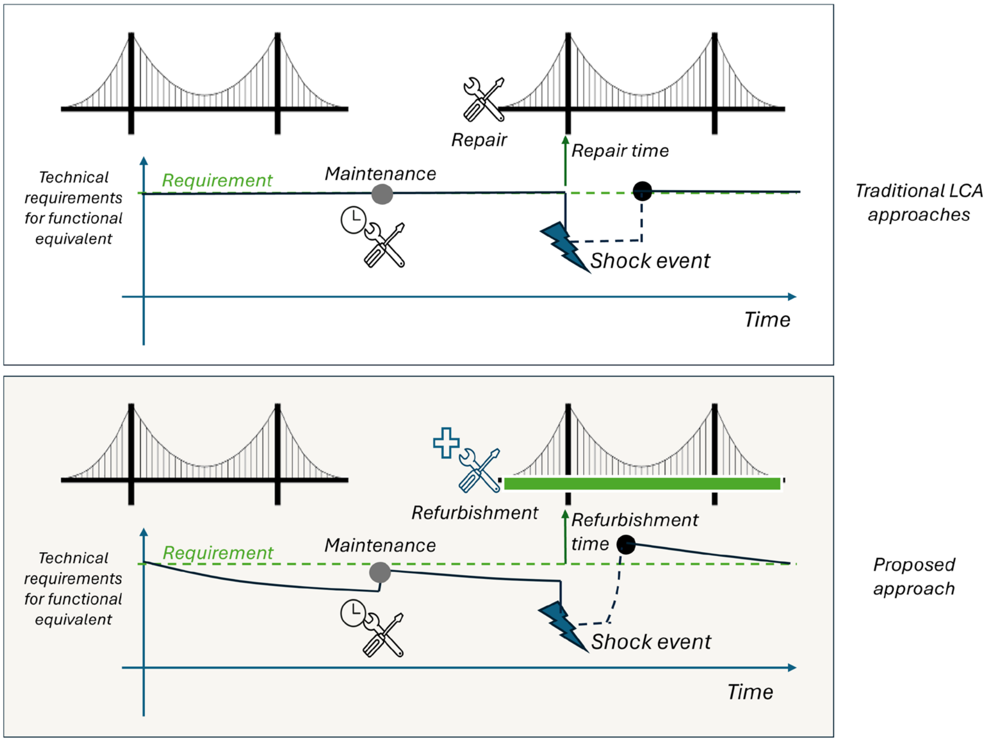


FIGURE 6 | Lack of applicability. Difference between state of the art and proposed approach. For simplicity, the effect of just one maintenance activity is depicted.

out concurrently. As a next task, a first static resilience and sustainability assessment is carried out, aiming at optimizing the design of the selected maintenance, repair, and refurbishment measures (T2). After the design optimization, a second assessment is set up (T3) and carried out for a second time. The second assessment takes into account the dynamic (here also called "evolutionary") performance of the construction (T4). Finally, the results are interpreted (T5) by all stakeholders. Details of each task are described in the following.

7.1 | Model Establishment

The output of this task is a list of relevant metrics and information regarding their interdependencies (see Figure 7). The model established is in line with Framework 3, as defined in Section 2. Four different *domains* (resilience, environmental, economic and social sustainability) are considered. None of the four domains is particularly prioritised, and interdependencies among different metrics are investigated.

7.1.1 | Selection of Metrics

The literature review highlighted a lack of studies with an extended list of sustainability indicators. Barriers for the assessment include low maturity of available methodologies, limited data availability, and the fragmented incorporation of the environmental, economic, and social dimensions Poderytė et al. (2025), Berges-Alvarez et al. (2024). To bridge this gap, during the model establishment, an extended list of sustainability indicators is selected and measured in T2 and T4 based on requirements of the analysis, uncertainties related to the evaluation methods, and data availability. Moreover, sustainability metrics obtained with quantitative methods (mathematical, economic methods, simulation, statistics) are preferred to ensure the accuracy of sustainability evaluations and foster more resilient and informed decision-making (Cerchione et al. 2025). If possible, resilience and sustainability metrics are evaluated over the whole life cycle, aiming at depicting long-term opportunities and losses. The four main resilience metrics outlined in Section 2.2 are maintained, following the *4R Resilience* Framework (see Section 2.2).

Relevant environmental sustainability metrics to be assessed are presented in Table 3. In comparison with the existing literature, which mostly focuses on the calculation of greenhouse gases and Climate Change total (CCtot), this list provides a wider set of metrics that quantify other impact categories to enable more informed decision-making. The investigated metrics are *direct* (embodied) and indirect impacts. In Table 3, a generic impact category (Embodied Impact—EI or Indirect Impact—II) is shown. Impact categories are selected from the list of environmental *core* impact indicators of the European standard EN 15804 + A2 (European Committee for Standardisation 2022). Examples are Climate Change biogenic (CCbio), Climate Change fossil (CCfoss), Acidification Potential (AP), Photochemical Ozone Creation Potential (POCP) and any other environmental impacts provided in Environmental Product Declarations (EPDs) and databases for construction materials. Impacts can also be derived dynamically, accounting for, or example, decarbonisation rates due to environmental improvements in the construction sector, as carried out in Di Bari et al. (2020). Along with the impact assessment, other environmental metrics can be considered. For instance, an Environmental Payback Period can

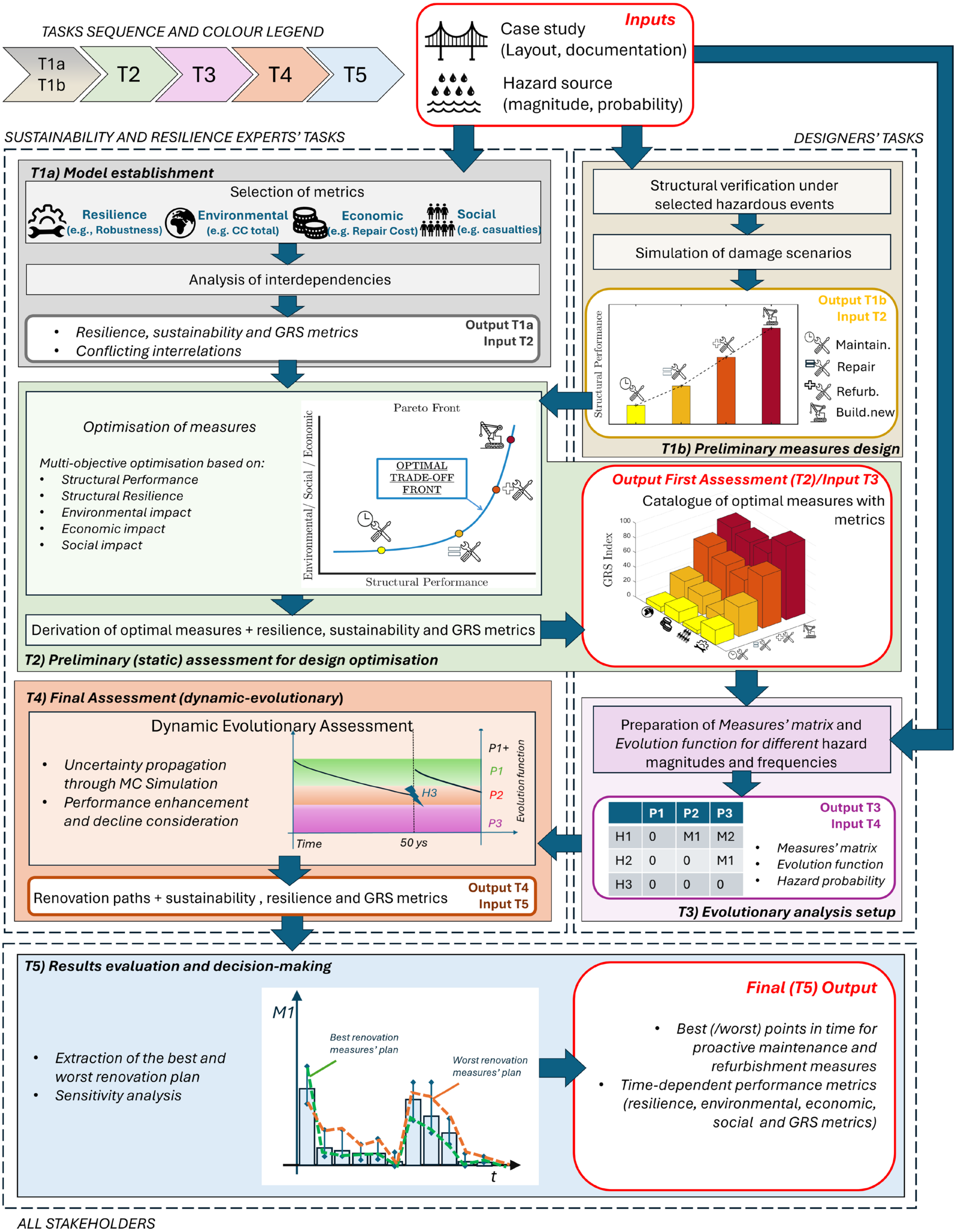


FIGURE 7 | Proposal for novel integrated sustainability and resilience assessment framework. Subtasks belonging to the same task are represented by square elements with the same shape fill colour (see colour legend). The output of each task is represented by rectangles with rounded corners and shape outlines identical to the colour assigned to the task. The input and final output are shown with red outlines.

TABLE 3 | Environmental sustainability metrics for novel framework proposal.

Indicator	Abbreviation	References
Embodied impact total	EI_{tot}	European Committee for Standardisation (2022)
Dynamic embodied Impact total	$EI_{dyn,tot}$	Di Bari et al. (2020)
Indirect impact total	II_{tot}	Navya Vishnu and Padgett (2023)
Indirect impact dynamic	$II_{tot,dyn}$	Navya Vishnu and Padgett (2023) and Di Bari et al. (2020)
Environmental payback	$PB_e nv$	
Recycling rate	$\%_{rec}$	Briz and Gandini (2023)
Reuse rate	$\%_{reu}$	Briz and Gandini (2023)

TABLE 4 | Economic sustainability metrics for novel framework proposal.

Indicator	Abbreviation	References
Direct costs total	C_{tot}	International Standardisation Organisation (2017)
Dynamic direct costs total	$C_{dyn,tot}$	Di Bari et al. (2020)
Indirect cost total	IC_{tot}	Mitoulis et al. (2023)
Indirect cost dynamic	$IC_{tot,dyn}$	Based on (Mitoulis et al. (2023), Di Bari et al. (2020))
Public investment	Inv	Buggin et al. (2019)
Investment payback	$PB_e co$	Buggin et al. (2019)
Total cost max	TC_{max}	Di Bari et al. (2020)
Total cost min	TC_{min}	Di Bari et al. (2020)
Total cost average	TC_{av}	Di Bari et al. (2020)

be assessed if environmental credits due to, for example, CO_2 absorption due to concrete carbonation, are included in the system boundaries. Finally, to investigate the circularity of the used technologies, relevant metrics are selected and assessed, depending on goal and scope of the analysis (Heisel and Rau-Oberhuber (2020)). In Table 3, recycling and reuse rates are mentioned as an example of metrics that can be directly obtained from technical documentation and additional information provided in environmental databases for construction materials.

Economic sustainability metrics are summarized in Table 4. As for environmental sustainability metrics, a wider range of metrics is generated compared to the existing literature. The investigated metrics are *direct* and *indirect* costs. Costs are calculated dynamically, accounting for, for example, discounting and price increases (Di Bari et al. 2020).

TABLE 5 | Social sustainability metrics for novel framework proposal.

Indicator	Abbreviation	References
Fatalities	C_{tot}	Padgett and Li (2016)
Injuries	$C_{dyn,tot}$	Padgett and Li (2016)
Downtime	IC_{tot}	Padgett and Li (2016)
Repair time	$IC_{tot,dyn}$	Qiu et al. (2024)
Employment	Inv	Benoît et al. (2010), Basu and Lee (2022)
Public Safety	PB	Benoît et al. (2010), Basu and Lee (2022)
Access to infrastructure	TC_{max}	Benoît et al. (2010)
Cultural heritage	TC_{min}	Benoît et al. (2010)

Besides costs, that is, economic losses, it is necessary to derive economic opportunities. Therefore, public investments in building and infrastructure security need to be considered along with investment return. The latter is assessed based on the Economic Payback Period.

Relevant social sustainability metrics cover losses and opportunities (see Table 5). The presented metrics are selected from guidelines for S-LCA (Benoît et al. (2010)). As for most works found in this review, fatalities, injuries, downtime, and repair time need to be estimated based on experts' judgments, and historical data are considered. The increase in the number of people employed for work in strategic buildings and infrastructures also needs to be evaluated. The list also entails the perceived perception of public safety of buildings and constructions, access to infrastructure, and (for historical assets) cultural heritage.

Structural resilience metrics are identical to the ones presented in Section 2.2; following the 4R framework.

For each of the four domains, a unique index is derived based on the work carried out in Mitoulis et al. (2023) and Kopiika et al. (2025). This is called Global Resilience and Sustainability (GRS) Index.

7.1.2 | Multi-Domain Analyses Based on Interdependencies

In the framework here developed, *multi-domain* analyses are carried out based on interdependencies, as outlined in Section 2. This means that metrics affecting others belonging to different domains are identified. If one metric enhances others, this is called an *enhancer*. If, vice versa, a metric worsens others, it is *detrimental*. In this second case, conflicting interdependencies are detected and optimal solutions that trade off different performance metrics must be detected. The quantification of interdependencies can be carried out based on, for example, correlation analyses between pairs of metrics and the following derivation of correlation factors as carried out in the holistic quality model (HQM) of (Haag et al. (2024)).

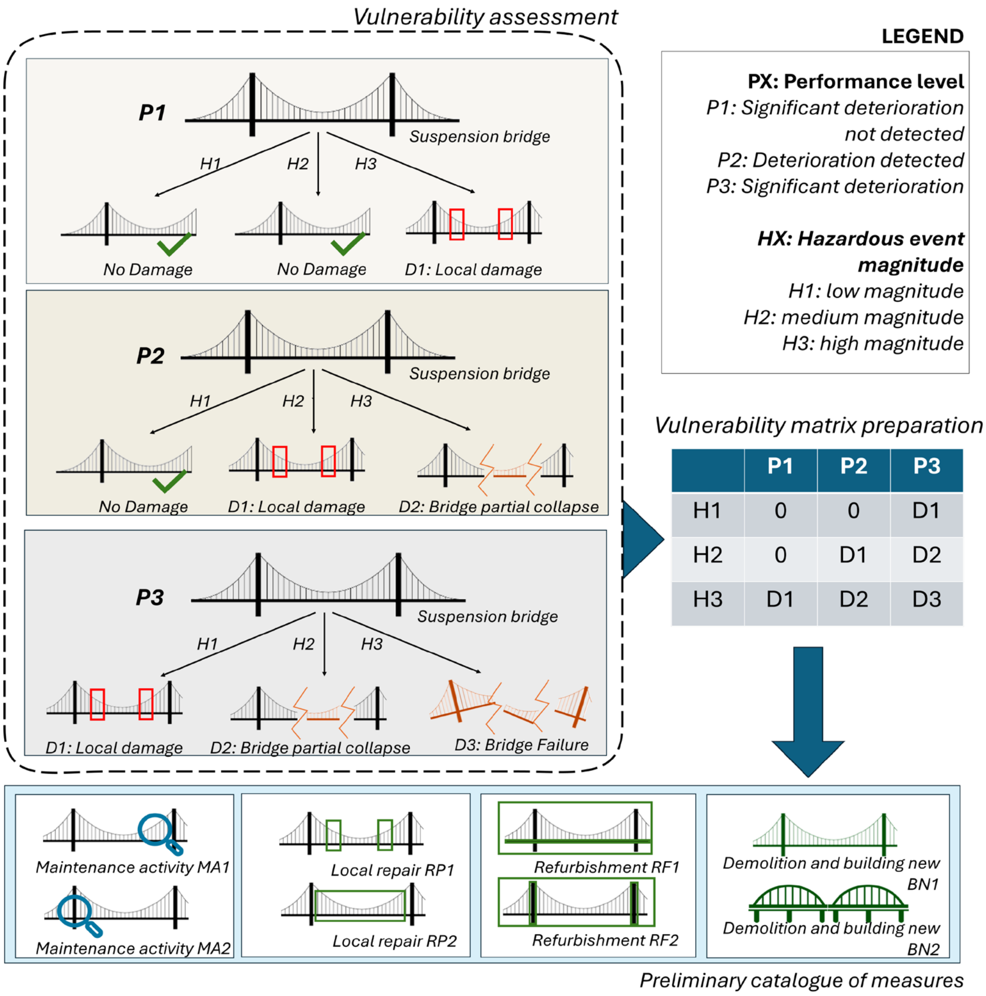
7.2 | Preliminary Design of Measures

The tasks of this step are mainly under the responsibility of designers.

The analysis of the case study and the identification of non-negligible hazard sources are inputs provided for the structural verification. Within this stage, the construction (building or infrastructure, new or existing) is verified for selected shock events. This allows for the derivation of damage scenarios.

In the example of a suspension bridge (see Figure 8), its performance under natural hazards can be affected by, for example, an ongoing deterioration. When the bridge performs like new construction (performance level P1 in 8) and no significant deterioration is detected, then the bridge will withstand loads as verified by designers. However, in the case of a shock event with extraordinary magnitude (in Figure 8, H3), the bridge could be damaged in its most vulnerable parts. If the same bridge presents significant deterioration and signs of aging (performance level P2), the asset will be more vulnerable to shock events with lower magnitudes (H1 and H2). In the worst-case scenario, this could lead to failures and collapses.

The information from structural performance simulation and fragility assessment fills in a matrix called the *vulnerability matrix*. The matrix allows for a more automatic selection of damage scenarios based on asset performance level and magnitude of a hazardous event. If the hazard source presents a dynamic nature, as for climate change and extreme events that are expected to increase their magnitude and frequency in the upcoming years, it will be necessary to consider such projections and



	P1	P2	P3
H1	0	0	D1
H2	0	D1	D2
H3	D1	D2	D3

FIGURE 8 | Vulnerability matrix and compilation of the preliminary measures' catalogue. Exemplification.

verify the structural performance of the assets under different shock events.

Based on the analyses of damage scenarios, measures to be implemented after shock events are designed. A preliminary catalogue of measures is prepared and will be the output of T1b (see Figure 7). The preliminary catalogue presents possible measures that can be performed, without accurate information regarding materials and quantities. The design of the measure is, at this stage, therefore only conceptual. However, for each measure, the expected structural performance can be identified. Possible measures entail maintenance, repair, or refurbishment as defined in Section 6.2, demolition, and building new activities, which could follow after major failures or total collapse (see Figure 8, BN1 and BN2). In Figure 8, maintenance activities like inspections of cables (MA1) and piers (MA2) are considered. Local repairs can be the substitution of damaged cables (RP1) and crack infills of decks (RP2). These re-establish the original structural performance. Refurbishment measures are the construction and installation of superstructures (RF1) or substructures (RF2). These can re-establish and also upgrade the structural performance of the bridge.

7.3 | Preliminary Assessment for Design Optimisation

As a second task of the developed framework, a first resilience and sustainability assessment of preliminary measure catalogues is carried out. The aim of this analysis is the identification of optimal design strategies. Relevant sustainability and resilience metrics are calculated for the generated design alternatives. A multiobjective optimisation between detrimental metrics can be carried out to identify trade-offs. The Pareto front generated at the end of the multiobjective optimisation will provide a list of optimised measures' options. This can be maintenance, repair, refurbishment, or building new interventions. For each of the designed options, their respective resilience, sustainability, and GRS metrics are derived (output of T2, see Figure 7).

This first assessment is *time-independent*. This means that the temporal dimension and the evolution of the construction are not considered. Within this stage, there is rather a focus on the design of measures that can be implemented. This stage provides the first output of the developed framework, that is, a list of options that can be performed, along with detailed design information and the respective performance metrics (resilience, environmental, economic, and social).

7.4 | Dynamic Evolutionary Assessment

Within the second step of the assessment, the temporal dimension and the *dynamic evolutionary* performance of building and infrastructure assets are considered. This represents a methodological novelty that bridges the applicability gap and enables the implementation of the approach outlined in Section 6 (see also Figure 6). The dynamic evolutionary assessment takes into account that the structural performance of assets can evolve and can *undergo* changing hazard conditions, or *react* and *adapt* to them. In particular, the design choices and points in time at which measures are performed could dictate the resilience and the environmental, economic, and social life cycle performance.

Based on the vulnerability matrix, a *matrix of measures* and the *evolution function* are established to carry out the dynamic evolutionary assessment (output of T3 in Figure 7).

The matrix of measures is a three-dimensional matrix that collects all possible combinations of measures, repair (RP), refurbishment (RF) and building new (BN) (see Figure 9), that can be carried out after the occurrence of shock events depending on the structural performance level of the asset. Structural performance evolution can be established based on literature, simulations, or experimental evidence. The number of combinations equals the matrix's third dimension. The number of hazardous events and the levels of structural performance, meanwhile, equal the number of rows and columns, respectively. The evolution function checks the time span and the structural performance before the provision of a measure. Depending on the evolution of the structural performance and the provided measures, the evolution function upgrades or downgrades the performance level.

The event occurrence is performed based on the hazard function and a random generation of an event (as proposed in the literature with a Monte Carlo Simulation—see Section 6.3). The generated hazard allows for the selection of a matrix row. The evolution function selects a column for each combination.

Figure 10 presents an exemplification based on the suspension bridge of Section 7.2, observed for 120 years. In the

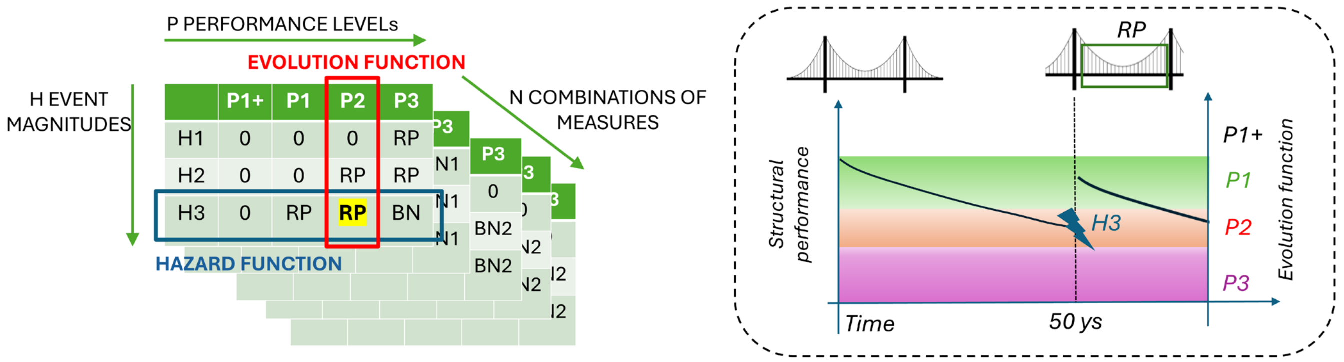
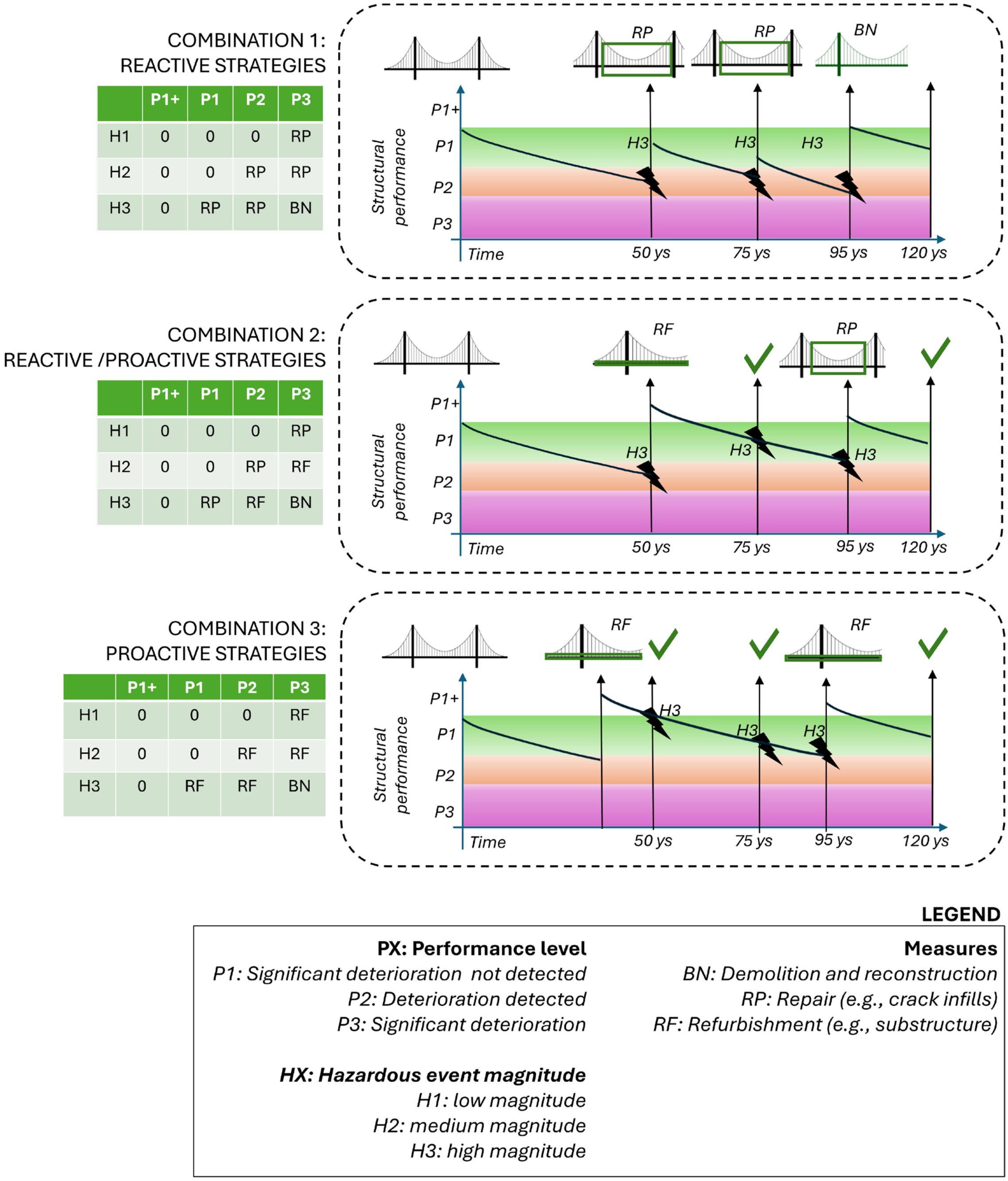


FIGURE 9 | Matrix of measures and selection of scenario based on hazard and evolution function.



COMBINATION 1: REACTIVE STRATEGIES

	P1+	P1	P2	P3
H1	0	0	0	RP
H2	0	0	RP	RP
H3	0	RP	RP	BN

COMBINATION 2: REACTIVE /PROACTIVE STRATEGIES

	P1+	P1	P2	P3
H1	0	0	0	RP
H2	0	0	RP	RF
H3	0	RP	RF	BN

COMBINATION 3: PROACTIVE STRATEGIES

	P1+	P1	P2	P3
H1	0	0	0	RF
H2	0	0	RF	RF
H3	0	RF	RF	BN

FIGURE 10 | Matrix of measures. Exemplification with three different combinations of measures.

exemplification, three possible combinations of measures are shown. Three shock events occur (50th, 75th and 95th years of the observation time), which have the same magnitude (H3) and frequency that increases over time (as projected for climate-change-related extreme events).

In the first combination, a full reactive strategy is undertaken. The performance level of the construction downgrades from P1 to P2 after 40 years due to ageing and consequent deterioration processes. In the 50th year, a shock event occurs. The damaged part of the bridge is repaired (with crack infills, e.g.). After the repair (RP in Figure 10), the structural performance improves, but the original performance cannot be ensured. In other words, the bridge does not perform like the early years of its service life. In the 75th year, another shock event occurs, and the bridge is repaired. The performance level is established (from P2 to P1). After 95 years, the structural performance is severely compromised by ageing, and the shock event leads to major failures. A new bridge (BN in Figure 10) is realized.

In the second combination, reactive and proactive strategies are undertaken. The performance level of the construction downgrades from P1 to P2 after 40 years due to aging and consequent deterioration processes. In the 50th year, a shock event occurs. The bridge is repaired and refurbished, for example with the provision of a substructure (RF in Figure 10). This allows for a service life extension. The performance upgrades to P1+. In the 75th year, a shock event occurs, and the bridge is not damaged. After 90 years, due to ongoing aging, the bridge is downgraded to P1. A shock event in the 95th year leads to repair measures; at the end of the observation time, the bridge is functional without significant deterioration issues.

In the third combination, a proactive strategy is considered. The performance level of the construction downgrades from P1 to P2 after 40 years due to aging and consequent deterioration processes. Proactive measures are undertaken, and the bridge is refurbished and provided with a substructure (RF in Figure 10). The performance upgrades to P1+. A shock event occurs in the 50th and 75th years without damage. The shock event in the 95th year leads to another refurbishment. At the end of the observation time, the bridge is functional.

As an output, this stage simulated all possible renovation pathways (output of T4 in Figure 7). The sustainability and resilience metrics are assessed for each path of renovation work. It is a responsibility of all stakeholders to evaluate the results and identify the best and worst renovation paths. Moreover, stakeholders identify the best and worst points in time at which specific proactive measures can be implemented (T5 final output in Figure 7). Though the generality of the proposed theoretical framework is mainly devoted to analyze the effect of different structural intervention measures, the preferred intervention should be identified by balancing structural, economic, social, and environmental qualities (a) comparing different retrofitting solutions (e.g., repairing or refurbishment techniques) at the same time to solve specific criticalities deriving from the single shock event Cucuzza et al. (2025) (e.g., embodied carbon emission and cost calculation of different mortars for crack infills, fiber composite materials instead of steel/concrete jacketing for local interventions, partially demolition versus demolition and reconstruction, dissipative or active control systems instead of invasive consolidation of the sub-structures); (b) estimating a global rate of the interventions series along the entire service life of the asset in order to evaluate the optimal strategy (e.g., preferring non-invasive and sustainable repairing measures after 50 years like in the combination 1 versus impactful refurbishment actions since the beginning). In particular, the stakeholders will be able to define the best points in time to perform proactive measures that lower the risk of unexpected losses caused by shock events. Until now, the identified strategies refer to a single asset, while the proposed approach can also be extended to infrastructural networks and urban areas where the social impact could play a crucial role.

8 | Summary and Conclusions

This study deals with the topic of integrated assessment of resilience and sustainability. The definition of resilience is associated with the notion of *structural resilience*, while sustainability encompasses environmental, economic, and social domains. Methodologies and tools for the integrated assessment of resilience and sustainability are currently needed since climate change will affect cities and communities. To this purpose, sustainability and resilience are clearly defined along with their interdependencies. The analysis of the state of the art is carried out with a systematic literature review, which led to the analysis of 69 papers. Overall, the literature review demonstrates that the integrated use of resilience and sustainability assessment is still not widely performed. Most studies rely on current design codes. Only the next generation of design standards will take into account, for example, climate change's impact on structural design to enhance structural resilience. Furthermore, most work focuses on environmental and economic sustainability, while the social dimension is not widely considered.

These gaps are covered in the developed novel framework, which enhances integrated resilience and sustainability assessments to support stakeholders during the decision-making process and life cycle management of buildings and civil engineering works. The framework accounts for a wider set of structural resilience, environmental, economic and social metrics. Moreover, it provides methodological and applicability advancements. In fact, it can be used for new and existing buildings and infrastructure assets to plan renovation works by considering the evolutionary performance of the built systems in a two-step assessment. As a result, the developed framework contributes to enhancing resilience against climate change and natural hazards and achieving sustainable cities and communities.

In future works, the framework conceptualized here will be applied in a case study and specified for extreme weather events caused by climate change. The framework can also be applied to more complex infrastructure networks and urban areas. To this purpose, methodological adjustments are, however, required to assess properly sustainability and resilience metrics.

Acknowledgments

The research leading to these results has received funding from the European Union under HORIZON-MSCA-2021-SE-01, grant agreement No: 101086413, ReCharged—Climate-aware Resilience for Sustainable Critical and Interdependent Infrastructure Systems enhanced by emerging Digital Technologies.

Conflicts of Interest

The authors declare no conflicts of interest.

References

Abbass, K., M. Z. Qasim, H. Song, M. Murshed, H. Mahmood, and I. Younis. 2022. "A Review of the Global Climate Change Impacts, Adaptation, and Sustainable Mitigation Measures." *Environmental Science and Pollution Research* 29, no. 28: 42539–42559. https://doi.org/10.1007/s11356-022-19718-6.

Adhikari, P., H. Mahmoud, A. Xie, K. Simonen, and B. Ellingwood. 2020. "Life-Cycle Cost and Carbon Footprint Analysis for Light-Framed Residential Buildings Subjected to Tornado Hazard." *Journal of Building Engineering* 32: 101657. https://doi.org/10.1016/j.jobe.2020.101657. https://www.sciencedirect.com/science/article/pii/S2352710220308482.

Ahern, J. 2013. "Urban Landscape Sustainability and Resilience: The Promise and Challenges of Integrating Ecology With Urban Planning and Design." *Landscape Ecology* 28, no. 6: 1203–1212. https://doi.org/10.1007/s10980-012-9799-z.

Ahmadie Amiri, H., and H. E. Estekanchi. 2023. "Life Cycle Cost-Based Optimization Framework for Seismic Design and Target Safety Quantification of Dual Steel Buildings With Buckling-Restrained Braces." *Earthquake Engineering Amp; Structural Dynamics* 52, no. 13: 4048–4081. https://doi.org/10.1002/eqe.3864.

Angeles, K., D. Patsialis, A. A. Taflanidis, T. L. Kijewski-Correa, A. Buccellato, and C. Vardeman. 2021. "Advancing the Design of Resilient and Sustainable Buildings: An Integrated Life-Cycle Analysis." *Journal of Structural Engineering* 147, no. 3: 4020341. https://doi.org/10.1061/(asce)st.1943-541x.0002910.

Anwar, G. A., Y. Dong, and C. Zhai. 2020. "Performance-Based Probabilistic Framework for Seismic Risk, Resilience, and Sustainability Assessment of Reinforced Concrete Structures." *Advances in Structural Engineering* 23, no. 7: 1454–1472. https://doi.org/10.1177/1369433219895363.

Asadi, E., A. M. Salman, and Y. Li. 2019. "Multi-Criteria Decision-Making for Seismic Resilience and Sustainability Assessment of Diagrid Buildings." *Engineering Structures* 191: 229–246. https://doi.org/10.1016/j.engstruct.2019.04.049.

Ayoub, N., F. Musharavati, S. Pokharel, and H. A. Gabbar. 2015. "Risk Based Life Cycle Assessment Conceptual Framework for Energy Supply Systems in Large Buildings." *Journal of Cleaner Production* 107: 291–309. https://doi.org/10.1016/j.jclepro.2015.04.075. https://www.sciencedirect.com/science/article/pii/S0959652615004503.

Babashamsi, P., S. H. Khahro, H. A. Omar, et al. 2022. "Perspective of Life-Cycle Cost Analysis and Risk Assessment for Airport Pavement in Delaying Preventive Maintenance." *Sustainability* 14, no. 5: 2905. https://doi.org/10.3390/su14052905.

Backes, J. G., and M. Traverso. 2022. "Life Cycle Sustainability Assessment as a Metrics Towards Sdgs Agenda 2030." *Current Opinion in Green and Sustainable Chemistry* 38: 100683. https://doi.org/10.1016/j.cogsc.2022.100683.

Basu, D., and M. Lee. 2022. "Chapter 21 - A Combined Sustainability-Reliability Approach in Geotechnical Engineering." In *Risk, Reliability and Sustainable Remediation in the Field of Civil and Environmental Engineering*, edited by T. Roshni, P. Samui, D. Tien Bui, D. Kim, and R. Khatibi, 379–413. Elsevier. https://www.sciencedirect.com/science/article/pii/B9780323856980000290.

Belleri, A., and A. Marini. 2016. "Does Seismic Risk Affect the Environmental Impact of Existing Buildings?" *Energy and Buildings* 110: 149–158. https://doi.org/10.1016/j.enbuild.2015.10.048.

Benoît, C., G. A. Norris, S. Valdivia, et al. 2010. "The Guidelines for Social Life Cycle Assessment of Products: Just in Time!" *International Journal of Life Cycle Assessment* 15, no. 2: 156–163. https://doi.org/10.1007/s11367-009-0147-8.

Berges-Alvarez, I., A. Martínez-Rocamora, and M. Marrero. 2024. "A Systematic Review of Bim-Based Life Cycle Sustainability Assessment for Buildings." *Sustainability* 16, no. 24: 11070. https://doi.org/10.3390/su162411070.

Bocchini, P., D. M. Frangopol, T. Ummenhofer, and T. Zinke. 2014. "Resilience and Sustainability of Civil Infrastructure: Toward a Unified Approach." *Journal of Infrastructure Systems* 20, no. 2: 04014004. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000177.

Briz, E., and A. Gandini. 2023. "Improving the Resilience of Historic Areas Coping With Natural and Climate Change Hazards: Interventions Based on Multi-Criteria Methodology." *International Journal of Architectural Heritage* 18, no. 8: 1–28. https://doi.org/10.1080/15583058.2023.2218311.

Bruneau, M., S. E. Chang, R. T. Eguchi, et al. 2003. "A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities." *Earthquake Spectra* 19, no. 4: 733–752.

Bruneau, M., and A. Reinhorn. 2007. "Exploring the Concept of Seismic Resilience for Acute Care Facilities." *Earthquake Spectra* 23, no. 1: 41–62.

Buggin, A., M. L. Gennusa, G. Peri, et al. 2019. "Towards Resilient Cities: Advancements Allowed by a Multi-Criteria Optimization Tool to Face the New Challenges of European Union's Climate and Energy Goals." *IOP Conference Series: Materials Science and Engineering* 609, no. 7: 72047. https://doi.org/10.1088/1757-899X/609/7/072047.

Cadenazzi, T., H. Lee, P. Suraneni, S. Nolan, and A. Nanni. 2021. "Evaluation of Probabilistic and Deterministic Life-Cycle Cost Analyses for Concrete Bridges Exposed to Chlorides." *Cleaner Engineering and Technology* 4: 100247. https://doi.org/10.1016/j.clet.2021.100247.

Cao, S., J. Wang, and T. K. T. Tse. 2023. "Life-Cycle Cost Analysis and Life-Cycle Assessment of the Second-Generation Benchmark Building Subject to Typhoon Wind Loads in Hong Kong." *Structural Design of Tall and Special Buildings* 32, no. 11–12: e2014. https://doi.org/10.1002/tal.2014.

Centre for Science and Technology Studies, Leiden University. 2023. "Vosviewer: Visualizing Scientific Landscape, 1.6.20." https://www.vosviewer.com/.

Cerchione, R., M. Morelli, R. Passaro, and I. Quinto. 2025. "A Critical Analysis of the Integration of Life Cycle Methods and Quantitative Methods for Sustainability Assessment." *Corporate Social Responsibility and Environmental Management* 32, no. 2: 1508–1544. https://doi.org/10.1002/csr.3010.

Chhabra, J. P. S., V. Hasik, M. M. Bilec, and G. P. Warn. 2018. "Probabilistic Assessment of the Life-Cycle Environmental Performance and Functional Life of Buildings due to Seismic Events." *Journal of Architectural Engineering* 24, no. 1: 04017035. https://doi.org/10.1061/(asce)ae.1943-5568.0000284.

Cimellaro, G. P., A. M. Reinhorn, and M. Bruneau. 2010. "Framework for Analytical Quantification of Disaster Resilience." *Engineering Structures* 32, no. 11: 3639–3649.

Commission, U.U.N.W. and Development. 1987. "Our Common Future (Brundtland Report)." http://www.un-documents.net/ocf-ov.htm.

Court, A., K. Simonen, M. Webster, W. Trusty, and P. Morris. 2012. Linking Next-Generation Performance-Based Seismic Design Criteria to Environmental Performance (Atc-86 and Atc-58), 922–928. https://doi.org/10.1061/9780784412367.082.

Cucuzza, R., G. Iovane, T. Lazzurri, J. Olivo, M. Domaneschi, and B. Faggiano. 2025. "Structural, Economic and Environmental Assessment of Steel and Timber Exoskeletons for the Retrofit of Rc Buildings." In *International Conference on Protection of Historical Constructions*, 334–339. Springer.

De Genaro Chiroli, D. M., M. G. Menezes, F. C. Zola, F. V. Aragão, R. D. de Almeida, and S. M. Tebcherani. 2023. "Integrating Resilience and Sustainability: A Systematic Analysis of Resilient Cities Using ISO 37123." *International Journal of Disaster Risk Reduction* 96: 103960. https://doi.org/10.1016/j.ijdrr.2023.103960.

De Luca Pena, L. V., S. E. Taelman, N. Preat, et al. 2022. "Towards a Comprehensive Sustainability Methodology to Assess Anthropogenic Impacts on Ecosystems: Review of the Integration of Life Cycle Assessment, Environmental Risk Assessment and Ecosystem Services Assessment." *Science Total Environment* 808: 152125. https://doi.org/10.1016/j.scitotenv.2021.152125.

Decò, A., and D. M. Frangopol. 2013. "Life-Cycle Risk Assessment of Spatially Distributed Aging Bridges Under Seismic and Traffic Hazards." *Earthquake Spectra* 29, no. 1: 127–153. https://doi.org/10.1193/1.4000094.

Di Bari, R., A. Belleri, A. Marini, R. Horn, and J. Gantner. 2020. "Probabilistic Life-Cycle Assessment of Service Life Extension on Renovated Buildings Under Seismic Hazard." *Buildings* 10, no. 3: 48. https://doi.org/10.3390/buildings10030048.

Dolce, M., A. Kappos, A. Masi, G. Penelis, and M. Vona. 2006. "Vulnerability Assessment and Earthquake Damage Scenarios of the

Building Stock of Potenza (Southern Italy) Using Italian and Greek Methodologies.” *Engineering Structures* 28, no. 3: 357–371.

Domaneschi, M., and R. Cucuzza. 2023. *Data Driven Methods for Civil Structural Health Monitoring and Resilience Latest Developments and Applications*, edited by M. Noori, C. Rainieri, M. Domaneschi, and V. Sarhosis. CRC Press. https://doi.org/10.1201/9781003306924.

Domaneschi, M., R. Cucuzza, R. Di Bari, S. Argyroudis, S. Mitoulis, and N. Kopiika. 2024. “Resilience and Sustainability Assessment of a Prestressed Concrete Viaduct.” In *Bridge Maintenance, Safety, Management, Digitalization and Sustainability*, 2594–2602. CRC Press.

Domaneschi, M., R. Cucuzza, L. Martinelli, M. Noori, and G. C. Marano. 2024. “A Probabilistic Framework for the Resilience Assessment of Transport Infrastructure Systems via Structural Health Monitoring and Control Based on a Cost Function Approach.” *Structure and Infrastructure Engineering*: 1–13. https://doi.org/10.1080/15732479.2024.2318231.

Dong, Y., D. M. Frangopol, and D. Saydam. 2013. “Time-Variant Sustainability Assessment of Seismically Vulnerable Bridges Subjected to Multiple Hazards.” *Earthquake Engineering and Structural Dynamics* 42, no. 10: 1451–1467. https://doi.org/10.1002/eqe.2281.

El-Din, M. N., and J. Kim. 2016. “Simplified Seismic Life Cycle Cost Estimation of a Steel Jacket Offshore Platform Structure.” *Structure and Infrastructure Engineering* 13, no. 8: 1027–1044. https://doi.org/10.1080/15732479.2016.1233286.

Eleftheriadou, A. K., and A. I. Karabinis. 2013. “Evaluation of Damage Probability Matrices From Observational Seismic Damage Data.” *Earthquakes and Structures* 4, no. 3: 299–324.

El-Khoury, O., A. Shafieezadeh, and E. Fereshtehnejad. 2018. “A Risk-Based Life Cycle Cost Strategy for Optimal Design and Evaluation of Control Methods for Nonlinear Structures.” *Earthquake Engineering and Structural Dynamics* 47, no. 11: 2297–2314. https://doi.org/10.1002/eqe.3069.

Elmqvist, T. 2017. “Development: Sustainability and Resilience Differ.” *Nature* 546, no. 7658: 352. https://doi.org/10.1038/546352d.

Elmqvist, T., E. Andersson, N. Frantzeskaki, et al. 2019. “Sustainability and Resilience for Transformation in the Urban Century.” *Nature Sustainability* 2, no. 4: 267–273. https://doi.org/10.1038/s41893-019-0250-1.

European Committee for Standardisation. 2022. “Sustainability of Construction Works - Environmental Product Declarations - Core Rules for the Product Category of Construction Products.”

European Committee for Standardisation. 2023. “Sustainability of Construction Work - Assessment of Environmental Performance of Buildings - Calculation Method.”

Fahimnia, B., J. Sarkis, and S. Talluri. 2019. “Editorial: Design and Management of Sustainable and Resilient Supply Chains.” *IEEE Transactions on Engineering Management* 66, no. 1: 2–7. https://doi.org/10.1109/TEM.2018.2870924.

Fajfar, P., and P. Gašperšič. 1996. “The n2 Method for the Seismic Damage Analysis of Rc Buildings.” *Earthquake Engineering & Structural Dynamics* 25, no. 1: 31–46.

Fawzy, S., A. I. Osman, J. Doran, and D. W. Rooney. 2020. “Strategies for Mitigation of Climate Change: A Review.” *Environmental Chemistry Letters* 18, no. 6: 2069–2094. https://doi.org/10.1007/s10311-020-01059-w.

Fereshtehnejad, E., and A. Shafieezadeh. 2016. “Multiple Hazard Incidents Lifecycle Cost Assessment of Structural Systems Considering State-Dependent Repair Times and Fragility Curves.” *Earthquake Engineering and Structural Dynamics* 45, no. 14: 2327–2347. https://doi.org/10.1002/eqe.2764.

Fereshtehnejad, E., and A. Shafieezadeh. 2018. “A Multi-Type Multi-Occurrence Hazard Lifecycle Cost Analysis Framework for Infrastructure Management Decision Making.” *Engineering Structures* 167: 504–517. https://doi.org/10.1016/j.engstruct.2018.04.049.

Fiksel, J. 2015. “Looking Ahead: From Resilience to Sustainability.” In *Resilient by Design*, 209–222. Island Press. https://doi.org/10.5822/978-1-61091-588-5_12.

Finkbeiner, M., E. M. Schau, A. Lehmann, and M. Traverso. 2010. “Towards Life Cycle Sustainability Assessment.” *Sustainability* 2, no. 10: 3309–3322. https://doi.org/10.3390/su2103309.

Francis, R. A., S. M. Falconi, R. Nateghi, and S. D. Guikema. 2010. “Probabilistic Life Cycle Analysis Model for Evaluating Electric Power Infrastructure Risk Mitigation Investments.” *Climatic Change* 106, no. 1: 31–55. https://doi.org/10.1007/s10584-010-0001-9.

Freeman, S. A. 2004. “Review of the Development of the Capacity Spectrum Method.” *ISET Journal of Earthquake Technology* 41, no. 1: 1–13.

Frost, D., O. Gericke, R. Di Bari, et al. 2022. “Holistic Quality Model and Assessment—Supporting Decision-Making Towards Sustainable Construction Using the Design and Production of Graded Concrete Components as an Example.” *Sustainability* 14, no. 18: 11269. https://doi.org/10.3390/su141811269.

Furuta, H., D. M. Frangopol, and K. Nakatsu. 2011. “Life-Cycle Cost of Civil Infrastructure With Emphasis on Balancing Structural Performance and Seismic Risk of Road Network.” *Structure and Infrastructure Engineering* 7, no. 1–2: 65–74. https://doi.org/10.1080/15732471003588346.

Gantner, J., W. Fawcett, and I. Ellingham. 2018. “Probabilistic Approaches to the Measurement of Embodied Carbon in Buildings.” In *Embodied Carbon in Buildings*, edited by F. Pomponi, C. De Wolf, and A. Moncaster, 23–50. Springer. https://doi.org/10.1007/978-3-319-72796-7_2.

Gernaat, D. E. H. J., H. S. de Boer, V. Daioglou, S. G. Yalew, C. Müller, and D. P. van Vuuren. 2021. “Climate Change Impacts on Renewable Energy Supply.” *Nature Climate Change* 11, no. 2: 119–125. https://doi.org/10.1038/s41558-020-00949-9.

Gong, C., D. M. Frangopol, and M. Cheng. 2019. “Risk-Based Life-Cycle Optimal Dry-Docking Inspection of Corroding Ship Hull Tankers.” *Engineering Structures* 195: 559–567. https://doi.org/10.1016/j.engstruct.2019.05.063.

Guerrero, J. A. R., T. Y. Yang, and O. Swei. 2023. “Earthquake and Deterioration Inclusive Probabilistic Life Cycle Assessment (Edp-Lca) Framework for Buildings.” *Resilient Cities and Structures* 2, no. 3: 30–40. https://doi.org/10.1016/j.rcns.2023.05.003.

Guinée, J. 2016. *Life Cycle Sustainability Assessment: What Is It and What Are Its Challenges?* 45–68. Cham. https://doi.org/10.1007/978-3-319-20571-7_3.

Haag, P., L. Balangé, R. Di Bari, et al. 2024. “Development of the Holistic Quality Model and Assessment – Integrating the Economic Quality Aspect and Establishing an Extended Interrelation Analysis.” *Developments in the Built Environment* 19: 100511. https://doi.org/10.1016/j.dibe.2024.100511.

Han, S. H., H. N. Cho, T. J. Cho, S. W. Shin, and T. S. Kim. 2010. “Risk Assessments of Long-Span Bridges Considering Life-Cycle Cost Concept and Near-Fault Ground Motion Effect.” *International Journal of Steel Structures* 10, no. 1: 51–63. https://doi.org/10.1007/BF03249511.

Hashemi, M. J., A. Y. Al-Attraqchi, R. Kalfat, and R. Al-Mahaidi. 2019. “Linking Seismic Resilience Into Sustainability Assessment of Limited-Ductility Rc Buildings.” *Engineering Structures* 188: 121–136. https://doi.org/10.1016/j.engstruct.2019.03.021.

Hasik, V., J. P. S. Chhabra, G. P. Warn, and M. M. Bilec. 2017. *Investigation of the Sustainability and Resilience Characteristics of Buildings Including Existing and Potential Assessment Metrics*, edited by

J. V. Volz, 1019–1033. Oklahoma City Oklahoma, American Society of Civil Engineers. https://doi.org/10.1061/9780784480502.085.

Heisel, F., and S. Rau-Oberhuber. 2020. “Calculation and Evaluation of Circularity Indicators for the Built Environment Using the Case Studies of Umar and Madaster.” *Journal of Cleaner Production* 243: 118482. https://doi.org/10.1016/j.jclepro.2019.118482.

Hennequin, T., H. J. D. Sorup, Y. Dong, and K. Arnbjerg-Nielsen. 2018. “A Framework for Performing Comparative Lca Between Repairing Flooded Houses and Construction of Dikes in Non-Stationary Climate With Changing Risk of Flooding.” *Science of the Total Environment* 642: 473–484. https://doi.org/10.1016/j.scitotenv.2018.05.404.

Höjer, M., S. Ahlroth, K. H. Dreborg, et al. 2008. “Scenarios in Selected Tools for Environmental Systems Analysis.” *Journal of Cleaner Production* 16, no. 18: 1958–1970. https://doi.org/10.1016/j.jclepro.2008.01.008.

Hossain, K. A., and B. Gencturk. 2016. “Life-Cycle Environmental Impact Assessment of Reinforced Concrete Buildings Subjected to Natural Hazards.” *Journal of Architectural Engineering* 22, no. 4: A4014001. https://doi.org/10.1061/(ASCE)AE.1943-5568.0000153.

Huijbregts, M. 2002. “Uncertainty and Variability in Environmental Life-Cycle Assessment.” *International Journal of Life Cycle Assessment* 7, no. 3: 173. https://doi.org/10.1007/bf02994052.

Huijbregts, M. A. J. 1998. “Application of Uncertainty and Variability in LCA.” *International Journal of Life Cycle Assessment* 3, no. 5: 273–280. https://doi.org/10.1007/bf02979835.

International Energy Agency (IEA). 2022. “World Energy Outlook 2022.” https://iea.blob.core.windows.net/assets/830fe099-5530-48f2-a7c1-11f35d510983/WorldEnergyOutlook2022.pdf.

International Standardisation Organisation. 2006a. “Environmental Management- Life Cycle Assessment - Principles and Framework.”

International Standardisation Organisation. 2006b. “Environmental Management- Life Cycle Assessment - Requirements and Guidelines.”

International Standardisation Organisation. 2017. “Buildings and Constructed Assets - Service Life Planning. Part 5: Life-Cycle Costing.”

International Standardisation Organisation. 2024. “Environmental Management—Principles and Framework for Social Life Cycle Assessment.”

Jennings, B. J., E. D. Vugrin, and D. K. Belasich. 2013. “Resilience Certification for Commercial Buildings: A Study of Stakeholder Perspectives.” *Environment Systems and Decisions* 33, no. 2: 184–194. https://doi.org/10.1007/s10669-013-9440-y.

Jiang, L., L. Jiang, Y. Hu, J. Ye, and H. Zheng. 2020. “Seismic Life-Cycle Cost Assessment of Steel Frames Equipped With Steel Panel Walls.” *Engineering Structures* 211: 110399. https://doi.org/10.1016/j.engstruct.2020.110399.

Kleingesinds, S., O. Lavan, and I. Venanzi. 2020. “Life-Cycle Cost-Based Optimization of Mtmds for Tall Buildings Under Multiple Hazards.” *Structure and Infrastructure Engineering* 17, no. 7: 921–940. https://doi.org/10.1080/15732479.2020.1778741.

Kleingesinds, S., O. Lavan, and I. Venanzi. 2021. “Multihazard Life-Cycle Cost Optimization of Active Mass Dampers in Tall Buildings.” *Structure and Infrastructure Engineering* 21, no. 1: 89–111. https://doi.org/10.1080/15732479.2023.2190131.

Kleingesinds, S., O. Lavan, and I. Venanzi. 2023. “Multihazard Life-Cycle Cost Optimization of Active Mass Dampers in Tall Buildings.” *Structure and Infrastructure Engineering* 21, no. 1: 23–89. https://doi.org/10.1080/15732479.2023.2190131.

Kopiika, N., R. Di Bari, S. Argyroudis, J. Ninic, and S. A. Mitoulis. 2025. “Sustainability and Resilience-Driven Prioritisation for Restoring Critical Infrastructure After Major Disasters and Conflict.” *Transportation Research Part D: Transport and Environment* 139: 104592. https://doi.org/10.1016/j.trd.2025.104592.

Lagaros, N. D. 2010. “The Impact of the Earthquake Incident Angle on the Seismic Loss Estimation.” *Engineering Structures* 32, no. 6: 1577–1589. https://doi.org/10.1016/j.engstruct.2010.02.006.

Lanza, C., P. Gardoni, L. Giresini, and M. Sassu. 2022. “A Stochastic Formulation to Assess the Environmental Impact of the Life-Cycle of Engineering Systems.” *Journal of Structural Engineering* 148, no. 1. https://doi.org/10.1061/(asce)st.1943-541x.0003201.

Leal Msc, O. J. U., A. Fekete, R. R. Eudave, J. C. Matos, H. Sousa, and E. R. Teixeira. 2024. “A Systematic Review of Integrated Frameworks for Resilience and Sustainability Assessments for Critical Infrastructures.” *Structural Engineering International* 34, no. 2: 266–280. https://doi.org/10.1080/10168664.2023.2265965.

Lew, A. A., P. T. Ng, C.-c. (N.) Ni, and T.-c. (E.) Wu. 2016. “Community Sustainability and Resilience: Similarities, Differences and Indicators.” *Tourism Geographies* 18, no. 1: 18–27. https://doi.org/10.1080/14616688.2015.1122664.

Linkov, I., D. Loney, S. Cormier, F. K. Satterstrom, and T. Bridges. 2009. “Weight-of-Evidence Evaluation in Environmental Assessment: Review of Qualitative and Quantitative Approaches.” *Science of the Total Environment* 407, no. 19: 5199–5205. https://doi.org/10.1016/j.scitotenv.2009.05.004.

Lounis, Z., and T. P. McAllister. 2016. “Risk-Based Decision Making for Sustainable and Resilient Infrastructure Systems.” *Journal of Structural Engineering* 142, no. 9. https://doi.org/10.1061/(asce)st.1943-541x.0001545.

Mahmoud, H., and G. Cheng. 2017. “Framework for Lifecycle Cost Assessment of Steel Buildings Under Seismic and Wind Hazards.” *Journal of Structural Engineering* 143, no. 3. https://doi.org/10.1061/(asce)st.1943-541x.0001663.

Marchese, D., E. Reynolds, M. E. Bates, H. Morgan, S. S. Clark, and I. Linkov. 2018. “Resilience and Sustainability: Similarities and Differences in Environmental Management Applications.” *Science of the Total Environment* 613-614: 1275–1283. https://doi.org/10.1016/j.scitotenv.2017.09.086.

Matthews, E., C. J. Friedland, and F. Orooji. 2016a. “Optimization of Sustainability and Flood Hazard Resilience for Home Designs.” *Procedia Engineering* 145: 525–531. https://doi.org/10.1016/j.proeng.2016.04.040.

Matthews, E. C., C. J. Friedland, and F. Orooji. 2016b. “Integrated Environmental Sustainability and Resilience Assessment Model for Coastal Flood Hazards.” *Journal of Building Engineering* 8: 141–151. https://doi.org/10.1016/j.jobe.2016.08.002.

Mauro, G., C. Menna, U. Vitiello, et al. 2017. “A Multi-Step Approach to Assess the Lifecycle Economic Impact of Seismic Risk on Optimal Energy Retrofit.” *Sustainability* 9, no. 6: 989. https://doi.org/10.3390/su9060989.

McKay, D. I. A., A. Staal, J. F. Abrams, et al. 2022. “Exceeding 1.5°c Global Warming Could Trigger Multiple Climate Tipping Points.” *Science* 377, no. 6611: eabn7950. https://doi.org/10.1126/science.abn7950.

Menna, C., D. Asprone, F. Jalayer, A. Prota, and G. Manfredi. 2012. “Assessment of Ecological Sustainability of a Building Subjected to Potential Seismic Events During Its Lifetime.” *International Journal of Life Cycle Assessment* 18, no. 2: 504–515. https://doi.org/10.1007/s11367-012-0477-9.

Mirzaeefard, H., M. Mirtaheri, and M. A. Hariri-Ardebili. 2021. “Life-Cycle Cost Analysis of Pile-Supported Wharves Under Multi-Hazard Condition: Aging and Shaking.” *Structure and Infrastructure Engineering* 19, no. 2: 269–289. https://doi.org/10.1080/15732479.2021.1940216.

Mitoulis, S. A., D. V. Bompa, and S. Argyroudis. 2023. "Sustainability and Climate Resilience Metrics and Trade-Offs in Transport Infrastructure Asset Recovery." *Transportation Research Part D: Transport and Environment* 121: 103800. https://doi.org/10.1016/j.trd.2023.103800.

Murtagh, N., L. Scott, and J. Fan. 2020. "Sustainable and Resilient Construction: Current Status and Future Challenges." *Journal of Cleaner Production* 268: 122264. https://doi.org/10.1016/j.jclepro.2020.122264.

Narjabadifam, P., F. Karazmay, M. Noori, et al. 2025. "Resilience-Based Assessment of Seismic Risk by Investigating the Socioeconomic and Structural Earthquake Engineering Factors." *Environmental Earth Sciences* 84, no. 10: 1–24.

Navya Vishnu, S. K., and J. E. Padgett. 2023. "Road Transportation Network Hazard Sustainability and Resilience: Correlations and Comparisons." *Structure and Infrastructure Engineering* 19, no. 3: 345–365. https://doi.org/10.1080/15732479.2021.1945114.

Noshadravan, A., T. R. Miller, and J. G. Gregory. 2017. "A Lifecycle Cost Analysis of Residential Buildings Including Natural Hazard Risk." *Journal of Construction Engineering and Management* 143, no. 7. https://doi.org/10.1061/(asce)co.1943-7862.0001286.

Noureldin, M., and J. Kim. 2020. "Parameterized Seismic Life-Cycle Cost Evaluation Method for Building Structures." *Structure and Infrastructure Engineering* 17, no. 3: 425–439. https://doi.org/10.1080/15732479.2020.1759656.

Nydahl, H., S. Andersson, A. P. Åstrand, and T. Olofsson. 2022. "Extended Building Life Cycle Cost Assessment With the Inclusion of Monetary Evaluation of Climate Risk and Opportunities." *Sustainable Cities and Society* 76: 103451. https://doi.org/10.1016/j.scs.2021.103451.

Omidian, P., and N. Khaji. 2023. "A Total Life-Cycle Cost–Resilience Optimization Framework for Infrastructures Management Using Different Retrofit Strategies." *Sustainable and Resilient Infrastructure* 8, no. 6: 675–698. https://doi.org/10.1080/23789689.2023.2257516.

Opabola, E. A., and C. Galasso. 2024. "Informing Disaster-Risk Management Policies for Education Infrastructure Using Scenario-Based Recovery Analyses." *Nature Communications* 15, no. 1: 325.

Padgett, J. E. 2020. "The Quest for Multi-Hazard Resilient and Sustainable Infrastructure." *Life-Cycle Civil Engineering: Innovation, Theory and Practice - Proceedings of the 7th International Symposium on Life-Cycle Civil Engineering, IALCCE* 2020: 78–87. https://doi.org/10.1201/9780429343292-7.

Padgett, J. E., K. Dennemann, and J. Ghosh. 2010. "Risk-Based Seismic Life-Cycle Cost–Benefit (lcc-b) Analysis for Bridge Retrofit Assessment." *Structural Safety* 32, no. 3: 165–173. https://doi.org/10.1016/j.strusafe.2009.10.003.

Padgett, J. E., and Y. Li. 2016. "Risk-Based Assessment of Sustainability and Hazard Resistance of Structural Design." *Journal of Performance of Constructed Facilities* 30, no. 2: 4014208. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000723.

Plumblee, J., and L. Klotz. 2014. "Marlo's Windows: Why It Is a Mistake to Ignore Hazard Resistance in Lca." *International Journal of Life Cycle Assessment* 19, no. 6: 1173–1178. https://doi.org/10.1007/s11367-014-0741-2.

Poderytė, I., N. Banaitienė, and A. Banaitis. 2025. "Life Cycle Sustainability Assessment of Buildings: A Scientometric Analysis." *Buildings* 15, no. 3: 381. https://doi.org/10.3390/buildings15030381.

Potrč Obrecht, T., R. Kunič, S. Jordan, and A. Legat. 2019. "Roles of the Reference Service Life (Rsl) of Buildings and the Rsl of Building Components in the Environmental Impacts of Buildings." *IOP Conference Series: Earth and Environmental Science* 323, no. 1: 12146. https://doi.org/10.1088/1755-1315/323/1/012146.

Qiu, Z., A. Prabhakaran, L. Su, and Y. Zheng. 2024. "Multihazard Resilience and Sustainability Evaluation of Coastal Rc Bridges Under Sequential Earthquake-Tsunami Events." *Ocean Engineering* 299: 117208. https://doi.org/10.1016/j.oceaneng.2024.117208.

Redman, C. L. 2014. "Should Sustainability and Resilience Be Combined or Remain Distinct Pursuits?" *Ecology and Society* 19, no. 2: art37. https://doi.org/10.5751/ES-06390-190237.

Rojahn, C., R. L. Sharpe, R. E. Scholl, A. S. Kiremidjian, R. V. Nutt, and R. Wilson. 1986. "Earthquake Damage and Loss Evaluation for California." *Earthquake Spectra* 2, no. 4: 767–782.

Roostaie, S., and N. Nawari. 2022. "The Dematel Approach for Integrating Resilience Indicators Into Building Sustainability Assessment Frameworks." *Building and Environment* 207: 108113. https://doi.org/10.1016/j.buildenv.2021.108113.

Sajjad, M., J. C. Chan, and S. S. Chopra. 2021. "Rethinking Disaster Resilience in High-Density Cities: Towards an Urban Resilience Knowledge System." *Sustainable Cities and Society* 69: 102850. https://doi.org/10.1016/j.scs.2021.102850.

Salgado, R. A., and S. Guner. 2021. "A Structural Performance-Based Environmental Impact Assessment Framework for Natural Hazard Loads." *Journal of Building Engineering* 43: 102908. https://doi.org/10.1016/j.jobe.2021.102908.

Sánchez-Silva, M., P. Gardoni, D. V. Val, et al. 2024. "Moving Toward Resilience and Sustainability in the Built Environment." *Structural Safety* 43: 102449. https://doi.org/10.1016/j.strusafe.2024.102449.

Sangha, K. K., J. Russell-Smith, J. Evans, and A. Edwards. 2020. "Methodological Approaches and Challenges to Assess the Environmental Losses From Natural Disasters." *International Journal of Disaster Risk Reduction* 49: 101619. https://doi.org/10.1016/j.ijdrr.2020.101619.

Sauve, G., and K. Van Acker. 2021. "Integrating Life Cycle Assessment (Lca) and Quantitative Risk Assessment (Qra) to Address Model Uncertainties: Defining a Landfill Reference Case Under Varying Environmental and Engineering Conditions." *International Journal of Life Cycle Assessment* 26, no. 3: 591–603. https://doi.org/10.1007/s11367-020-01848-z.

Schuldt, S. J., M. R. Nicholson, Y. A. Adams, and J. D. Delorit. 2021. "Weather-Related Construction Delays in a Changing Climate: A Systematic State-Of-The-Art Review." *Sustainability* 13, no. 5: 2861. https://doi.org/10.3390/su13052861.

Seo, D. W., and L. Caracoglia. 2013. "Estimating Life-Cycle Monetary Losses due to Wind Hazards: Fragility Analysis of Long-Span Bridges." *Engineering Structures* 56: 1593–1606. https://doi.org/10.1016/j.engstruct.2013.07.031.

Sesana, M. M., and P. Dell'Oro. 2024. "Sustainability and Resilience Assessment Methods: A Literature Review to Support the Decarbonization Target for the Construction Sector." *Energies* 17, no. 6: 1440. https://doi.org/10.3390/en17061440.

Shen, Z., H. Zhou, and S. Shrestha. 2021. "Lcc-Based Framework for Building Envelope and Structure Co-Design Considering Energy Efficiency and Natural Hazard Performance." *Journal of Building Engineering* 35: 102061. https://doi.org/10.1016/j.jobe.2020.102061.

Simon, F., J. Gironás, J. Rivera, et al. 2023. "Toward Sustainability and Resilience in Chilean Cities: Lessons and Recommendations for Air, Water, and Soil Issues." *Heliyon* 9, no. 7: e18191. https://doi.org/10.1016/j.heliyon.2023.e18191.

Soleimani-Chamkhorami, K., A. H. S. Garmabaki, A. Kasraei, S. M. Famurewa, J. Odelius, and G. Strandberg. 2024. "Life Cycle Cost Assessment of Railways Infrastructure Asset Under Climate Change Impacts." *Transportation Research Part D: Transport and Environment* 127: 104072. https://doi.org/10.1016/j.trd.2024.104072.

Spreafico, C. 2021. "A Review About Methods for Supporting Failure Risks Analysis in Eco-Assessment." *Environmental Monitoring and Assessment* 193, no. 7: 439. https://doi.org/10.1007/s10661-021-09175-y.

Stewart, M. G., and X. Deng. 2015. "Climate Impact Risks and Climate Adaptation Engineering for Built Infrastructure." *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering* 1, no. 1: 4014001. https://doi.org/10.1061/ajrua6.0000809.

Streatfield, D., and S. Markless. 2009. "What Is Impact Assessment and Why Is It Important?" *Performance Measurement and Metrics* 10, no. 2: 134–141. https://doi.org/10.1108/14678040911005473.

Tanguay, X., and B. Amor. 2024. "Assessing the Sustainability of a Resilient Built Environment: Research Challenges and Opportunities." *Journal of Cleaner Production* 458: 142437. https://doi.org/10.1016/j.jclepro.2024.142437.

Tapia, C., J. Ghosh, and J. E. Padgett. 2011. "Life Cycle Performance Metrics for Aging and Seismically Vulnerable Bridges." In *Structures Congress 2011, Las Vegas Nevada United States, American Society of Civil Engineers*, edited by D. Ames, T. L. Droessler, and M. Hoit, 1937–1948. ASCE. https://ascelibrary.org/doi/abs/10.1061/41171.

United Nations Environmental Programm. 2022. "Emissions Gap Report 2022." https://www.unep.org/resources/emissions-gap-report-2022.

United Nations, Department of Economic and Social Affairs Sustainable Development. 2015. "Transforming Our World: The 2030 Agenda for Sustainable Development." https://sdgs.un.org/publications/transforming-our-world-2030-agenda-sustainable-development-17981.

Venanzi, I., O. Lavan, L. Ierimonti, and S. Fabrizi. 2018. "Multi-Hazard Loss Analysis of Tall Buildings Under Wind and Seismic Loads." *Structure and Infrastructure Engineering* 14, no. 10: 1295–1311. https://doi.org/10.1080/15732479.2018.1442482.

Weber, M. M. 2023. "The Relationship Between Resilience and Sustainability in the Organizational Context—A Systematic Review." *Sustainability* 15, no. 22: 15970. https://doi.org/10.3390/su152215970.

Whitman, R. V. 1973. "Damage Probability Matrices for Prototype Buildings." *Structures* Publication, 380.

Wulf, C., J. Werker, P. Zapp, A. Schreiber, H. Schlör, and W. Kuckshinrichs. 2018. "Sustainable Development Goals as a Guideline for Indicator Selection in Life Cycle Sustainability Assessment." *Procedia CIRP* 69: 59–65. https://doi.org/10.1016/j.procir.2017.11.144.

Wuni, I. Y. 2024. "Developing a Multidimensional Risk Assessment Model for Sustainable Construction Projects." *Engineering Construction and Architectural Management* 32: 4155–4173. https://doi.org/10.1108/ecam-11-2023-1201.

Xue, F., B. Luan, Y. Fan, et al. 2024. "Assessing the Lifecycle Environmental Resilience of Urban Green Infrastructures Coping With Acute Disturbances and Chronic Stresses." *Water* 16, no. 8: 1162. https://doi.org/10.3390/w16081162.

Zheng, Y., Y. Dong, and Y. Li. 2018. "Resilience and Life-Cycle Performance of Smart Bridges With Shape Memory Alloy (SMA)-Cable-Based Bearings." *Construction and Building Materials* 158: 389–400. https://doi.org/10.1016/j.conbuildmat.2017.10.031.

Appendix A

Matrix for SLR

List of abbreviations	
OR	First order reliability method
AES	Aesthetic
AG	Aging
AP	Acidification potential
B/C	Benefit cost ratio
CC	Climate change hazard
Ccar	Social cost carbon
CCfos	Climate change fossil
CCtot	Climate change total
Cind	Indirect cost
Cinj	Social cost injuries
CO	Corrosion
D	Deterministic approach
Disturb	Disturbance
DT	Deterioration
DT	Downtime
Dur	Durability
EE	Embodied energy
Emp	Employment
Epfw	Eutrophication potential freshwater
Esav	Energy savings
Fat	Fatalities
FL	Floods
Func	Functionity
HU	Hurricane
Inj	Injuries
IRR	Investment return rate
LoP	Loss of performance/loss of functionality
LUP	Land use patterns
MCDA	Multi criteria decision analysis
MCS	Monte carlo simulation
MissTr	Missed travels
ND	Non-deterministic approach
NPV	Net present value
ODP	Ozone depletion potential
PACT	Performance assessment calculation tool
PB	Payback
PEr	Primary energy renewable
PubS	Public safety
RA	Risk assessment
REC	Recycling rate
Rec	Recovery time
RecT	Recovery time
Red	Redudancy
RepT	Repair time
Resp	Response
RI	Resilience index
RiskA	Risk avoidance
Rloss	Loss of resilience
Rob	Robustness
RU	Reuse rate
Sprov	Site provision
StrcInt	Structural integrity
TO	Tornados
TrD	Travel distance
TrT	Travel time
TS	Tsunami
UsT	User time
W	Wind
WDP	Water depletion potential
Wh	Work hours

TABLE A1 | SLR - methodology, part 1.

	Methodology							
	Sustainability							
	Metrics			RA			Resilience	Sust + Res
Source	Env	Eco	Social	Approach	Tool	Hazard	Metrics	Framework
Adhikari et al. (2020)	CCtot	NPV		ND	MCS	TO		0
Ahmadie Amiri and Estekanchi (2023)				ND	MCS	EQ; TS		0
Angeles et al. (2021)	EE	NPV		ND	MCS	EQ		0
Anwar et al. (2020)	CCtot			ND	MCS	EQ	Func	3
Asadi et al. (2019)	CCtot; EE; Pollution; WCD	NPV	Inj; DT; Fat	ND	MCDA	EQ	RepT	3
Ayoub et al. (2015)	CCtot; EPfw; ODP; AP; WDP			n/a		n/a		0
Babashamsi et al. (2022)		NPV		D/ND		DT	RepT	0
Di Bari et al. (2020)	CCtot	NPV		D/ND	MCS	EQ		0
Basu and Lee (2022)	CCtot; EE	NPV	Emp; PubS; AES; LUP	D		n/a	0	0
Belleri and Marini (2016)	CCtot	NPV		ND	PACT	EQ		0
Briz and Gandini (2023)	CCtot; RU; REC	NPV (+Cind)		n/a	MCDA	CC	LoP; RI; RecT	3
Buggin et al. (2019)	EE; CCtot; Esav	NPV; IRR; PB; Wh		D	MCDA	n/a		0
Cadenazzi et al. (2021)		NPV		D/ND	MCS	CH		0
Cao et al. (2023)	CCtot	NPV		D		T(CC)		0
Chhabra et al. (2018)	CCtot			ND	PACT	EQ		0
Court et al. (2012)	CCtot			ND	PACT	EQ		0
Decò and Frangopol (2013)		NPV (+Cind) (+Cinj)		ND	MCS	EQ		0
De Luca Pena et al. (2022)	CCtot	NPV	DT; Fat	D		EQ		0
El-Din and Kim (2016)		NPV		D		EQ		0
El-Khoury et al. (2018)		NPV		n/a		EQ		0
Fereshtehnejad and Shafieezadeh (2018)		NPV		ND	MCS	EQ	RecT	1
Fereshtehnejad and Shafieezadeh (2016)		NPV		ND	MCS	EQ; FL	RepT	1
Francis et al. (2010)	CCtot	NPV		ND	MCS	HU		0
Furuta et al. (2011)		NPV		D		EQ		0
Gong et al. (2019)		NPV		ND	MCS	CO		0
Guerrero et al. (2023)	CCtot			ND	MCS	EQ; DT		0
Han et al. (2010)		NPV		ND	MCS	EQ		0
Hashemi et al. (2019)	CCtot; EE	NPV	DT	D		EQ	LoP; RI; RecT	3
Hasik et al. (2017)				ND	MCS	n/a	StrucInt; SProv	0
(Hennequin, Sorup, et al. 2018)	CCtot; EPfw; ODP; AP; WDP; LU			D		FL		0
Hossain and Gencturk (2016)	CCtot; EPfw; ODP; AP; WDP; LU	NPV	DT; Fat; Inj; Disturb	D		EQ	0	0

TABLE A2 | SLR - methodology, part 2.

	Methodology							
	Sustainability							
	Metrics			RA			Resilience	Sust + Res
Source	**Env**	**Eco**	**Social**	**Approach**	**Tool**	**Hazard**	**Metrics**	**Framework**
Jiang et al. (2020)		NPV		D		EQ		0
Kleingesinds et al. (2023)		NPV		D		EQ		0
Kleingesinds et al. (2020)		NPV		D		EQ; W		0
Kleingesinds et al. (2021)		NPV		D		EQ; W		0
Lagaros (2010)		NPV (+Soc cost)		ND		EQ		0
Lanza et al. (2022)	CCtot			ND	MCS	EQ	Rob	1
Lounis and McAllister (2016)	CCtot; Waste	NPV (+Cind)	Accident; UsT	D		CO	LoP; RI; RecT	3
Mahmoud and Cheng (2017)		NPV		ND	1. OR	EQ; W		0
Matthews et al. (2016a)	CCtot; WDP; EE			ND	MCS	FL		0
Matthews et al. (2016b)	CCtot; WDP; EE			ND	MCS	FL		0
Mauro et al. (2017)		NPV		D		EQ		0
Menna et al. (2012)	CCtot; HH; EQ; ADP			D		EQ		0
Mirzaeefard et al. (2021)		NPV		D		CO; EQ		0
Mitoulis et al. (2023)	CCtot	NPV (+Cind)		D		CC	LoP; RI; RecT	3
Noshadravan et al. (2017)		NPV; PB		D		n.d.		0
Noureldin and Kim (2020)		NPV		D		EQ		0
Nydahl et al. (2022)		NPV (+Ccar)		D		n/a		0
Omidian and Khaji (2023)		NPV		D		EQ	Res index	3
Padgett (2020)				n/a		n/a		1
Padgett et al. (2010)		NPV		D		EQ		0
Padgett and Li (2016)	CCtot; EE	NPV	DT; Inj; Fat	D		EQ		0
Qiu et al. (2024)	CCtot	NPV	RepT	D		EQ; TS	RepT; Rloss	3
Roostaie and Nawari (2022)	Waste; Cctot; PEr			D		n/a	RiskA; Dur; Resp; Rec; Red	1
Salgado and Guner (2021)	CCtot; CCfos; AP; EP; ODP			D		EQ; TS		0
Seo and Caracoglia (2013)		NPV		ND	MCS	W		0
Shen et al. (2021)		NPV		D		EQ		0
Soleimani-Chamkhorami et al. (2024)		NPV		D		CC	RepT	1
Stewart and Deng (2015)		NPV; B/C		D		CC		0
Tapia et al. (2011)	CCtot; EE			D		AG; EQ		0
citevenanzi		NPV		D		EQ; W		0
Navya Vishnu and Padgett (2023)	CCtot (+ind)	NPV (+Cind)	MissTr	ND	MCS	EQ	TrT; TrD	1
citewuni2024					Fuzzy Set	n/a		0
Zheng et al. (2018)		NPV (+Cind)			1.RO	EQ	RepT; Rloss	1

TABLE A3 | SLR - Applicability.

	Applicability					
	Construction type		Activities			
	Building	Infrastructure	Maintenance	Repair	Refurbishment	Comments
Adhikari et al. (2020)	✓		✓	✓		
Ahmadie Amiri and Estekanchi (2023)	✓			✓		
Angeles et al. (2021)	✓			✓		
Anwar et al. (2020)	✓			✓		
Asadi et al. (2019)	✓			✓		
Ayoub et al. (2015)	✓					
Babashamsi et al. (2022)		✓	✓	✓		
Di Bari et al. (2020)	✓			✓	✓	
Basu and Lee (2022)		✓	✓	✓		MO opt
Belleri and Marini (2016)	✓			✓		
Briz and Gandini (2023)		✓		✓		
Buggin et al. (2019)	✓			✓	✓	
Cadenazzi et al. (2021)		✓	✓	✓		
Cao et al. (2023)	✓			✓		
Chhabra et al. (2018)	✓			✓		
Court et al. (2012)	✓			✓		
Decò and Frangopol (2013)		✓		✓		
Dong et al. (2013)		✓		✓		
El-Din and Kim (2016)		✓		✓		
El-Khoury et al. (2018)	✓		✓	✓		MO opti
Fereshtehnejad and Shafieezadeh (2016)		✓	✓	✓		
Fereshtehnejad and Shafieezadeh (2018)		✓	✓	✓		
Francis et al. (2010)		✓	✓	✓		
Furuta et al. (2011)			✓	✓		
Gong et al. (2019)		✓	✓	✓		
Guerrero et al. (2023)		✓		✓		
Han et al. (2010)		✓		✓		
Hashemi et al. (2019)	✓			✓		
Hasik et al. (2017)	✓		✓	✓		
(Hennequin, Sorup, et al. 2018)	✓			✓		
Hossain and Gencturk (2016)	✓			✓		Struc optimisation
Jiang et al. (2020)	✓			✓		
Kleingesinds et al. (2023)	✓			✓		MO opt
Kleingesinds et al. (2020)	✓			✓		MO opt
Kleingesinds et al. (2021)	✓			✓		MO opt
Lanza et al. (2022)	✓			✓		

(Continues)

TABLE A3 | (Continued)

	Applicability					
	Construction type		Activities			
	Building	Infrastructure	Maintenance	Repair	Refurbishment	Comments
Lounis and McAllister (2016)		✓	✓	✓		
Mahmoud and Cheng (2017)	✓			✓		
Matthews et al. (2016a)	✓			✓		
Matthews et al. (2016b)	✓			✓		
Mauro et al. (2017)	✓			✓	✓	Optimisation
Menna et al. (2012)	✓			✓		
Mirzaeefard et al. (2021)		✓	✓	✓		
Mitoulis et al. (2023)		✓		✓		
Noshadravan et al. (2017)	✓			✓		
Noureldin and Kim (2020)	✓			✓		
Nydahl et al. (2022)	✓			✓	✓	
Omidian and Khaji (2023)		✓		✓		Optimisation
Padgett (2020)		✓		✓		
Padgett et al. (2010)		✓		✓	✓	
Padgett and Li (2016)	✓	✓		✓		
Qiu et al. (2024)		✓		✓		
Roostaie and Nawari (2022)	✓		✓	✓		
Salgado and Guner (2021)	✓			✓		
Seo and Caracoglia (2013)		✓		✓		
Shen et al. (2021)		✓		✓	✓	
Soleimani-Chamkhorami et al. (2024)		✓		✓		
Stewart and Deng (2015)		✓		✓	✓ (adaptation)	
Tapia et al. (2011)		✓		✓		
Venanzi et al. (2018)		✓		✓		
Navya Vishnu and Padgett (2023)		✓		✓		
Wuni (2024)	✓	✓		✓		
Zheng et al. (2018)		✓		✓		