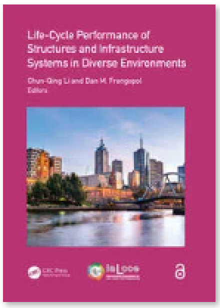

Life-Cycle Performance of Structures and Infrastructure Systems in Diverse Environments

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Editors

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Accessibility Information

Book

Life-Cycle Performance of Structures and Infrastructure Systems in Diverse Environments

Edited By Chun-Qing Li, Dan M. Frangopol

Edition	1st Edition
First Published	2025
eBook Published	14 July 2025
Pub. Location	London
Imprint	CRC Press
DOI	https://doi.org/10.1201/9781003595120
Pages	1920
eBook ISBN	9781003595120
Subjects	Engineering & Technology

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Citation

Life-Cycle Performance of Structures and Infrastructure Systems
in Diverse Environments – Li & Frangopol (Eds)

Life Cycle Structural Engineering: Enforcing LCT-based criteria from an early stage of the construction design to improve effective sustainability

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ABSTRACT: The transition to a more sustainable construction sector is crucial for reducing environmental impacts and enhancing the resilience of the built environment. By integrating Life Cycle Thinking (LCT) principles from the early stages of design, structural engineers can significantly influence the sustainability of a structure. Life Cycle Structural Engineering (LCSE) can indeed foster the design and construction of buildings that are not only efficient and resilient but also minimize environmental, economic, and social impacts over their entire life cycle.

This paper explores LCSE, outlining key principles for a sustainable and resilient construction sector and assessing compliance with global and European sustainability goals. Then, it discusses LCT-based design performance objectives, such as design for disassembly, adaptability, and durability. Technical choices, design targets and structural models/schemes aimed at translating the sustainable objectives into practice are finally introduced. Some best practice examples, in terms of innovative techniques and real applications, are also presented.

1 INTRODUCTION

The concept of sustainability was defined by UN in 1987 as “meeting the needs of the present without compromising the ability of future generations to meet their own needs” (Bruntland Report, UN 1987), considering the interaction of **environmental, social and economic aspects**, which are often referred to as the three dimensions/aspects/pillars of sustainability (Purvis et al., 2019). In 2015, UN also introduced 17 Sustainable Development Goals (SDGs), a “blueprint to achieve a better and more sustainable future for all.” (UN 2015a).

The construction sector, which is responsible for a great share of the globally generated impacts, embraced this traditional definition of sustainability, relating it to “how the attributes of the activities, products or services used in the construction works, or their use, contribute to the maintenance of ecosystem components and functions for future generations” (ISO 15932 2019). Concerning buildings and civil engineering works, ISO 15932 also specifies that the three pillars of sustainability should be pursued while also meeting the requirements for **technical and functional performances** of the construction works. Such “enlarged concept” of sustainability of the construction sector is also envisioned by the UN with the 11th SDG “sustainable cities and communities”,

DOI: 10.1201/9781003595120-35

which includes the concepts of safety and resilience, and by the UN Sendai Framework for Disaster Risk Reduction (2015), which relates sustainability to risk reduction. Also, the EU framework for sustainable buildings Level(s) (European Commission 2020) includes adaptation and resilience among its macro-objectives, but only with reference to climate change (Macro-objective 5).

The concept of sustainability is also historically related to the concept of **Life Cycle Thinking**, a holistic approach examining and minimizing the impacts of a product, a process, or an assembly of components, from raw materials extraction, through production, use, and final disposal (UNEP/SETAC 2012), while also maximizing multiple functional performances (Marini et al. 2017, Passoni et al. 2022a, b). The advantage of adopting a Life Cycle perspective, indeed, is to "allow decision makers to make choices that anticipate and optimally avoid any potential shifts of the environmental burden to other phases in the life cycle, to other impact categories, to other social groups, or in our globalized economy, to other regions of the world" (UNEP/SETAC 2012). The adoption of such an approach, recognized by ISO 15932 as one of the 9 fundamental principles for sustainability in construction sector, is thus essential for designers and structural engineering to design truly sustainable projects (Huang et al. 2020, Passoni et al. 2022a, b).

Although there is a general consensus about these definitions across the construction sector, there is a great confusion about the potential application of these concepts in practice. Being the stakeholders of this sector numerous, diverse and specialized in different expertise areas, the focus is often made on single, very sectorial aspects of sustainability, risking to lose the big picture. Codes, standards and frameworks contribute to fueling this confusion, addressing in every document different stakeholders, with different viewpoints, and defining from time to time different goals, principles, objectives and macro-objectives, targets, indicators, issues of concerns, metrics, etc. In such a scenario, there is an urgent need to define a shared language across the whole sector and provide practical indications to designers, with a particular focus on structural engineers.

In this contribution, the authors are aimed at shedding a light on this "multidimensional puzzle" – as defined by ISO 12720, with the scope of summarizing and systematizing the most relevant information that can be found in the standards and frameworks to support structural engineers during the design of sustainable buildings and civil engineering works.

In the following, a new three-level framework to classify concepts related to sustainability in the construction sector is proposed (Section 2) and some practical examples of translating abstract concepts into current design practices are presented (Section 3).

2 DESIGN PRINCIPLES, OBJECTIVES, CHOICES: A THREE-LEVEL CLASSIFICATION

A framework is first proposed to classify all the concepts connected to sustainability in the construction sector. This framework, which has structural engineers as the reference stakeholder, is defined by three levels of information:

1- Sustainability **principles**: universal concepts to be always pursuit in the design of a sustainable building or construction works.
2- Design **performance objectives**: LCT-based performance objectives for the design of sustainable constructions
3- Design **choices and criteria**: practical choices that should be adopted to translate design performance objectives into practice.

At the end of the design process, some **indicators** (i.e. metrics or KPI) should also be defined to allow designers to measure the level of sustainability of the designed buildings.

Sustainability principles are here defined according to the previously-discussed "enlarged vision" of sustainability, which should contextually pursue the minimization of the environmental, economic and social impacts, while maximizing technical and functional performances along the lifecycle of the structure and across geographical and generational boundaries. Sustainability principles should thus encompass: **functionality, safety and resilience, eco-efficiency, economic sustainability, social sustainability, equity, accessibility, health and comfort, circularity and adaptability**.

These principles, which are aimed at defining an extended concept of sustainability of the construction sector, should not be confused with the 9 “general principles for the contribution of construction works to sustainable development” introduced by ISO 15932, which are instead some guidelines about how the sustainability objectives may be reached.

Performance-based design, first introduced by SEAOC (2000), is the method currently adopted by designers to set structural targets and to conceive and design seismic resistant structural systems. Adopting the same approach, familiar to structural engineers, it is here proposed to introduce additional sustainability-oriented **performance objectives** inspired by Life Cycle Thinking and aimed at pursuing all the principles of sustainability through a multi-disciplinary approach. A review of these new performance objectives is reported in Table 1. In the Table, the performance objectives are related to the building life cycle phases, as defined in EN 15978 (2011), and to the design principles previously introduced. Reference is also made to the “sustainability objectives” of ISO 15932:2019 and ISO 12720:2024 and other references such as SDGs (UN 2015a), Level(s) (European Commission 2020), and the Sendai Framework (UN 2015b).

Table 1. LCT-based additional performance objectives inspired by the design principles for enlarged sustainability (note: in the table, reference is made to the objectives presented in ISO 15932 and ISO 12720, the reference standards for sustainability for construction works).

PRINCIPLE	PERFORMANCE OBJECTIVE (DESIGN FOR…)	LC PHASE	REF.
	provision of base requirements (provision of functionality, health, comfort, safety and accessibility) – (objective A in ISO 12720)		ISO 15932/ISO 12720
functionality	Serviceability (*objective A2 in ISO 12720*)	B2-B5	
	Functional flexibility (*objective A3 in ISO 12720*)	B2-B5	
	Durability and easy maintenance	B2-B5	
safety and resilience	Safety and resistance during exceptional events (*objective A8 in ISO 12720*)	B2-B5	+ Sendai Framework + SDG 1/11/13
	Resilience to exceptional events and loss reduction	B2-B5	+ Sendai Framework
	Resilience to climate change	B2-B5	+ Levels
accessibility	Accessibility for all (*objective A9 in ISO 12720*)	B2-B5	
health and comfort	Good indoor air quality (*objective A4 in ISO 12720*)	B2-B5	+ SDG11.6 + Levels (4.1)
	Good visual comfort (*objective A5 in ISO 12720*)	B2-B5	+ Levels (4.3)
	Good acoustic comfort (*objective A6 in ISO 12720*)	B2-B5	+ Levels (4.4)
	Good thermal comfort (*objective A7 in ISO 12720*)	B2-B5	+ Levels (4.2)
	adaptability – (objective H in ISO 12720)		ISO 15932/ISO 12720
adaptability	Adaptability for different uses (*objective H1 in ISO 12720*)	B2-B5	+ Levels (2.3)
	Adaptability in response to climate change (*objective H2 in ISO 12720*)	B2-B5	+ Levels (5) + SDG13.1
	Adaptability/flexibility in response to change in functional requirements (obsolescence) (*objective H3 in ISO 12720*)	B2-B5	+ Levels (2.3)
	provision of economic value over time – (objective D in ISO 12720)		ISO 15932/ISO 12720
economic sustainability	Economic viability (*objective D2 in ISO 12720*)	all	
	Removing barriers to renovation	A5	
	Consideration of impacts of the construction works and related activities on the local economy (*objective D5 in ISO 12720*) (also: design for easy construction)	A5	
	Life cycle cost optimization (*objective D3 in ISO 12720*)	all	+ Levels (6.1)
	Value over time (*objective D6 in ISO 12720*)	all	+ Levels (6.2)

(*Continued*)

Table 1. (*Continued*)

PRINCIPLE	PERFORMANCE OBJECTIVE (DESIGN FOR…)	LC PHASE	REF.
	provision of social and cultural value over time and for all – (objective E in ISO 12720)		ISO 15932/ISO 12720
equity	Contribution to social equity and improvement in the social climate (*objective E4 in ISO 12720*)	all	
social sustainability	Quality of social life (*objective E1 in ISO 12720*)	all	
	Quality of cultural life (*objective E2 in ISO 12720*) (also: design for preservation)	all	+ SDG11.4
	Security (*objective E3 in ISO 12720*)	all	
	Social and functional diversity (*objective E5 in ISO 12720*)	all	
	Socio-economic conditions (*objective E6 in ISO 12720*)	all	
	limitation of adverse environmental impacts and where possible, maintenance or provision of environmental value over time – (objective G in ISO 12720)		ISO 15932/ISO 12720
eco-efficiency	Use of resources (materials) (*objective G1 in ISO 12720*) (also: design for construction material sustainability)	A1; B2-B5	+ Levels (2.1, 2.2) + SDG12.2
	Energy resources consumption (*objective G2 in ISO 12720*)	all	+ Levels (1.1)
	Water resources consumption (in use - *objective G3 in ISO 12720*)	all	+ Levels (3.1)
	Efficiency of land use (*objective G4 in ISO 12720*)	A1, A5	
	Reduction of GHG emissions (*objective G5 in ISO 12720*)	all	+ Levels (1.2)
	Waste reduction and management (construction and operation - *objective G7 in ISO 12720*)	All	+ Levels (2.2) + SDG12.4
	Protection and/or enhancement of biodiversity (*objective G8 in ISO 12720*)	all	+ SDG11.4
	Reduction of construction site pollution (*objective G9 in ISO 12720*)	A5	
	Management of other Environmental Risks (*objective G10 in ISO 12720*)	all	
	minimization of adverse end-of-life impacts – (objective F in ISO 12720)		ISO 15932/ISO 12720
circularity	Ease of disassembly (*objective F1 in ISO 12720*)/ Deconstruction	B2-B5; C1	+ ISO 20887 + Levels (2.4)
	Recovery of materials for reuse and recycling potential (*objective F2 in ISO 12720*)	C1-C4; D	+ ISO 20887 + Levels (2.4) + SDG12.5

The achievement of these LCT-based performance objectives in practice can be reached by adopting new **design choices and criteria** that can be clustered into 7 different facets of the design:

- *Global design strategies* (e.g., coupling structural and energy upgrading measures, retrofit from the outside of the building, damage control, lumped into sacrificial elements, zero residual displacements, etc.)
- *Structural schemes* (e.g., schemes that reduce the impact of foundations, lumped dissipative replaceable devices, structural redundancy, etc.)
- *Structural techniques* (e.g., dry solutions, adoption of modularity, prefabrication, standardization, reusable elements, etc.)
- *Structural details* (e.g., recentering systems, demountable systems, dissipative devices, standard connections, etc.)
- *Materials* (e.g., recycled, recyclable, durable, reused, reusable, etc.)

- *Structural modelling* (e.g., evolution of material properties with time, evolution of risks with time, climate-change related risks, etc.)
- *Business models* (e.g., incremental rehabilitation, etc.)

A description of such choices and criteria may be found in the references of Table 1, or in sectorial papers such as Huang et al. 2020 or Passoni et al. 2022b, among others.

The pursuit of each design objective may require the adoption of one or more of these sustainable choices; on the other hand, each one of these choices may contribute to the achievement of more than one design objective (Figure 1). For example, “design for adaptability” may require some choices in terms of structural schemes, such as the adoption of wider column grid spans or non-loading bearing internal walls in new buildings, some choices in terms of structural techniques, such as easy prefabricated, dry, demountable, modular easily inspectable solutions, and these choices should be translated into structural details, such as, modular, standardized, dissipative elements, or dry reversible and plug and play connections. On the other hand, a single choice, such as the adoptions of a modular structural system, may impact multiple design objectives, such as “design for easy construction”, “design for maintenance”, “design for adaptability and flexibility”, “design for deconstruction and reuse”, etc.”

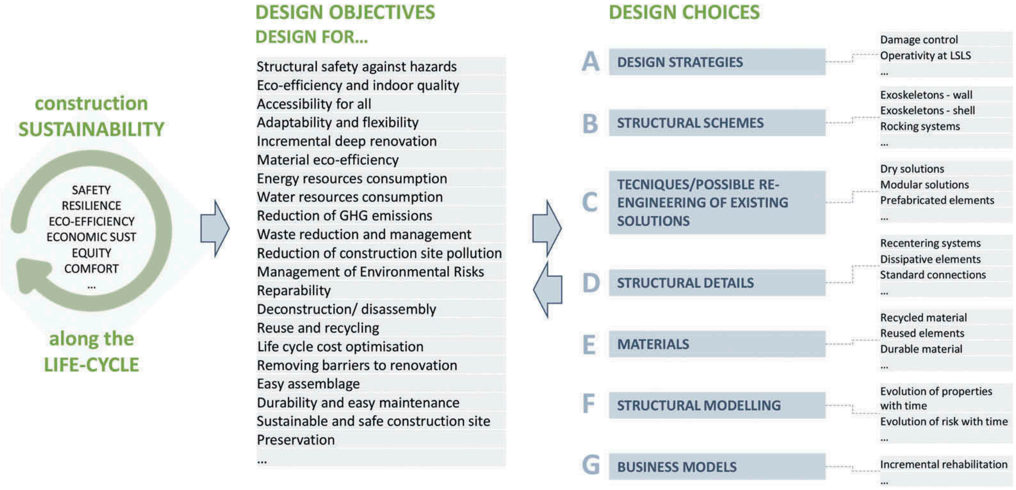

Figure 1. Three-Level Classification based on Life Cycle Thinking, designed to guide the development of sustainable interventions.

Life Cycle Structural Engineering (LCSE) is a discipline which integrates in the concept and in the design of structural systems principles, performance objectives and design choices coherent with this three-level classification (Figure 1).

In the following, some best-practice examples on how applying this approach in the current LCSE design practice are presented and discussed.

3 FROM THEORY TO BEST-PRACTICE EXAMPLES

In order to give an overview of LCSE in practice, some examples of practical design choices are here reported, considering different categories among the ones previously introduced.

A first example of the inclusion of an LCT approach in the design of sustainable interventions is the introduction of time in the evaluation and in the adoption of **time-dependent structural models**. Incorporating the potential progression of material decay in the *structural models* enables the understanding of the evolution of structural performances over time, thus allowing engineers to gain a clearer understanding of the potential damages that may occur throughout the structure’s life cycle, as well as the remaining lifespan of the structure itself (Biondini and Frangopol 2008, among others). These models, which can also be combined with Artificial Intelligence algorithms to exploit and manage the great amount of available data, may lead to more precise maintenance plans of buildings and infrastructures, also enhancing the resilience of the built environment.

Besides the application of time-dependent models, considering an enlarged vision of LCSE, more can be done during the preliminary phases of a project to include in the design other LCT-based design choices and criteria.

Considering the *Structural concept* category, a best-practice example is represented by **structural shell systems** for the seismic upgrading of existing structures. Previous studies have shown how the need to introduce a new foundation system for the seismic interventions is a hotspot in the Life Cycle of a building, in terms of environmental, social and economic impacts (Passoni et al. 2022b). Being these systems usually realized with reinforced concrete elements, great impacts are produced in terms of GHG emissions, water, costs, and time for the construction, and general disturbance to the inhabitants. Studies about the major barriers to the renovation of existing buildings show that such disturbance may prevent the realization of the intervention itself, thus missing the chance to renovate an unsafe structure. In such a scenario, conceiving novel structural schemes that can reduce overstresses of the foundation, thus reducing the impacts connected to the foundation system, may be crucial.

Structural shell systems are systems which exploit the extension of the façades of a building to reduce the stresses in the elements of the shell and of the foundation system (Figure 2a) (Marini et al. 2017, Passoni et al. 2020). These systems are effective considering the bidimensional extension of each façade, and find their full potential by exploiting the tridimensional effect of the whole shell (Zanni et al. 2025), such as made in the diagrid exoskeletons in new constructions (Moon et al. 2007, Labò et al. 2020). A comparison of the effectiveness of shell systems with respect to more traditional wall systems is reported in Passoni et al. (2022b). In this research, the impacts connected to different wall or shell exoskeletons were compared based on simplified LCA analyses, which considered the sole impacts connected to production (A1-A3) and end-of-life (C3-4-D) phases, with data from EPDs (Environmental Product Declarations). From this study, it emerged that, for the considered case study, the adoption of a steel shell system led to a 47% reduction of the GWP (Green Warming Potential) with respect to a steel wall system, due to the minor impact of the required foundation system (Figure 2b). The advantages further increased when considering waste disposal, since, in this case, wall systems required a high number of foundation piles which cannot be recovered at the end of life of the building.

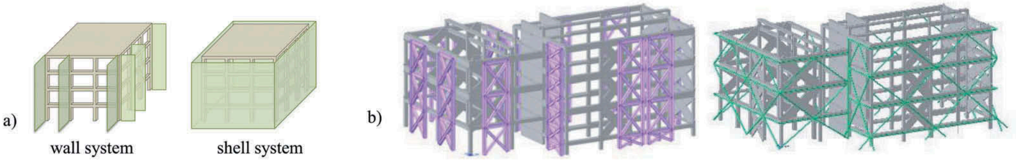

Figure 2. A) concept of structural exoskeletons conceived as wall or shell systems (adapted from Marini et al. 2017); b) application of steel wall and shell (diagrid) system to a reference case study (from Passoni et al. 2022b).

Design choices are another facet of the design process where structural engineers play a significant role for the achievement of sustainable structures. Used to the common performance-based design approach, designers are required to set some structural design targets in terms of EDPs (Engineering Demand Parameters; i.e., design top displacement and base shear, interstorey drifts and accelerations, etc.) in order to reach predefined performance levels. These parameters are usually set in accordance with existing codes to satisfy code safety performance levels. When new sustainability-related performance objectives are set at the beginning of the design process, however, new design targets, even stricter than those required by the codes, may be set to pursue a reduction of the impacts along the life cycle.

For example, when the performance objective “design for resilience to exceptional events and loss reduction” is considered, **full operability at LSLS**, which is usually required by the codes only for strategic buildings only, may be considered to remarkably reduce indirect losses and impacts associated with recovery. This choice could be translated into design strategies including damage control, such as the setting of stricter EDPs for the structure, e.g., lower interstorey drift to prevent damage to drift-sensitive structural and non-structural elements (such as infills), etc., but also into the adoption of structural systems conceived to reduce damage during an earthquake, such as dissipative or rocking systems, recentering systems, or systems able to lump damage into sacrificial replaceable structural fuses.

These latter design choices have some repercussions on the *structural techniques* and *structural details* categories. An example of details that might be conceived, designed and adopted to improve the sustainability of structural systems is the **connections** between adjacent structural elements, of possible exoskeletons to the existing structures. Connections play a critical role for the achievement of multiple LCT-based design performance objectives, such as: “design for adaptability”, “design for easy construction”, “design for easy maintenance”, “design for resilience to exceptional events and loss reduction”, “design for disassembly”, “design for recovery”, etc. To pursue all these objectives, connections should be conceived as standardized, reversible, plug-and-play, and possibly dissipative, to act as structural fuses. Some remarkable considerations about the role of connections in sustainable constructions may be found in ISO 12720:2024, and some more practical indications in ISO 20887:2020. Specific studies about sustainable connections may also be found in the literature, such as the study carried out by Labò et al. (2024), for the development of an innovative connection to be placed between existing buildings and seismic retrofit exoskeletons.

Considering retrofit interventions conceived for the integrated (i.e., seismic, architectural, energy) upgrading of existing buildings, a review of techniques and methods which include one or more LCT-based design performance objectives of Table 1 and/or design choices is reported in Passoni et al. (2024).

Among the reviewed integrated solutions, an example of LCSE was developed by Zanni et al. (2021) and (2022). These papers describe two **LCT-based integrated retrofit interventions** realized on an existing precast RC school gym hall – the former, and to a residential masonry building – the latter, both conceived to include many of the previously mentioned design performance objectives and choices. Such retrofit solutions encompassed hybrid timber-steel shell exoskeletons for the seismic renovation of the buildings, coupled with an additional thermal layer (Figure 3). Shell systems allowed the minimization of the foundation systems; in particular, in the former solution, only four piles at the corners were required. The structural system was also conceived to control the damage, guaranteeing the operativity at the LSLS and lumping the damage into sacrificial replaceable connections in case of stronger earthquakes. The elements of the exoskeletons were prefabricated, rapidly assembled on the construction site, and rapidly demountable at the end of life thanks to a dry and standardized connection system with the existing structure and the foundations, which also allows the elements to be reused (Figure 3). As for the material, the superstructures were realized with bio-based material (CLT panels) and the connections with recycled steel. The reusability of the elements also reduces the impacts of the interventions when including phase D (“beyond end of life”) in the LC environmental and cost analyses. The latter intervention, in addition, considered also the “design for functional flexibility” performance objectives, thus including in the exoskeleton devices for the structural health monitoring and cavities for the positioning of additional plants in case of obsolescence or changes in the inhabitants’ needs.

Figure 3. An example of LCT-based integrated retrofit intervention (from Zanni et al. 2021).

4 CONCLUDING REMARKS

The transition towards a more sustainable construction sector is crucial for mitigating social, economic and environmental impacts and improving the resilience of the built environment. This paper has tried to decline the definition of sustainability within the construction sector, emphasizing its importance in shaping responsible practices. A key contribution of this work is the introduction of a Three-Level Classification based on Life Cycle Thinking, designed to guide the development of sustainable interventions. This classification serves as a foundation for Life Cycle Structural Engineering, encouraging a holistic approach to decision-making throughout the lifespan of construction projects. Additionally, the paper highlighted several best practice examples, showcasing innovative techniques and real-world applications that illustrate the potential for sustainability in the construction industry. These examples not only demonstrate the feasibility of sustainable solutions but also serve as a call to action for the designers to integrate sustainability into construction practices and embrace a Life Cycle Thinking approach.

ACKNOWLEDGMENTS

This research was carried out within the ReLUIS-DPC 2024-26 project - WP13 Sustainability and Life Cycle of structures and infrastructures, financed by the Italian national Department of the Civil Protection.

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