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Doctoral Dissertation

Doctoral Program in Civil and Environmental Engineering (38°Cycle)

Modern Paradigm for the Conceptual Design of Structures

A Cross-Disciplinary Method Applied to Footbridges Design

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Valeria Gozzi
Turin, July 2026

Summary

The conceptual design phase determines a substantial share of the structural, environmental, and functional performance of infrastructure systems, yet it remains weakly formalised within structural engineering practice. Although early design decisions define structural topology, material strategy, robustness, and lifecycle behaviour, existing codes and analytical tools primarily address detailed verification and provide limited support for the systematic comparison of alternative concepts under uncertainty. This limitation has become increasingly critical as contemporary infrastructure projects require the early integration of structural performance, architectural quality, sustainability, and long-term resilience.

This doctoral research develops a cross-disciplinary decision-support framework for early-stage structural design, formalising conceptual design as a multi-criteria decision problem. The proposed method integrates architectural and planning quality, structural resilience, including resistance to disproportionate collapse, inspectability, and maintainability, and environmental and lifecycle performance, encompassing sustainability, circularity, and adaptability. A coherent system of quantitative indicators is defined to enable transparent, reproducible, and scenario-based comparison of conceptual alternatives prior to detailed analysis.

The methodology is operationalised through a dedicated Python-based computational tool that implements indicator evaluation, normalisation, weighting, and multi-criteria aggregation, and supports graphical exploration of trade-offs and interdependencies. The framework is validated through three real-world footbridge case studies, including design competitions and feasibility studies characterised by heterogeneous constraints and objectives. These case studies are employed primarily as methodological instruments to test, demonstrate, and refine the proposed framework rather than as isolated project analyses.

The results show that the proposed approach improves the explicitness and traceability of early-stage design reasoning, supports informed comparison of alternative structural concepts, and clarifies the implications of conceptual choices on long-term performance. The research positions conceptual design as a decision-critical and knowledge-intensive engineering phase and provides a methodological basis that can be extended beyond the specific case of footbridges.

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Introduction

This research originates from my professional experience in the field of structural and bridge design. Unlike many doctoral projects that begin at the start of an academic career, I undertook this PhD while already engaged in professional practice. The motivation for this research developed gradually from the desire to reflect more systematically on questions that frequently arise in design activity, particularly those related to the conceptual phase of structural projects.

From the beginning of my professional path, I have been interested in the relationship between structure and architecture. Structural systems do not simply respond to technical requirements; they also contribute to shaping space, form, and the overall architectural quality of a project. This interest has been reinforced through more than ten years of teaching structural and construction-related topics within architecture programs, where structural design is addressed not only as a matter of calculation and verification, but also as a conceptual discipline that interacts with architectural thinking. Alongside teaching, I have collaborated with several architecture-related publications, contributing to discussions on structural design and on the broader cultural dimension of infrastructure. These experiences have helped consolidate my interest in the conceptual aspects of structural design and in the dialogue between engineering reasoning and architectural intentions.

My professional activity takes place within a design office that focuses primarily on structural engineering but also addresses broader themes related to sustainability, lifecycle performance, and circularity in infrastructure projects. In this context, many projects have progressively brought sustainability considerations to the same design table where architecture and structural engineering traditionally interact. In particular, sustainability is increasingly approached through its three interrelated dimensions (environmental, social, and economic) which influence design decisions from the earliest conceptual stages. As a result, aspects such as durability, resource efficiency, lifecycle performance, and long-term adaptability have become integral components of the design process. This perspective has gradually become part of both my professional work and my academic activity.

In professional practice, the conceptual phase is often the moment in which the most influential design decisions are made. At this stage the structural typology, load-bearing system, material strategy, and the relationship between the structure and its context are defined. Although these choices strongly influence the long-term

performance and sustainability of a project, the conceptual phase remains only partially formalized within structural engineering practice. Designers frequently rely on experience and reference projects when exploring alternatives, while analytical tools and design codes mainly support later stages of verification and detailed development. Starting from this observation, the research presented in this dissertation investigates conceptual structural design as a structured decision-making process. The objective of the work is to develop a methodological framework capable of supporting the comparison and evaluation of alternative structural concepts during the early stages of design. The proposed approach integrates criteria related to structural performance, architectural quality, sustainability, durability, and lifecycle considerations, enabling a more transparent exploration of design alternatives.

The research adopts an operational perspective that connects academic investigation with professional design practice. The methodological framework developed in this dissertation is conceived both as a theoretical contribution and as a practical approach to support early-stage design reasoning.

The case studies presented in the thesis reflect this orientation. Rather than being hypothetical examples, they correspond to real design projects developed within my professional practice, including design competitions and feasibility studies for pedestrian and cycling bridges. These projects are used as methodological testbeds to apply and evaluate the proposed framework under realistic design conditions. Within this research, footbridges are adopted as a representative field of investigation. Their manageable scale, structural diversity, and strong interaction with architectural and urban contexts make them particularly suitable for analyzing how conceptual structural decisions are generated and assessed. The dissertation is structured into five chapters.

Chapter 1 reviews the theoretical and historical background of conceptual design in structural engineering and identifies the main contemporary criteria influencing early-stage design decisions.

Chapter 2 presents the methodological framework developed in this research, including the system of indicators used to evaluate alternative solutions and the computational tool supporting the multi-criteria assessment process.

Chapter 3 introduces the case studies and describes the methodological protocol used to apply the framework to real design projects.

Chapter 4 discusses the results obtained from the comparative analysis of the case studies, highlighting patterns, trade-offs, and methodological implications.

Finally, Chapter 5 summarizes the main contributions of the research and outlines possible directions for future developments.

Chapter 1

Conceptual Design of Structures: Background, Criteria, and Research Gaps

1.1 Conceptual design as an early-stage structural problem

The conceptual design phase plays a crucial role in the lifecycle of structural and infrastructure projects. It is during this early stage that the basic structural concept is defined, including the load-bearing system, the overall geometry, the choice of materials, and the relationship between structure and space. These decisions are made before detailed calculations or numerical simulations are available, yet they strongly influence the final performance of the structure. Once the conceptual choices are fixed, many aspects related to structural performance, as well as long-term project quality, become difficult or costly to modify (Cabeza et al., 2014; Gagnon et al., 2012).

Despite its importance, conceptual design is still weakly formalized in structural engineering practice. In many projects, this phase relies mainly on experience, intuition, and precedent, while formal tools and design codes focus on later stages of verification and optimization. As a result, early decisions are often taken without a transparent comparison of alternative solutions, even though they determine a significant portion of the technical, environmental, and economic performance of the structure over its entire lifecycle (Pomponi & Moncaster, 2017).

In contemporary practice, the limitations of a weakly formalised conceptual design phase have become increasingly evident. Structural designers are required to address a growing number of interrelated criteria from the very beginning of the design process. In addition to structural safety and efficiency, early-stage design decisions should also consider aspects such as architectural quality, integration into the surrounding context, and the feasibility of construction. At the same time, they must increasingly consider emerging parameters, including durability, environmental impact, maintenance, and future adaptability. Nevertheless, while these aspects are widely acknowledged in theory, current engineering tools provide limited support for their systematic and combined assessment during the conceptual phase.

This situation reveals a clear gap between the recognized importance of conceptual design and the methods available to support it. Design standards and codes are mainly oriented toward detailed verification and assume that a coherent structural concept has already been selected.

Consequently, conceptual design is often treated as a preliminary and partly subjective step, rather than as a phase in which different structural options should be explicitly explored, compared, and evaluated. The absence of structured early-stage evaluation increases the risk of late design changes, reduced overall performance, or missed opportunities for innovation and sustainability.

The recognition of conceptual design as a core engineering activity is not new. In 1996, Jörg Schlaich formally introduced the term *conceptual design* into the structural engineering debate at the International Association for Shell and Spatial Structures (IASS) Symposium in Stuttgart. In that context, conceptual design was explicitly framed as a central phase of structural reasoning, preceding numerical verification and representing a shared intellectual domain between engineers and architects (J. Schlaich & Schober, 1996). Schlaich's contribution can therefore be understood as a modern founding act within structural engineering, as it formally acknowledged the conceptual phase as a legitimate and critical object of engineering design.

However, the importance of early-stage reasoning, as a trigger factor for architecture–structure dialogue, can be traced back too much earlier conceptual frameworks. As early as the first century BCE, Vitruvius identified three fundamental qualities of architecture (*firmitas*, *utilitas*, and *venustas*) establishing an archetypal view in which structural safety, functional performance, and architectural value are conceived as inseparable dimensions of design (Vitruvius Pollio, 1960). Although developed in a pre-engineering context, this triad anticipates a core issue that remains central to contemporary structural design, namely the need to integrate multiple criteria within the earliest conceptual decisions.

With the advent of modern engineering¹, this integrative vision gradually evolved from an intuitive practice rooted in craftsmanship and proportion to a more analytical process informed by scientific reasoning and technological innovation. Within this shift, the conceptual phase has progressively regained attention as a critical determinant of structural quality. This idea is well established in the

¹ Modern engineering: The term “modern engineering” refers to the scientific and industrial transformation of design practice that occurred from the nineteenth century onward, when construction evolved from empirical craftsmanship to a rational discipline grounded in mechanics, material science, and analytical methods. This shift marked the emergence of a shared intellectual framework between engineering and architecture, in which structure was conceived as both a technical and expressive medium (Frampton, 2000; Heyman, 1999)

theoretical discourse of structural design, as reflected in the works of Billington(1983), Macdonald (2001) and Allen & Zalewski (2009), which emphasize the formative role of early conceptual choices on the structural and architectural quality of built form.

In contemporary practice, the notion of conceptual design is therefore being revisited and expanded. Beyond the traditional emphasis on form and architectural expression, it now encompasses additional parameters such as durability, maintenance, life-cycle performance, and sustainability. This renewed perspective positions the conceptual phase not merely as a creative moment of synthesis, but as a strategic opportunity to embed long-term performance and environmental awareness into the very logic of structural form. Such an evolution has been formally recognized by the international engineering community, as demonstrated by the fib Symposium on Conceptual Design of Structures (started in 2019) and the ongoing research activities of the IASS. These initiatives confirm the growing acknowledgement of conceptual design as a key phase in structural engineering, acting as the interface between creative intent and technical control, where structural logic, architectural quality, and long-term performance objectives are defined together (fib, 2021, 2023).

On this basis, conceptual design can be understood as a structured reasoning process rather than as an intuitive or purely creative act. When a clear structural logic is established at the outset, detailed numerical analyses tend to refine and validate the initial concept rather than compensate for fundamental weaknesses introduced at the early stage. This understanding is further reinforced by recent studies on sustainability and lifecycle assessment, which demonstrate that a substantial share of environmental and economic impacts is determined by early design choices related to structural systems and material strategies (Cabeza et al., 2014; De Wolf et al., 2020; Passer et al., 2012).

From a structural point of view and according to this interpretation, the limits of a purely linear design process are particularly evident in the context of contemporary architecture, engineering, and construction practice. Climate change, resource scarcity, and extended service-life requirements demand structural concepts that consider not only initial performance, but also long-term environmental and functional implications. In fact, several studies have shown that a large share of environmental and economic impacts over the lifecycle of a structure are determined during the conceptual phase, mainly through choices related to materials, structural typologies, and construction strategies (Bragança et

al., 2014; Corres Peiretti et al., 2022; Gagnon et al., 2012). This confirms the conceptual phase as the primary leverage point at which design decisions influence long-term performance.

Although tools such as life-cycle assessment, sustainability rating systems, and risk-based frameworks are increasingly adopted in engineering practice, they are typically applied after a preferred design option has already been selected. As a result, they primarily function as post-selection evaluation tools rather than as decision-support instruments for early-stage design. These tools are rarely conceived to enable objective and quantitative comparisons between alternative conceptual solutions during the conceptual phase. This limitation highlights the need for methods capable of linking qualitative design reasoning with quantitative performance indicators in a consistent and transparent manner.

Building on this perspective, the present thesis addresses the lack of structured methods for conceptual design by proposing a multi-criteria framework to support early-stage structural decision-making rooted in numerical and objective metrics. The framework is developed and tested through the design of footbridges, a typology that enables clear comparison between alternative solutions while simultaneously involving strong architectural, structural, and contextual aspects. By treating conceptual design as an explicit and evaluable decision process, this research aims to contribute to a more rigorous, transparent, and interdisciplinary approach to early-stage structural design.

1.2 Contextualization within structural and infrastructural projects

1.2.1 Definition, scope and role in the design process

Conceptual design in structural and infrastructure projects refers to the phase in which the fundamental configuration of a structural system is established. It is the stage where designers define the structural typology, the primary load paths, the hierarchy of elements, and the basic construction logic, translating programmatic and architectural intentions into a coherent structural idea. At this point, the design remains relatively flexible, and decisions can still be revised without major impacts on time and cost. At the same time, the choices made at this stage strongly constrain what can be achieved in later phases, because subsequent analysis and detailing typically refine the selected concept rather than redefine it (Gozzi & Guante Henriquez, 2025a).

This condition creates a well-known asymmetry within the design process: while uncertainty is still high and several alternatives remain open, the potential to influence the overall performance of the project is at its maximum during the early stages. As the project advances, design freedom progressively decreases, whereas the cost and consequences of change increase. As a result, many technical, environmental, and organizational implications of a project are effectively determined during conceptual or preliminary design, even if they only become fully visible at later stages.

From a process perspective, this phase corresponds in professional practice to the transition from feasibility and planning to preliminary design, situated before detailed design and verification. International standards generally describe the design process as a sequence of stages progressing from early conceptual definition to detailed development and delivery, during which fundamental project decisions are progressively fixed.

The relationship between decision impact, design flexibility, and cost of change across project stages is schematically illustrated in Figure 1.

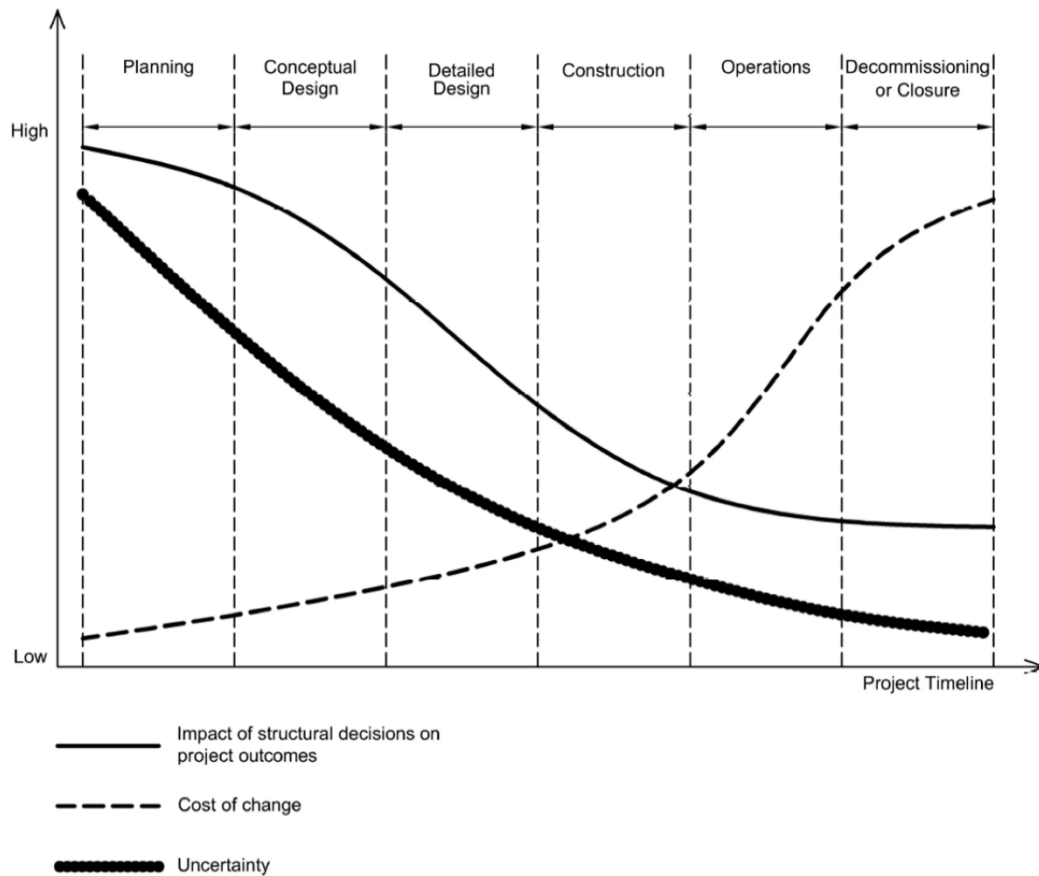


Figure 1 Relationship between decision impact, design flexibility, and cost of change across project stages.

From a process perspective, this phase corresponds in professional practice to the transition from feasibility and planning to preliminary design, situated before detailed design and verification. International standards generally describe the design process as a sequence of stages progressing from early conceptual definition to detailed development and delivery, during which fundamental project decisions are progressively fixed.

The output of this phase is therefore not a finalised or optimised solution, but a limited number of consistent concepts that can be compared, discussed with stakeholders, and progressively validated through increasing levels of analysis.

For terminological clarity, and in line with the taxonomy of design stages defined in EN 16310:2013 (CEN, 2013), the term conceptual design is used here as equivalent to preliminary or early-stage design, all referring to the formative phase in which the main structural principles are established.

Within project management frameworks, conceptual design occupies a foundational position in the overall process, providing the strategic basis upon which subsequent technical, organisational, and operational decisions are built. In industrial and engineering practice, this early stage is widely recognised as decisive for ensuring the project’s long-term performance and feasibility. This hierarchical interpretation of the design process is commonly represented through the project management pyramid, in which the conceptual design phase forms the base supporting all subsequent planning, development, and execution activities.

This model is broadly recognised and codified in international standards such as ISO 21502 (2020), EN 16310 (2013), and the *PMBOK® Guide* (PMI, 2021), which collectively underscore the decisive influence of early design decisions on long-term project outcomes. Figure 2 illustrates this project management hierarchy as adapted to civil engineering projects according to EN 16310 project phases.

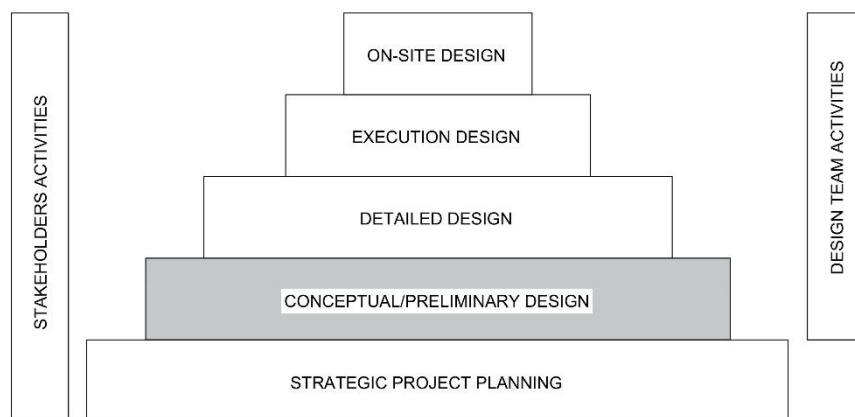


Figure 2 Schematic representation of the project management hierarchy adapted to civil engineering project stages.

Conceptual design thus acts as an interface between qualitative intentions and technical feasibility, where structural reasoning begins to interact with requirements related to function, context, constructability, durability, and long-term performance.

The relevance of early-stage reasoning is highlighted in systematic design methodologies such as VDI (*VDI 2221*, 1987). Although originally conceived for industrial product development, this guideline provides a foundational framework for structuring conceptual design processes, including the formulation of requirements, principles, and design variants before detailed verification.

In the field of civil and structural engineering, however, such systematic approaches to conceptual design are not yet fully established. This gap is not primarily related to a lack of theoretical awareness, but rather to the limited translation of conceptual design principles into operational methodologies, formalised tools, and codified procedures applicable in everyday engineering practice. Only in recent years, in parallel with the growing emphasis on sustainability, life-cycle performance, and resource efficiency, has academic research begun to explore the potential of structured methodologies for the early design stages. These approaches aim to move beyond the predominantly intuitive, experience-based, and sketch-driven practices that still characterize much of contemporary design activity (Choobdarian & Biondini, 2025; Gozzi & Chiaia, 2023).

Nevertheless, conceptual design has a long-standing and distinguished tradition within architectural and structural culture. Throughout history, it has been a subject of reflection and experimentation among designers and theorists, continuously evolving in response to contextual and technological contingencies. This historical continuity confirms both its inherently site-specific character and its adaptive capacity across different technological and cultural contexts.

The following section therefore traces the historical development of conceptual design, with the aim of clarifying the origins of its renewed relevance in contemporary practice and the emerging need for a more systematic and integrated approach.

1.2.2 Historical background of conceptual structural design

From the earliest written accounts of architectural theory, the conceptual foundations of design can be traced back to Vitruvius, who, in *De Architectura*, articulated the triad of *firmitas*, *utilitas*, and *venustas* as the essential and inseparable qualities of architecture.

From late antiquity through the medieval period, the transmission and transformation of structural and geometric knowledge unfolded across a broad cultural continuum encompassing both the Islamic and European worlds. Early Islamic architecture, exemplified by the Great Mosque of Samarra (848–851) and the Al-Azhar Mosque in Cairo (970–972), demonstrated a refined mastery of proportion, curvature, and stereotomic construction. These achievements were further developed in the Friday Mosque of Isfahan (11th–12th centuries), where the systematic use of geometry in the design of domes and vaults reached remarkable sophistication. Similar principles of geometric control and structural rationality can also be observed in infrastructure works such as the Pont du Gard aqueduct (1st century) and numerous Roman masonry bridges, where structural form emerged directly from constructional logic and material constraints.

In parallel, within Europe, Romanesque and early Gothic builders progressively evolved their empirical understanding of structure through experimentation on site, as seen in the Abbey Church of Sainte-Foy at Conques (1088–1130) and Durham Cathedral (1093–1133). As observed by Miccoli (2023), these concurrent developments, rather than isolated traditions, formed part of a continuous and cross-cultural lineage of conceptual reasoning. Through the reciprocal exchange of constructive knowledge across the Mediterranean, the synthesis of geometric logic and structural intuition laid the groundwork for the scientific and formal approaches that would emerge during the Renaissance.

In the Middle Ages, master builders and cathedral designers embodied a synthesis of structural understanding and symbolic articulation, even though their knowledge remained largely empirical. Figures such as Villard de Honnecourt (13th century), through his sketches and diagrams, exemplify an early attempt to formalize structural intuition through geometric representation (Wirth, 2015).

Similarly, the anonymous *maîtres d'œuvre* responsible for the cathedrals of Chartres (1194–1220) and Reims (1211–1311) developed construction systems in

which spatial expression, structural logic, and material constraints were inseparably linked.

Major infrastructure works such as the Pont Saint-Bénézet in Avignon (1177–1185) demonstrate how geometry provided a common framework for reconciling structural stability, constructability, and functional requirements. In these works, as in the contemporary cathedrals, conceptual reasoning was expressed not through calculation but through drawing, proportion, and constructional experimentation.

During the Renaissance, a decisive shift occurred with the explicit theorization of construction principles and the emergence of architectural treatises. Masters such as Filippo Brunelleschi (1377–1446) and Leon Battista Alberti (1404–1472) embodied a renewed synthesis between the roles of architect and engineer, the *maestro costruttore* who combined intellectual speculation with technical mastery. Brunelleschi's achievements, culminating in the dome of Santa Maria del Fiore (1420–1436), demonstrated that structural conception, material strategy, and construction process could be deliberately integrated within a coherent conceptual framework. Alberti, in turn, codified this integration into a theoretical system. In *De re aedificatoria* (Alberti & Rivera, 1991), he established architecture as a rational discipline governed by proportion, geometry, and structural logic, articulating a vision in which form and construction were unified by design reasoning. His writings transformed what had previously been an empirical craft into a conscious and intellectual practice, bridging the gap between intuition and analytical thought. The same integration of conceptual and technical reasoning can be found in the studies of Leonardo da Vinci (1452–1519), whose investigations of bridges, hydraulic works, and construction techniques extended conceptual design principles beyond architecture into the broader domain of civil engineering.

This redefinition of the architect-engineer figure marked a turning point in the history of conceptual design, laying the groundwork for the emergence of scientific structural thought in the centuries that followed. During the seventeenth century, the synthesis of artistic intuition and technical reasoning evolved into a more analytical understanding of structural behaviour. The rise of the scientific method introduced new means of observing and quantifying mechanical phenomena, transforming construction knowledge into the foundation of modern structural mechanics.

Galileo Galilei (1564–1642), with his *Discorsi e dimostrazioni matematiche intorno a due nuove scienze* (1638), and Robert Hooke (1635–1703), through his

Lectures on Spring (1678), were among the first to establish explicit relationships between geometry, material behaviour, and mechanical forces. Their contributions marked the transition from qualitative intuition to quantitative analysis, providing a theoretical framework capable of predicting, rather than merely describing, structural performance.

In the eighteenth century, Giovanni Poleni (1683–1761) further advanced this rationalization of structural thought by combining empirical observation with mathematical modelling in his studies of St. Peter's dome. His work exemplified the gradual transformation of structural design into a discipline rooted in scientific reasoning, formalizing methods of verification that would influence engineering practice for the next two centuries.

The rationalization of structural behaviour initiated by Poleni paved the way for a new visual and analytical language of structure. In the nineteenth century, the development of graphic statics reconnected the intuitive, form-based reasoning of historical builders with the analytical precision of modern engineering. Through the pioneering works of Karl Culmann (1821–1881), author of *Die graphische Statik* (1866), and later of James Clerk Maxwell (1831–1879), the equilibrium of forces could be represented geometrically, allowing designers to visualize the flow of loads and internal stresses with unprecedented clarity. The practical significance of graphic statics became particularly evident in the design of nineteenth-century railway bridges and viaducts. Landmark structures such as the Garabit Viaduct (1884) and the Forth Bridge (1890) demonstrated how graphical methods could be used not only for structural verification but also as conceptual tools for understanding force flow and shaping structural form.

This approach provided not only a powerful computational tool but also a conceptual framework for understanding the relationship between form and force, a theme that resonated deeply with the intuitive logic of historical construction.

The graphic method thus re-established a bridge between artistic representation and scientific analysis, uniting drawing and calculation within a single structural language. It marked a crucial step in the evolution of structural reasoning, confirming that conceptual design, whether intuitive or analytical, is fundamentally a visual act of understanding structure through form.

The rational and geometric understanding of structure developed through graphic statics in the nineteenth century provided the intellectual framework for a new aesthetic of construction. Thinkers and designers such as Eugène Viollet-le-

Duc (1814–1879) argued that structural form should be the direct and honest expression of its mechanical principles, establishing a moral link between constructional truth, material logic, and architectural beauty. This idea, rooted in the rationalist tradition, profoundly influenced the emergence of modern architecture, in which light, space, and structure became essential components of form.

In the early twentieth century, Louis Sullivan (1856–1924) condensed this philosophy into the maxim *form follows function* (Sullivan, 1896) which later evolved into the structural reading of *form follows forces*. Architects such as Le Corbusier (1887–1965) reinterpreted this notion in spatial and tectonic terms, integrating light, proportion, and material logic into an architectural order guided by reason (Le Corbusier, 2017).

This convergence of rational structure, functional clarity, and expressive form set the stage for the rise of the “great engineers” of the twentieth century, engineers and architects such as Robert Maillart (1872–1940), Eduardo Torroja (1899–1961), Pier Luigi Nervi (1891–1979), Félix Candela (1910–1997), and Heinz Isler (1926–2009) whose works embodied a renewed synthesis of analysis and intuition, transforming structural design into a creative act where geometry, material efficiency, and spatial expression were inseparable (Gozzi & Boller, 2022).

David P. Billington (1983) later described this approach as structural art, emphasizing how efficiency, economy, and expressive quality can emerge from well-defined conceptual decisions taken at the earliest stages of design. These engineers demonstrated that structural design, when rooted in conceptual synthesis, transcends technical problem-solving to become a cultural act, one that unites scientific reasoning with creative intuition in the design process.

This integration between analytical reasoning and creative intuition has been further interpreted through conceptual frameworks such as Rich Gold’s diagram of the “four hats of creation” (Gold, 2007) later discussed by Heggade in *Conceptual Design of Structures* (2020) and applied to Maillart’s Salginatobel Bridge (Figure 3).

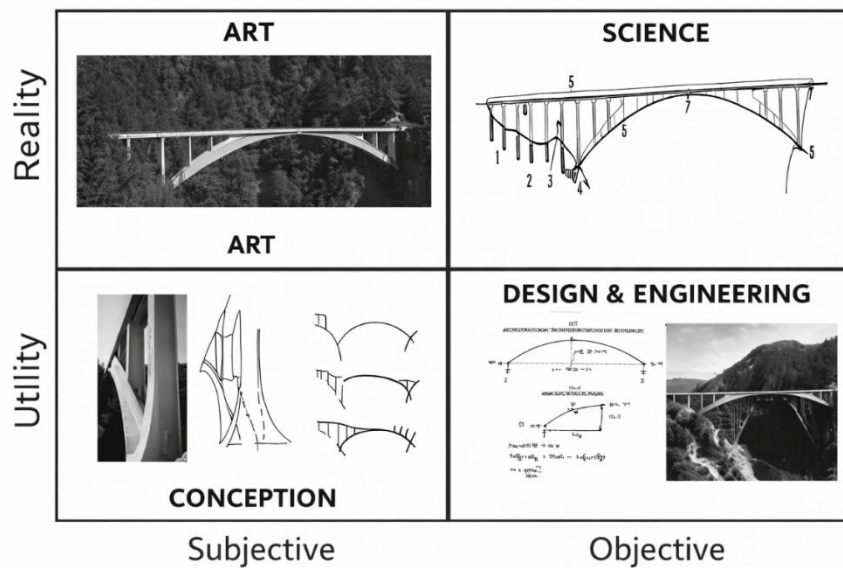


Figure 3 Gold's “Four Hats of Creation” applied to Maillart’s Salginatobel Bridge

Applied to structural design, this framework highlights how scientific, engineering, design, and artistic modes of thinking coexist within the conceptual phase, reinforcing the idea that conceptual synthesis is not opposed to rigor, but constitutes its cognitive foundation.

As anticipated, currently the role of conceptual design has gained renewed prominence within the international structural engineering community. Since the launch of the fib Symposium on Conceptual Design of Structures in 2019, the discipline has evolved into a structured field of inquiry, with conferences, workshops, and publications systematically dedicated to its theoretical and practical dimensions (D’Acunto et al., 2024). These initiatives, together with the continuous efforts of the International Association for Shell and Spatial Structures (IASS), have fostered a collective reflection on how the early design stages shape long-term performance, efficiency, and aesthetic quality.

What distinguishes this contemporary phase is the integration of conceptual thinking with the advanced tools and methods of digital design. The traditional sketch-based reasoning that characterized the twentieth century is expanding through a systemic approach thanks to parametric modelling, form-finding, Building Information Modelling (BIM), and artificial intelligence (AI), enabling designers to explore and evaluate complex solution spaces from the earliest stages (Ajtayné Károlyfi & Szép, 2023; Ao et al., 2025; Melchiorre et al., 2025). Projects such as the Striatus bridge (2021) illustrate how digital modelling, advanced

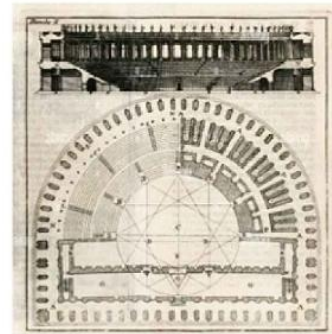
structural analysis, and performance-driven design can be integrated from the conceptual phase to support the development of innovative bridge forms. As a result, conceptual design is no longer viewed as a purely intuitive act but as a systemic and data-informed process, capable of combining creativity with analytical depth (Conzett & Mostafavi, 2006).

This convergence between technological innovation and conceptual reasoning has produced a new generation of engineers and researchers who build upon the legacy of structural pioneers while exploiting contemporary computational opportunities. Through this synthesis, conceptual design has reaffirmed its role as the strategic core of structural design, where geometry, material logic, environmental performance, and constructability are defined together in an integrated framework.

Read as a whole, this historical trajectory does not describe a linear evolution toward increasing complexity or technological sophistication. Rather, it reveals a recurring oscillation between phases of strong conceptual integration and periods of disciplinary fragmentation. Recognizing this pattern provides a critical background for understanding why conceptual design remains a central yet unresolved issue in contemporary structural practice, and why current research increasingly focuses on methods capable of supporting early-stage integration under present technical, environmental, and societal constraints.

The historical background discussed above is synthesized in Figure 4, which presents a comparative visual timeline of key moments in the evolution of conceptual design. The gallery does not aim to provide an exhaustive historical survey, but to highlight recurring patterns of conceptual integration across different periods, structural typologies, and cultural contexts. By juxtaposing built works and design paradigms, the figure emphasizes how the relationship between form, structure, and construction logic has repeatedly been addressed at the conceptual level, reinforcing the interpretative framework introduced in this section.

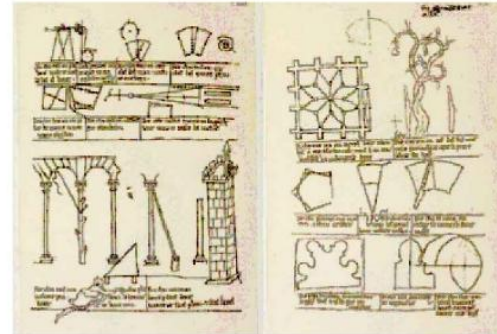
Plan of the Roman Theatre from "L'architettura generale de Vitruve" published in 1681



Vitruvian Foundations (I century BCE)

Unity of structure, function, and beauty (firmitas–utilitas–venustas).

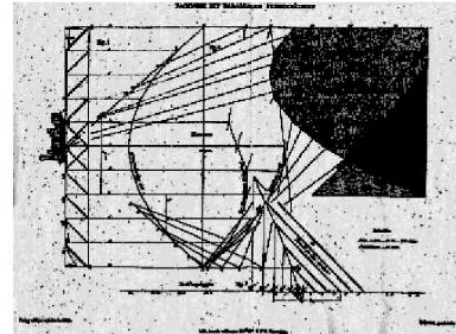
Sketchbook of Villard De Honnecourt from the 15th century (Villard et al. 1859)



Medieval Craft (11th–13th centuries)

Empirical construction refined into geometric structural reasoning.

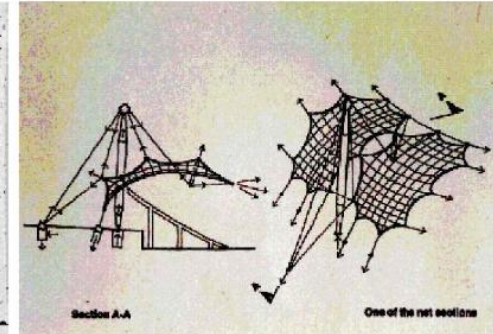
Karl Culmann: static graphic applied to rail bridge, Die graphische statik 1866



Geometric Rationalization (17th–19th century)

Mechanics and geometry transform structural intuition into analytical understanding.

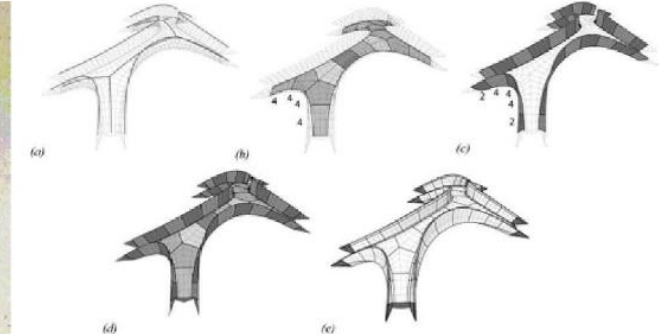
Section and Axonometric Diagrams of the Munich Olympic Stadium. Munich, Germany - Frei Otto 1968-72



Structural Art (1950–1980)

Efficiency, economy, and elegance as conceptual synthesis.

The striatus Bridge
Zaha Hadid Architects + Block
Research Group 2021

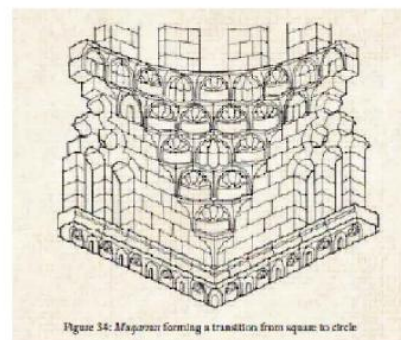


Contemporary Conceptual Design (2019–present)

Integration of new design criteria, systemic approaches and digital tools,

Islamic Geometry (9th–12th centuries)

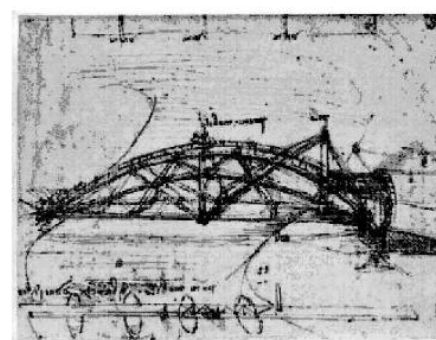
Geometry as structure; continuity through proportion and stereotomy.



Technical drawing - Muqarnas forming a transition from square to octagon.

Humanist Synthesis (15th century)

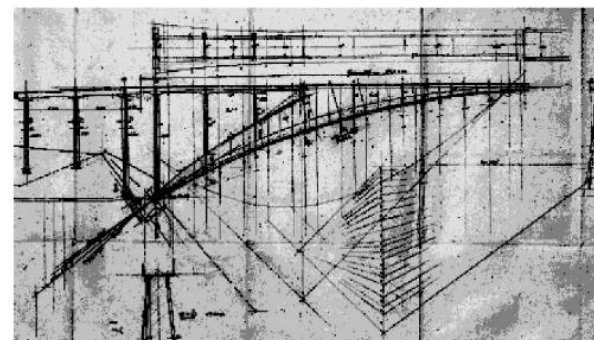
The architect-engineer emerges: intellect, design, and construction unified.



Leonardo da Vinci, bridge sketches, c. 1485–1500.

Structural Rationalism (1920–1935)

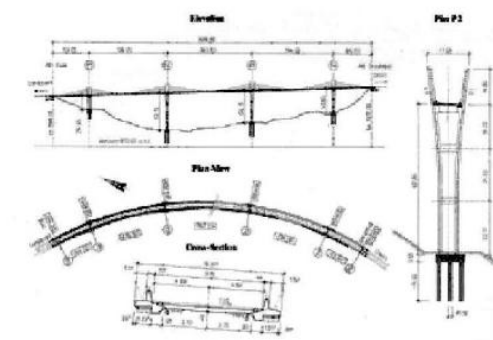
Form follows forces — structure expresses load paths and logic.



Forces drawing of Salginatobel brucke, Robert Maillart 1928.

Conceptual Discipline (1990–2010)

Early design clarity through architecture–engineering collaboration.



Elevation, plan, cross-sections of Sunninberg Bridge in Switzerland, C. Menn 2006.

Figure 4 Synthetic comparative visual timeline of the evolution of conceptual design.

1.2.3 Specificities of Footbridge Projects

The selection of footbridges as the focus of this research is grounded in methodological considerations rather than in typological preference. As introduced, this dissertation investigates conceptual structural design as the phase in which fundamental decisions concerning structural configuration, form, construction logic, sustainability and contextual integration are taken under conditions of uncertainty. To analyse this process in a rigorous and transparent manner, it is necessary to identify a structural typology in which early-stage decisions are both decisive for the final outcome and clearly observable. Within the broader domain of bridges and infrastructures, footbridges provide particularly favourable conditions for this purpose. Compared to road and railway bridges, footbridges are characterized by a reduced structural scale and by the absence of extreme traffic loads and rigid operational requirements. As noted by Baus and Schlaich (2008), this condition limits the dominance of purely technical constraints and allows the conceptual configuration of the structural system to play a more explicit role in shaping the overall design. Choices concerning typology, geometry, material strategy, and construction approach are not obscured by scale or regulatory complexity but remain legible throughout the project. As a result, the influence of conceptual decisions on the final structural form can be directly traced and critically examined (M. Schlaich et al., 2005).

At the same time, footbridges are characterized by a high degree of public exposure and direct interaction with users. Unlike large transport infrastructures, they are experienced at walking speed and perceived from close range, often through repeated daily use. This condition amplifies the role of structural form, proportions, and spatial continuity, making the relationship between form and force immediately legible. Structural choices adopted during the conceptual phase therefore influence not only technical performance, but also perception, comfort, and social acceptance of the structure.

In fact, footbridges operate at the scale of the human body in at least two ways: from the viewpoint of the user who traverses them, and from that of the inhabitant who perceives them as an urban or landscape object from a different perspective. Structural depth, rhythm of elements, curvature, and material articulation are read sequentially along the path and directly contribute to the spatial experience of crossing. The coherence between structural logic and architectural expression becomes immediately evident, and early conceptual decisions strongly condition the experiential quality of the bridge. In this sense, conceptual design decisions

cannot be regarded as neutral or purely technical, as they shape how the structure is perceived, understood, and appropriated by its users (Živanović et al., 2005).

Beyond perception, footbridges are deeply embedded in their urban or landscape context and often play a strategic role in reconnecting fragmented territories. Their alignment, geometry, and structural typology influence visual relationships, landscape continuity, and the integration of infrastructure within sensitive environments. Unlike major transport bridges, which are often governed primarily by efficiency and capacity requirements, footbridges frequently function as urban or landscape artefacts, where structural form contributes to place-making and territorial identity. Structural reasoning and contextual interpretation are therefore inherently intertwined already at the conceptual stage (Siviero et al., 2014; S. Yang & Huang, 1997).

Another defining feature of footbridge projects is the absence of rigid functional standardization. Unlike large transport infrastructures, footbridges are rarely designed according to repetitive typologies or predefined layouts. Each project typically responds to a specific site condition, spatial constraint, and programmatic requirement, often shaped by urban morphology, topography, or landscape features. This openness generates a design space in which alternative structural concepts can be meaningfully explored and compared during the early stages, rather than being reduced to minor variations of a predetermined scheme. The conceptual phase therefore becomes the primary ground in which design quality is negotiated, as fundamental choices regarding structural system, span arrangement, and construction logic remain genuinely open.

Moreover, on a broader scale of territorial planning, as indicated in latest ITF report (*Improving the Quality of Walking and Cycling in Cities: Summary and Conclusions*, 2024) footbridges play a central role within contemporary strategies for slow mobility and sustainable territorial planning. As elements of pedestrian and cycling networks, they contribute to social inclusion by improving accessibility, supporting non-motorized transport, and enhancing everyday spatial connectivity. From an environmental perspective, they enable modal shifts toward low-impact mobility and often require careful integration within sensitive urban or natural contexts. From an economic standpoint, their lifecycle performance, durability, and maintenance strategies are closely linked to early conceptual decisions, particularly with respect to material choice and construction logic. These three dimensions (social, environmental, and economic) are strongly interdependent and must be

addressed simultaneously from the outset, reinforcing the need for integrated reasoning during conceptual design (M. Wang et al., 2023).

Footbridges therefore concentrate a wide range of interacting requirements within a manageable scope. This intrinsic complexity makes footbridge projects particularly demanding from a conceptual standpoint and inherently cross-disciplinary, even before formal analysis or optimization takes place (Penadés-Plà et al., 2016).

Indeed, footbridges have “historically” served as a field of experimentation for structural and architectural innovation. Their reduced scale and relative freedom from heavy infrastructural constraints have made them suitable for testing new structural systems, materials, and construction techniques. In many cases, footbridges function as demonstrators in which conceptual clarity and structural expression are intentionally foregrounded. This role further reinforces their suitability as objects of study for investigating how conceptual design decisions are generated, articulated, and evaluated.

Taken together, these characteristics make footbridges a paradigmatic field for investigating conceptual structural design. Their manageable scale, contextual sensitivity, and openness to innovation allow for a focused yet comprehensive exploration of how early-stage decisions shape structural and architectural outcomes.

1.2.4 Implications for Early-Stage Decision-Making

The discussion above has revealed that conceptual reasoning in footbridge design involves a complex interaction of structural, spatial, contextual, environmental, and perceptual factors. These aspects, while consistently emerging across the previous sections, remain only partially clarified in terms of their hierarchy and interdependence. In contemporary practice, they often coexist in an implicit balance, intuitively managed by the designer rather than explicitly defined or systematically assessed. As a result, the conceptual phase continues to operate largely through qualitative synthesis and precedent-based reasoning, even though it is the stage where the greatest leverage on long-term performance and integration exists. This condition exposes a gap in both theory and methodology. On one hand, the diversity of parameters that influence conceptual design reflects the inherently interdisciplinary nature of footbridge projects. On the other, it also underscores the absence of a clear taxonomy capable of distinguishing between those aspects that

can be addressed analytically at the conceptual stage and those that remain primarily qualitative or perceptual. Establishing such a taxonomy is crucial for transforming conceptual design from an intuitive exploration into a structured process that allows consistent evaluation of alternative solutions.

The following section (1.4) therefore focuses on identifying and defining a set of contemporary design criteria that can be meaningfully considered during the conceptual phase and expressed in objective, measurable, or analytically comparable terms. These criteria form the foundation of the methodological framework developed in the subsequent chapters, where they will be used to construct a transparent and reproducible basis for multi-criteria evaluation of conceptual alternatives. By delimiting this analytical subset, the research aims not to reduce the creative and integrative character of conceptual design, but to clarify its structure and make its reasoning explicit.

1.3 Contemporary design criteria for footbridge design

1.3.1 From Discipline-Oriented Design to Multidisciplinary Dimensions

In contemporary structural and infrastructure projects, the limitations of discipline-oriented design approaches have become increasingly evident. Traditional design workflows were historically organized around sequential and specialized contributions, where architecture, structural engineering, specialist design, construction, and recently sustainability assessment were addressed as largely separate phases. In contemporary bridge design, project requirements converge at the conceptual stage into a limited set of fundamental design decisions. These early choices generate multiple, interdependent implications across structural, spatial, environmental, and construction-related domains, exposing the limits of discipline-oriented design reasoning.

In support of this, it can be observed that recent research in structural and infrastructure design shows that conceptual design is increasingly framed not as a purely technical sketching phase, but as a cross-disciplinary decision process in which structural logic, sustainability objectives, life-cycle performance, and contextual criteria are negotiated concurrently. For instance, frameworks that integrate sustainability and performance indicators demonstrate that early decisions exert strong influence on structural performance, environmental impact, and economic costs across the life of a structure, especially in footbridges and urban

infrastructure projects (Gozzi & Guante Henriquez, 2025a; Milić & Bleiziffer, 2024). Furthermore, holistic conceptual models have been proposed to account for deep uncertainties, such as those arising from climate change or future risk profiles, highlighting the need to embed resilience, adaptability, and environmental foresight into initial design stages (Nasr et al., 2021). Decision-support tools based on multi-criteria methods provide operational means to compare alternative solutions under multiple criteria and to support designers in balancing feasibility, architectural, structural, economic, and sustainable objectives early in the design process (ElMarkaby et al., 2023; Tanner & Hingorani, 2021). That demonstrates how the emerging body of work confirms that conceptual design is no longer limited to preliminary sketches or qualitative considerations, but rather functions as a disciplined, evidence-based stage where objective and quantitative performance indicators are jointly explored to guide subsequent technical development.

A growing body of research shows that the transition toward cross-disciplinary conceptual design is closely linked to the increasing prominence of resilience- and sustainability-oriented objectives in contemporary infrastructure projects. These objectives do not simply introduce additional performance criteria but fundamentally change the way structural systems are conceived at the early design stage. Structural resilience-oriented approaches require designers to reason in terms of system behaviour, robustness, and redundancy, while sustainability-oriented frameworks highlight how choices related to structural configuration, materials, and construction strategies determine long-term environmental and economic performance thus relating with the final form and architectural expression (Casas et al., 2024, 2024; Vimonsatit & others, 2014; Voulpiotis et al., 2021).

Beyond academic research, this shift toward cross-disciplinary conceptual design is increasingly reflected in normative frameworks and procurement practices. Recent standards and policy documents addressing sustainable construction, life-cycle performance, and infrastructure resilience consistently identify the early design stages as those with the greatest leverage on long-term outcomes, implicitly requiring coordination between various construction-related considerations from the outset. In parallel, public tenders and design competitions for bridges and infrastructures increasingly demand multidisciplinary teams from the earliest project phases, explicitly requiring integrated proposals that simultaneously address structural concept, architectural quality, durability, environmental performance, and constructability, a tendency also reflected in recent European procurement directives and international competition regulations (Directive 2014/24/EU of the European Parliament and of the Council of

26 February 2014 on Public Procurement and Repealing Directive 2004/18/EC Text with EEA Relevance, 2014).

Obviously, advances in digital design environments have reinforced this transition. Parametric and generative workflows increasingly support early-stage exploration of alternative structural concepts, allowing designers to evaluate multiple performance criteria, including architectural, structural, environmental, and economic aspects, already during conceptual design. Rather than replacing subjective judgement, these tools promote a more explicit and transparent comparison of design alternatives and foster dialogue between disciplines at a stage when changes are still feasible and cost-effective (Ajtayné Károlyfi & Szép, 2023; Arbulu et al., 2024).

This convergence between research, professional practice, and institutional requirements explains the growing use of terms such as holistic design or integrated design in contemporary context. Rather than representing a stylistic trend, this terminology reflects the recognition that structural and infrastructure projects have become multi-performance systems, whose behaviour and value cannot be decomposed into independent disciplinary problems. Holistic or cross-disciplinary conceptual design thus emerges as a pragmatic response to increasing project complexity, uncertainty, and societal expectations.

For bridge and footbridge design in particular, this transition has significant implications. As discussed in the previous sections, footbridges inherently embody the interaction between form, structure, material, and context. In contemporary practice, this interaction must now also encompass environmental performance, durability, and resilience. Conceptual design thus becomes the critical interface where these dimensions are negotiated and aligned. It is precisely within this space that structured, multi-criteria approach to conceptual design are required, capable of supporting informed decision-making under uncertainty.

Within this paradigm, the conceptual design of footbridges can no longer be framed through isolated disciplinary requirements. Instead, it unfolds through a set of interacting design dimensions that address, in parallel, architectural and contextual integration, functional and urban performance, structural behaviour and resilience, environmental sustainability, and long-term adaptability. These multidisciplinary dimensions provide the conceptual structure for discussing contemporary footbridge design criteria and are examined individually in the following sections (§§1.4.2–1.4.6).

1.3.2 Aesthetics and Contextual Integration

Aesthetic quality in bridge design has long been a field of disciplinary tension, oscillating between structural rationalism and architectural expressiveness. Within engineering-oriented traditions, aesthetic value has often been associated with the legibility and efficiency of structural action. In this perspective, Leonhardt (1982) argued that bridge beauty arises from the clarity of force flow and structural logic, suggesting that elegance is not an external attribute but an intrinsic outcome of rational and efficient design.

Conversely, architectural and interdisciplinary approaches have emphasized the cultural and contextual dimensions of bridge aesthetics. Gottemoeller (1998) described bridges as cultural artefacts whose meaning and perceived beauty emerge through interaction with place, collective memory, and public interpretation. From this standpoint, aesthetic quality is not reducible to formal or structural coherence alone but is shaped by how infrastructure mediates relationships between territory, users, and societal values.

Building on this broader interpretation, Frampton (2001) introduced the concept of tectonics as a critical lens through which structural form can be understood as a synthesis of materiality, construction logic, and cultural expression. In Frampton's view, the articulation of structure is not merely a technical necessity, but a carrier of meaning rooted in place-specific construction practices and material choices. Structural form thus becomes a medium through which cultural identity and territorial belonging are expressed.

This theoretical position anticipates more recent frameworks that seek to formalize the cultural and contextual dimensions of design within evaluative systems. In this sense, Frampton's tectonic interpretation resonates with the Davos Baukultur Quality System (2021), which proposes a comprehensive approach to assessing the quality of the built environment. Within this framework, aesthetic value is not treated as an isolated or subjective ambition, but as a component of civic responsibility, requiring designers to consider how spatial interventions contribute to collective meaning, social coherence, and long-term territorial identity.

Importantly, both perspectives converge in implying that aesthetic and contextual qualities are largely determined by early design decisions. Choices related to structural typology, material expression, geometry, and integration with

the surrounding landscape are typically established during the conceptual phase and are difficult to fundamentally alter at later stages. As such, aesthetic quality and contextual integration cannot be relegated to post-rationalization or superficial formal refinement but must be embedded within the initial structural concept.

From the standpoint of conceptual design, aesthetics and contextual integration therefore function as strategic criteria rather than secondary outcomes. Their consideration at the early stage enables the alignment of structural logic, cultural meaning, and site-specific constraints within a coherent design framework. This reinforces the role of conceptual design as the phase in which technical feasibility, architectural expression, and contextual responsibility are negotiated simultaneously, shaping both the perceptual and performance-related qualities of bridge infrastructure over its entire lifecycle.

1.3.3 Function and urban planning

Beyond form, footbridges must meet functional and urban requirements that strongly influence design choices. They are vectors for pedestrian and cyclist movements, but increasingly they also operate as civic spaces, connective devices, and, in many contexts, recognizable landmarks. Their effectiveness depends not only on structural performance, but also on usability, accessibility, and integration within the spatial and social context of the city.

From a functional perspective, contemporary footbridge design is closely aligned with human-centred and *Design for All* principles, where accessibility and inclusive geometry constitute core design requirements. Key parameters include longitudinal gradient, deck alignment and curvature, clear width, railing transparency, tactile surfaces, and vibration comfort. Together, these factors directly influence perceived safety, usability, inclusivity, and user satisfaction, particularly for vulnerable users such as children, older people, and persons with disabilities (CEN/CLC JTC 11., 2021).

At the same time, functional performance in footbridges cannot be dissociated from urban planning considerations. Footbridges increasingly contribute to broader urban strategies by reconnecting fragmented districts, activating underused spaces, and acting as symbolic thresholds between neighbourhoods (Gehl, 2010; UN-Habitat, 2020). In this sense, function extends beyond circulation efficiency and becomes a spatial and social mediator, enabling urban continuity, visual orientation, and public realm cohesion. Functional and urban criteria therefore do not operate

independently, but interact through the spatial configuration of the bridge, influencing alignment, landing points, section geometry, and relationships with surrounding public spaces.

This interaction implies that functional requirements simultaneously serve urban objectives, and vice versa. Decisions concerning accessibility, geometry, and user comfort directly affect how a footbridge integrates into its context, supports inclusive mobility, and contributes to spatial legibility at the urban scale. As a result, functional performance becomes a key driver through which urban relationships and social accessibility are structurally enabled, rather than a secondary aspect addressed after formal or structural choices have been made.

At the regulatory level, structural codes such as the Eurocodes for pedestrian bridges (Palmisano & others, 2003) and AASHTO (2020) define minimum requirements related to safety, serviceability, and accessibility. However, these documents provide limited guidance on issues of spatial integration, cultural significance, and user experience at the urban scale. Such aspects therefore remain largely outside the scope of prescriptive codes and must be addressed upstream, within the conceptual definition of the structural system. This reinforces the role of conceptual design as the phase in which functional, urban, and regulatory criteria are interpreted jointly, allowing compliance requirements to be reconciled with broader objectives of inclusivity, urban integration, and spatial quality.

1.3.4 Resistance to Disproportionate Collapse

In recent years, the normative framework for infrastructure design, and bridge design in particular, has expanded beyond traditional performance requirements associated with ultimate and serviceability limit states (ULS and SLS). While ULS and SLS verification ensures adequate behaviour under predefined design load combinations, it does not explicitly address structural response to accidental, exceptional, or unforeseen events, nor the potential consequences of localised damage. To overcome this limitation, contemporary standards increasingly require explicit consideration of accidental design situations and failure consequences, introducing the concepts of structural robustness and resistance to disproportionate collapse as integral components of structural performance (Zhao et al., 2022).

Structural robustness refers to the capacity of a system to tolerate unforeseen events, such as accidental actions, material defects, or localised failures, without triggering disproportionate or progressive (Biondini & Frangopol, 2016; Starossek

& Haberland, 2012). Unlike traditional safety concepts, which are largely deterministic and component-oriented, robustness concerns the behaviour of the structural system, including its ability to redistribute loads through redundancy, continuity, and alternative load paths under abnormal scenarios. This system-level perspective is particularly relevant for footbridges, which are often slender, lightly redundant, and sensitive to phenomena such as vibration, thermal effects, fatigue, or local disruption.

This shift reflects the broader transition toward performance-based design, in which structural safety is framed in relation to uncertainty, risk, and potential consequences rather than solely through prescriptive compliance. Within this context, Eurocode EN 1990, Annex A2 (2023), explicitly requires verification against disproportionate collapse for critical infrastructure, positioning robustness as a primary design objective rather than a secondary verification step. Similarly, bridge-specific guidelines such as CNR DT 214/2018 (2018), link robustness requirements to risk-based considerations, explicitly accounting for exposure conditions, environmental context, and the indirect consequences associated with structural failure.

From this perspective, robustness and resistance to disproportionate collapse emerge as core criteria of conceptual design rather than issues to be addressed only during detailed verification. Decisions related to structural topology, continuity, redundancy, and hierarchy are intrinsically connected to early choices of geometry, functional layout, and spatial organisation. In footbridge projects, these aspects are closely intertwined with architectural configuration and functional planning, as the position of supports, span arrangement, structural depth, and accessibility requirements directly influence both system behaviour under accidental scenarios and the consequences of potential failure.

The introduction of failure scenarios and robustness criteria marks a departure from the classical “form follows forces” paradigm, where structural form is optimised with respect to a dominant and predictable load flow. In robustness-oriented design, form is required to remain effective under multiple, competing, and partially indeterminate force paths arising from accidental actions and localised damage, thereby dissolving the notion of a unique correspondence between form and force (Tanner et al., 2022).

Robustness-oriented conceptual design therefore requires an integrated approach in which structural safety, functional organisation, and architectural intent

are developed concurrently. By embedding risk- and consequence-based reasoning at the conceptual stage, designers can align structural performance objectives with functional use, spatial quality, and contextual constraints, ensuring that robustness is not treated as an isolated technical requirement but as an integral dimension of overall design coherence.

1.3.5 Durability as a necessary pre-requisite

Within contemporary performance-based design frameworks, structural robustness and durability represent complementary and interdependent dimensions of structural reliability. Robustness addresses the ability of a structural system to withstand accidental or exceptional events without disproportionate collapse, focusing on the system's capacity to tolerate localised damage through redundancy, continuity, and alternative load paths. However, this capacity is meaningful only if it can be preserved over time. For this reason, durability is introduced as a necessary extension of robustness from an event-based perspective to a time-dependent performance framework. Durability concerns the ability of a structure to maintain its robustness and safety-related properties throughout its design working life, despite the effects of environmental exposure, material ageing, fatigue, and use. In the absence of adequate durability, the structural mechanisms that ensure robustness progressively degrade, undermining the system's capacity to redistribute loads and to resist accidental scenarios.

Within structural reliability theory, durability therefore governs the temporal evolution of both resistance and robustness, linking immediate structural safety to long-term reliability. From a conceptual design perspective, this relationship implies that robustness-oriented strategies, such as redundancy, continuity, and hierarchical organization, must be supported by material choices, detailing, and management strategy capable of preserving these attributes over time. As a result, durability is not introduced as an independent or secondary requirement, but as an integral condition for ensuring that robustness, and structural performance, remains effective throughout the service life of the structure.

Within this perspective, inspectability and maintainability are intrinsic components of durability, rather than residual concerns delegated to post-construction asset management. A structure that cannot be adequately inspected or maintained cannot ensure reliable performance over time, even if it satisfies static safety requirements at commissioning. This shift toward lifecycle-oriented design is reflected in normative frameworks such as ISO 15686-5 (2017a) and ISO 13822

(2010), which explicitly frame durability planning, condition assessment, and intervention strategies as responsibilities to be addressed from the earliest design stages.

On these bases it is evident that, from the earliest design stages, durability-oriented conceptual design requires explicit consideration of design for inspectability and design for maintainability. These aspects are not operational additions, but structural qualities that determine whether long-term performance objectives can be effectively preserved over time.

Inspectability concerns the ability to reliably assess the condition and behaviour of the structure over time. It refers to the accessibility, visibility, and legibility of structural components, connections, and interfaces, enabling the detection and interpretation of degradation mechanisms before they compromise safety or functionality. In normative terms, inspectability is implicitly embedded in standards such as ISO 13822 (2010), which recognise that effective condition assessment depends on design transparency and physical access to critical elements. At the conceptual level, inspectability is therefore governed by early decisions on geometry, spatial organisation, structural configuration, eventual monitoring strategy which determine whether the structural system remains readable and accessible throughout its service life.

Maintainability, by contrast, addresses the ability of the structure to accommodate interventions aimed at preserving or restoring performance. As defined in EN 13306 (2017), maintainability refers to the capacity of a system to be retained or restored to a state in which it can perform its required functions under defined conditions and procedures. In design terms, maintainability concerns the feasibility, frequency, and impact of maintenance, repair, replacement, or upgrading operations. Conceptual design choices related to structural typology, component hierarchy, protection, modularity, and reversibility strongly influence whether interventions can be localised, predictable, and carried out without disproportionate disruption to service. The distinction between inspectability and maintainability is particularly relevant in bridge design, where a structure may be technically maintainable in principle but effectively uninspectable in practice, or conversely, easily inspectable but difficult to repair without extensive intervention. Recognising this difference at the conceptual stage prevents durability from being reduced to an abstract or assumed property and allows designers to explicitly address both performance dimensions in a coherent manner.

Within this perspective, design for inspectability and design for maintainability operate as distinct yet complementary design drivers. Together, they ensure that robustness and durability are not merely achieved at commissioning, but can be actively preserved throughout the service life, reinforcing conceptual design as the primary phase in which long-term asset performance is established.

1.3.6 Structural resilience

In light of the above discussion, robustness, inspection, and maintenance emerge as interrelated components of structural resilience. Within this framework, structural resilience is understood as the capacity of a structural system to withstand disruptive or extreme events, to limit performance degradation, and to sustain or restore acceptable levels of safety and functionality over its life cycle. This conception of resilience builds upon the interplay of three mutually reinforcing properties: robustness, which governs the system's ability to tolerate damage; inspectability, which enables the timely detection and monitoring of degradation; and maintainability, which allows for effective mitigation and recovery actions. When explicitly incorporated from the conceptual design stage, these attributes guide design decisions that enhance structural safety and durability while improving life-cycle efficiency and sustainability (Casas et al., 2022).

1.3.7 Sustainability dimension

Sustainability has become a central criterion in the conceptual design of civil infrastructures, extending the scope of structural decision-making beyond traditional concerns of safety and cost. Contemporary design is increasingly required to address a broader set of interconnected demands driven by climate policies, societal expectations, and sustainable economy models.

Within this perspective, sustainability is commonly articulated through three interrelated dimensions (environmental, social, and economic) which together define the long-term value and responsibility of infrastructure projects according to first definition in Brundtland Report (1987) and more recent ISO 21929-2 (2015) as shown in Figure 5.

	Environmental aspects	Economic aspects	Social aspects
Methodological basics	ISO 15392 ISOTR 21932	General principles Terminology	
	ISO 219229-1 PART 1	Sustainability Indicators Framework for the development of indicators and a core set of indicators for buildings	
	► ISO/TS 21929-2 PART 2	Sustainability Indicators Framework for the development of indicators for civil engineering works	
Buildings or civil engineering works	► ISO 21931-1 PART 1	Framework for methods of assessment of the environmental performance of construction works Buildings	
	PART 2	Framework for methods of assessment of the sustainable performance of construction works Civil engineering works (<i>to be defined</i>)	
Building products	► ISO 21930	Environmental declaration of building products	
	► ISO 21930	Environmental declaration of building products	

Figure 5 Suite of related International Standards for sustainability in buildings and civil engineering works (ISO 15392:2019).

Thus, from a conceptual design standpoint, sustainability is not an additional constraint applied after the definition of form, but a structuring principle that informs early decisions on structural typology, material strategy, construction logic, and spatial integration. At this stage, fundamental choices exert a disproportionate influence on life-cycle performance, while design freedom remains high and trade-offs between competing objectives can still be meaningfully explored (Corres Peiretti et al., 2022; Milić & Bleiziffer, 2024).

In the specific context of bridge engineering, recent research has increasingly framed sustainability within a life-cycle perspective, moving beyond assessments limited to construction impacts toward integrated Life Cycle Sustainability Assessment (LCSA) approaches encompassing environmental (LCA), economic (LCC), and social (S-LCA) dimensions. As highlighted by Milić and Bleiziffer (2024) sustainability research on bridges has historically emerged more recently than that of buildings, despite the long service life, strategic relevance, and high resource intensity of bridge infrastructures.

The reviewed literature consistently shows that design decisions made during the early planning and conceptual stages, particularly those related to structural system selection, material choice, and durability strategies, have a dominant influence on life-cycle environmental impacts, costs, and social effects (Bocchini et al., 2014; Choobdarian & Biondini, 2025; Faber et al., 2020; Gupta et al., 2016; Kustova et al., 2024; Milani & Kripka, 2020a; Penadés-Plà et al., 2016). Comparative studies demonstrate that solutions characterised by higher initial material intensity or cost may achieve superior sustainability performance over time due to reduced maintenance requirements, extended service life, and improved adaptability.

In this background, structural configuration, durability, inspectability, and maintenance strategies emerge as key factors linking structural design to sustainability outcomes, as maintenance interventions significantly affect environmental burdens, user disruption, and long-term economic performance (Gozzi & Guante Henriquez, 2025a). These findings support a shift toward sustainability-oriented conceptual bridge design, in which structural, functional, and architectural decisions are evaluated jointly within a life-cycle and context-sensitive framework.

1.3.8 Circularity and Adaptability

In recent years, increasing attention has been directed toward the concept of circularity in the design of civil infrastructures, particularly in relation to resource efficiency, material flows, and end-of-life strategies. In the context of infrastructure design, circularity can be defined as a design paradigm aimed at maintaining the value of materials, components, and structural systems over time by enabling reuse, disassembly, adaptation, and recovery across successive life cycles, thereby reducing resource depletion, waste generation, and irreversible losses.

Although circularity is often addressed within broader sustainability frameworks, recent bridge-specific research indicates that it operates at a distinct and more operational level. Sustainability provides an overarching evaluative framework integrating environmental, social, and economic dimensions, whereas circularity addresses how design decisions influence material loops, reversibility, and the potential for value retention across uncertain and extended life cycles. As highlighted by Coenen et al. (2021) the circular performance of bridges depends strongly on design-oriented attributes such as reusability, disassemblability, and life-span extension, that cannot be fully represented through conventional

sustainability assessment metrics. Adaptability represents a further and separate design concept, referring to the capacity of an infrastructure to accommodate future changes in use, demand, or context without requiring major structural interventions (Andrade & Bragança, 2019; Mondoro et al., 2018) . While adaptability may influence the timing of interventions or the extension of service life, it is not intrinsically defined by material loops or end-of-life strategies and therefore cannot be reduced to circularity. Instead, adaptability addresses functional and contextual flexibility under uncertainty, operating independently from circular material logic.

This distinction is also reflected in contemporary normative and methodological frameworks, which address sustainability, circularity, and adaptability through different instruments and assessment logics. Sustainability is primarily framed through life-cycle–based evaluation standards, such as ISO 21929-2 and ISO 14044, which define environmental, social, and economic performance indicators. Circularity is instead addressed through design-oriented standards, most notably ISO 20887:2020, which focuses on reversibility, modularity, design for disassembly, and material recovery strategies. Adaptability is treated through frameworks concerned with service life, functional flexibility, and long-term performance under changing conditions. At the methodological level, the Level(s) framework reflects this differentiated approach by explicitly addressing life-cycle performance, modular construction, and functional adaptability as distinct evaluation themes rather than as a single aggregated sustainability criterion (European Commission, 2020).

1.3.9 Project-Specific References: selected examples

The following project sheets present a selection of built footbridges as project-specific references, intended to illustrate how contemporary conceptual design criteria discussed in the previous sections are addressed in practice at the preliminary design stage, without implying a formal evaluation or comparative assessment.

Albi Footbridge (France): Landscape and Historical Context



Location: Albi, France

Context: River Tarn crossing adjacent to a 19th-century railway viaduct within the UNESCO-listed Episcopal City

Completion: 2025

Design team: Ney & Partners (structural and architectural design)

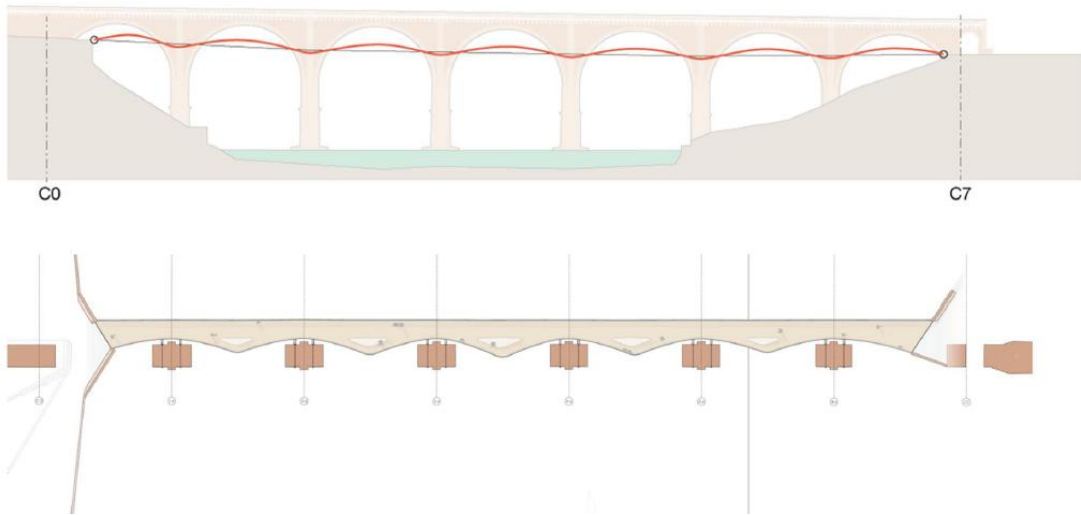
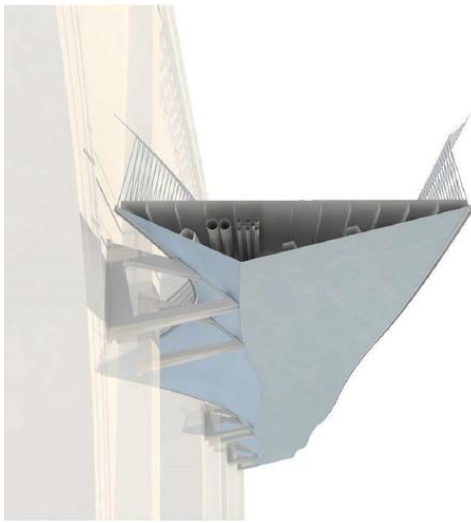
Typology: Continuous multi-span steel box footbridge attached to existing infrastructure

Primary material: Steel

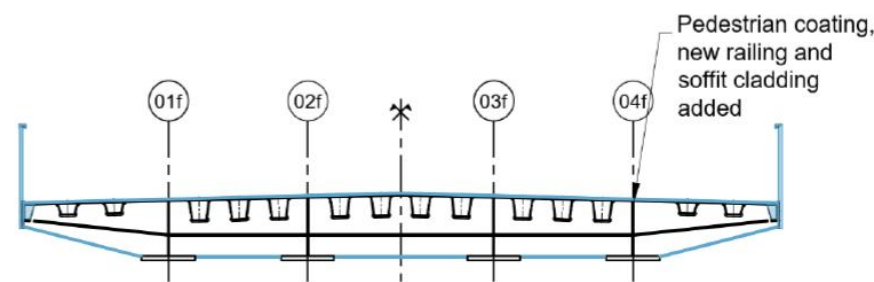
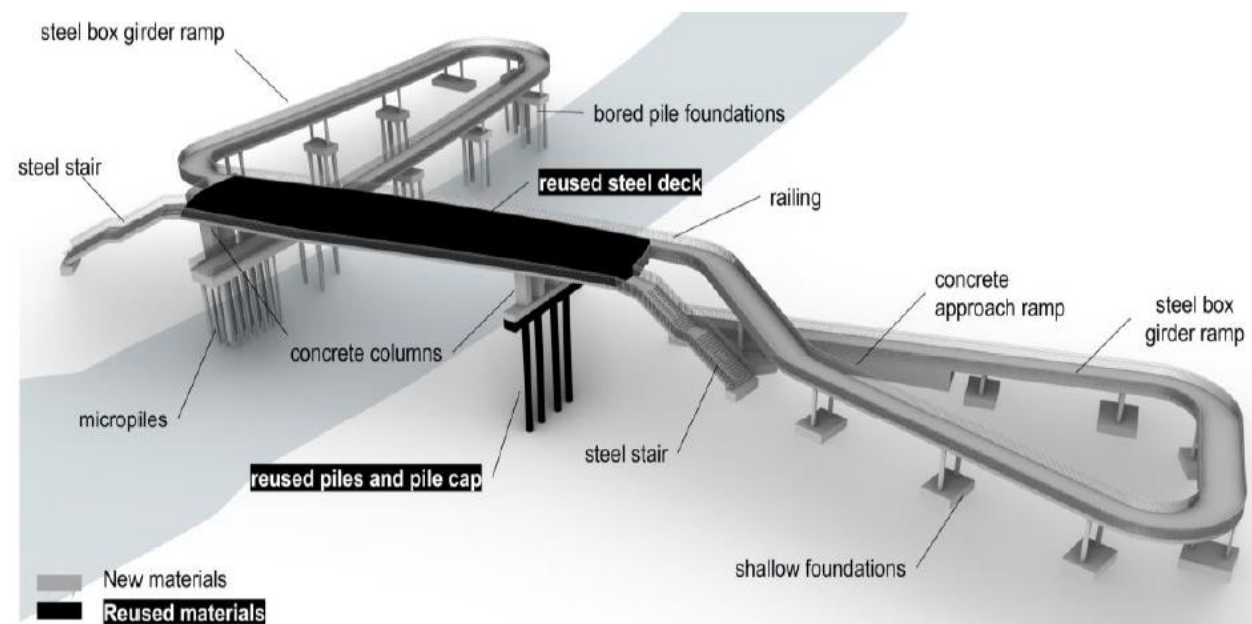
Use: Pedestrian and cycling bridge

Conceptual relevance

Albi Footbridge is presented as a project-specific reference in which architectural and landscape considerations frame the early structural concept. The footbridge is explicitly positioned to improve soft-mobility connectivity between the historic centre and surrounding neighbourhoods, responding to a strategic urban mobility agenda that prioritises continuity, safety, and reduced reliance on vehicular transport. At the conceptual stage, decisions regarding alignment, support placement, and deck configuration are directly shaped by the presence of a 19th-century masonry railway viaduct and by the adjacent heritage landscape. Rather than treating these constraints as external limitations, the structural concept is articulated to establish a deliberate dialogue between the existing infrastructure and the new intervention, mediating between contemporary construction logic and historical context through contrast, scale, and spatial sequencing. In this sense, architectural and contextual drivers do not operate independently from structural reasoning but actively inform the definition of the structural typology itself. The project is discussed here qualitatively to illustrate how context-sensitive architectural intentions interact with early-stage structural choices, without implying any formal evaluation or comparative assessment.



Lucie Bréard Footbridge (France): Structural Reuse and Circular Design



Location: Saint-Denis, France

Context: Canal Saint-Denis, connecting Stade de France to Francs-Moisins and Bel-Air districts

Completion: 2024

Design team: schlaich bergemann partner (structural engineering), Explorations Architecture (architecture), August (landscape architecture)

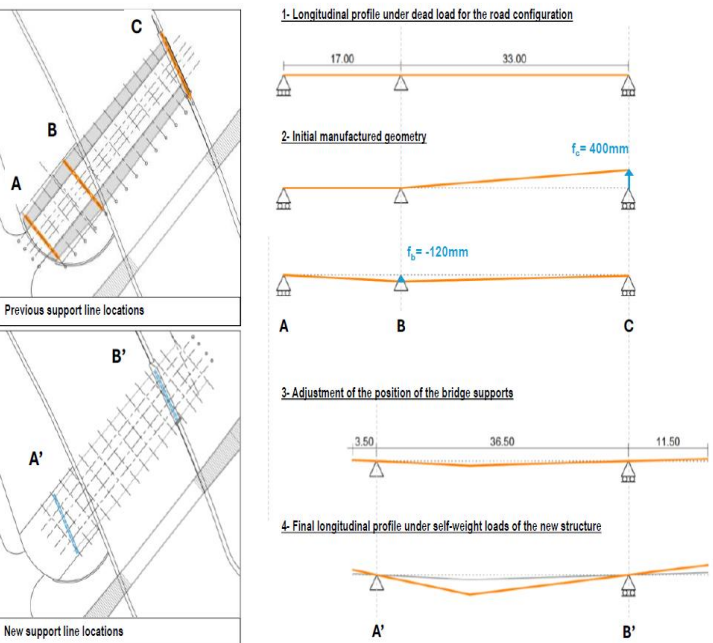
Typology: Simply supported steel footbridge with reused main span

Primary material: Reused steel deck (S355) + new steel ramps

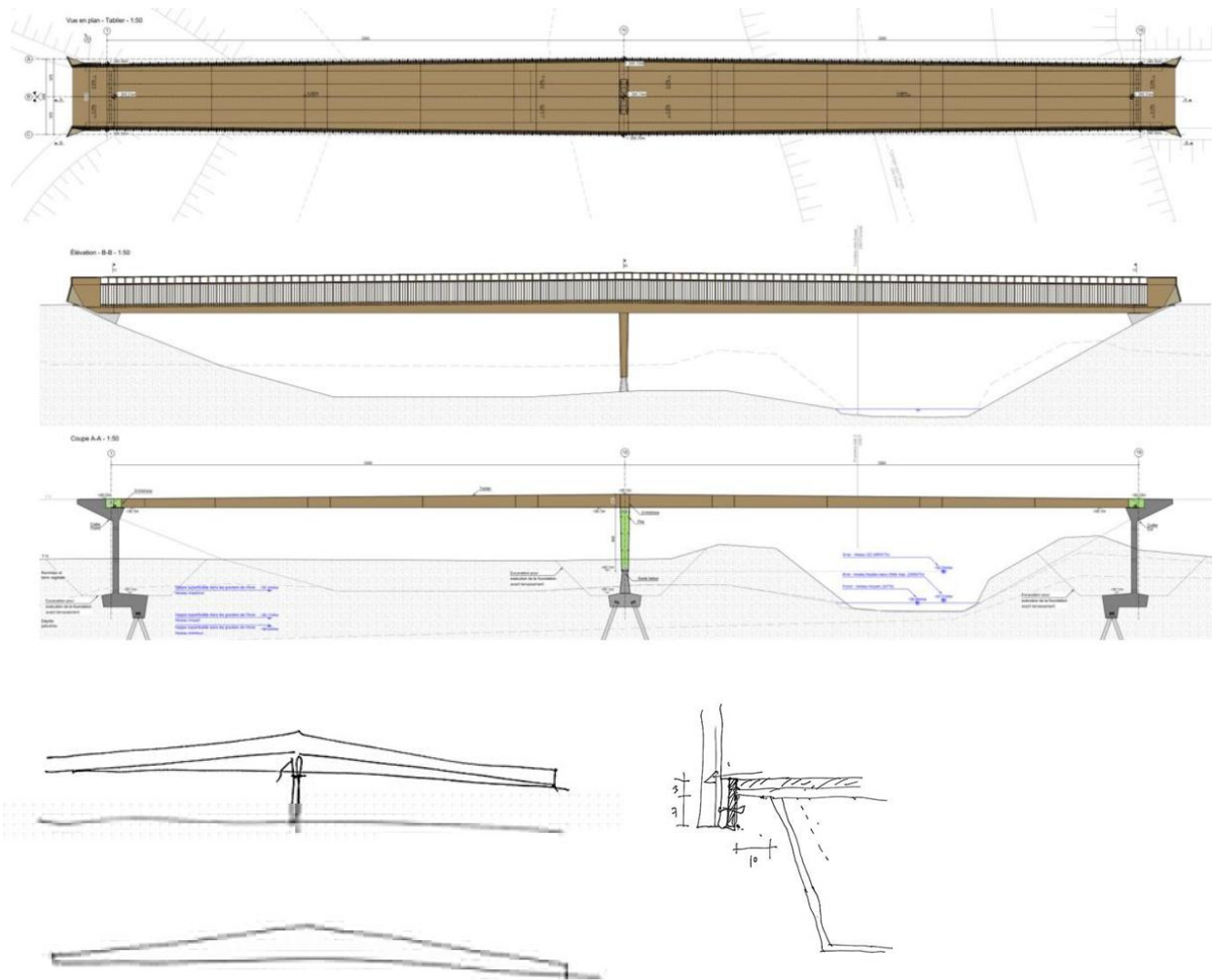
Use: Pedestrian and cycling bridge (Design for All accessibility)

Conceptual relevance

The Lucie Bréard Footbridge is presented as a project-specific reference in which structural reuse and circularity constitute the primary drivers of the conceptual design. By challenging the initial brief to demolish two existing bridges, the design team proposed the in-situ reuse of the deck of a 20-year-old movable bridge as the main span of the new crossing, aligning the project with the Paris 2024 objectives of carbon reduction and long-term infrastructural legacy. At the conceptual stage, decisions concerning alignment, static scheme, and deck geometry were governed by the constraints and opportunities associated with reuse. These included the verification of material properties, the redefinition of boundary conditions resulting from a modified support configuration, the reassessment of durability performance, and the anticipation of construction and logistics constraints related to lifting, relocation, and integration of the existing structure. Architectural and landscape design choices were subsequently developed to accommodate and reinterpret the reused structural element within a new urban and public-space configuration. In this sense, circularity-oriented structural reasoning operates as a generative principle of the overall design, shaping spatial organisation and architectural expression from the outset, rather than being addressed as a post-hoc optimisation or compensatory sustainability measure.



Foron River Footbridge (Switzerland): Design for Inspectability and Maintainability



Location: Canton of Geneva, Switzerland

Context: Natural river crossing within a sensitive environmental corridor

Completion: 2025

Design team: structurame (structural engineering), Atelier Bonnet (architecture)

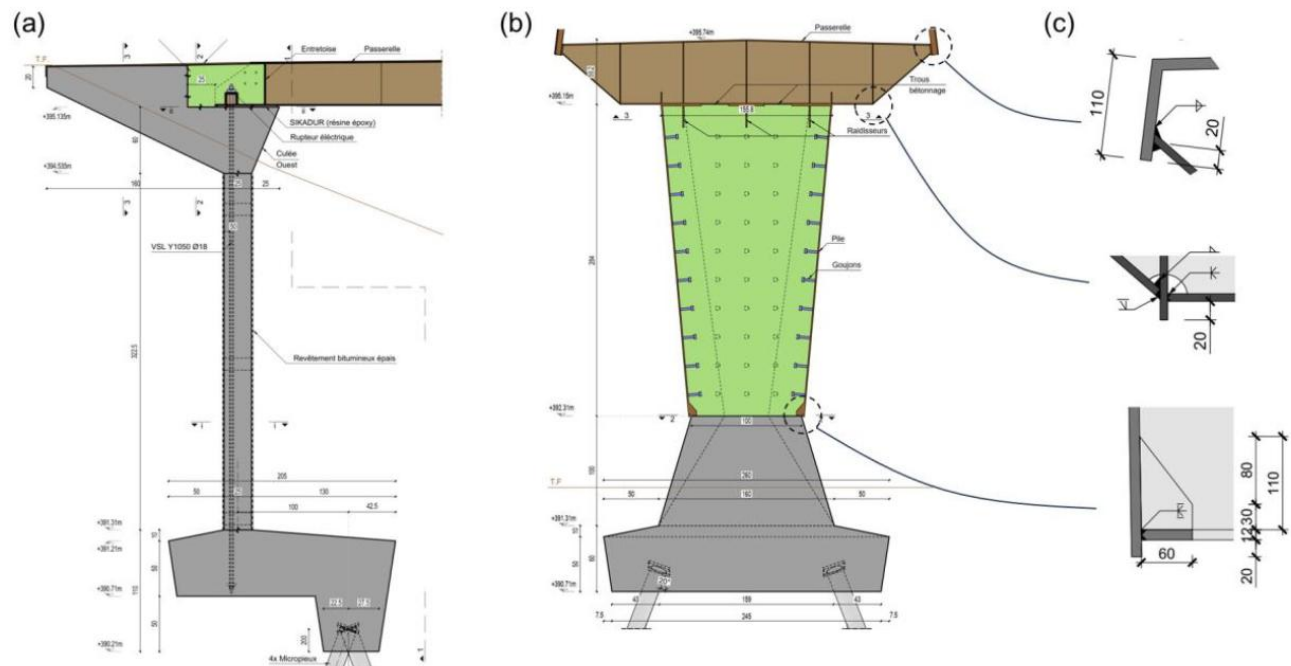
Typology: Integral steel footbridge (no bearings, no expansion joints)

Primary material: Weathering steel

Use: Pedestrian and cycling bridge

Conceptual relevance

The Foron River Footbridge is presented as a project-specific reference in which inspectability, and maintainability constitute primary drivers of the conceptual design. From the earliest design stages, long-term performance and asset management requirements directly informed the choice of structural typology, material strategy, and construction logic. In particular, the selection of an integral structural system reflects a deliberate conceptual strategy aimed at eliminating bearings and expansion joints, which are typically among the most maintenance-intensive and degradation-prone components in footbridge structures. This choice directly links structural behaviour, durability, and inspection strategy, shifting maintenance considerations from the detailing stage to the definition of the static scheme itself. Furthermore, the positioning of critical structural connections above frequent flood levels and the adoption of a legible load-bearing hierarchy illustrate how inspection and intervention requirements are explicitly embedded within the spatial and geometric configuration of the bridge. In this sense, maintainability and inspectability do not emerge as secondary performance checks but act as generative criteria shaping the conceptual design of the structure.



1.4 Taking a decision: MCDM and quality

1.4.1 Integrating Criteria and Defining Quality

Taken together, the dimensions discussed in §§1.4.2–1.4.6 show how contemporary footbridge conceptual design is shaped by a wide and heterogeneous set of criteria that progressively accumulate as the project evolves from strategic definition toward preliminary design. Alongside feasibility-related parameters typically addressed at the planning and briefing stage and not discussed as emerging new in this study although still present, such as regulatory compliance, spatial constraints, functional requirements, and budgetary limits, growing number of quality-oriented criteria emerge at the conceptual level.

At the preliminary design stage, these parameters coexist and interact, but they operate at different logical levels. Feasibility-related conditions define the admissible solution space within which design alternatives can be generated, whereas the multidimensional criteria discussed in this chapter differentiate feasible options in terms of their overall quality and long-term value. It is therefore common that several alternative concepts satisfy basic feasibility requirements while exhibiting significantly different performance profiles when assessed against the broader set of structural, environmental, functional, and life-cycle-related objectives. In this context, the selection of a preferred preliminary design solution cannot be reduced to compliance with minimum requirements, nor to the optimisation of a single dominant criterion. Quality emerges instead from the capacity of a design option to integrate multiple performance dimensions simultaneously, reflecting their relative importance within a specific project context and under conditions of uncertainty. As the number of relevant criteria increases, and as trade-offs between them become unavoidable, intuitive or purely qualitative judgement becomes insufficient to support transparent and reproducible design decisions. As Tang (2013) and Gkoumas and Bontempi (2020) observe, contemporary infrastructure design requires structured frameworks capable of navigating trade-offs and conflicting priorities.

This condition transforms preliminary design into an explicit decision-making problem, in which alternative solutions must be compared, prioritised, and justified on the basis of multiple, and often competing, criteria. Addressing this challenge requires structured evaluation approaches capable of integrating heterogeneous performance indicators and of making explicit the value assumptions underlying the notion of quality adopted for a given project. The following section introduces

Multi-Criteria Decision-Making methods and quality evaluation systems as the methodological framework through which such comparisons can be conducted in a rational and systematic manner.

This redefinition has implications for the conceptual design phase. As shown in §1.1, this phase is characterized by freedom of exploration but also by maximum influence over long-term performance. Embedding evaluation tools, such as Multi-Criteria Decision-Making (MCDM) methods and Infrastructure Rating Systems (SIRS), within conceptual workflows offers a way to operationalize quality from the outset. These tools enable designers to translate qualitative aspirations into quantifiable criteria, providing the foundation for transparent, interdisciplinary decision-making. Within this evolving framework, the assessment of quality becomes closely linked to the act of conceptual design itself. Rather than an external verification process, it represents an intrinsic form of reasoning, a continuous negotiation among performance, sustainability, and meaning. When supported by structured evaluation tools, the conceptual phase can transcend intuition alone, allowing designers to test ideas against transparent, interdisciplinary criteria without suppressing creativity. In this sense, quality is not the outcome of design but its method: a generative principle that aligns technical excellence with cultural intention, transforming conceptual reasoning into a measurable and shared foundation for structural innovation.

1.4.2 Multi-Criteria Decision-Making (MCDM) Methods

As discussed in the previous sections, contemporary conceptual design in bridge and footbridge projects is characterised by the presence of multiple heterogeneous criteria that must be considered simultaneously at the preliminary design stage. These criteria operate at different decision levels and cannot be meaningfully reduced to a single performance objective. As a result, alternative design options may all satisfy basic feasibility requirements while showing significantly different behaviours when examined across the broader set of design dimensions. In this context, early-stage design cannot be framed as a problem of optimisation with respect to a single target, but rather as a decision-making problem involving trade-offs among competing and often non-commensurable objectives. Approaches based on isolated checks or single-objective optimisation are therefore insufficient to support transparent and reproducible choices. This condition provides the rationale for adopting Multi-Criteria Decision-Making methods, which have been developed to structure, compare, and prioritise multiple criteria within a coherent evaluation framework (Favi et al., 2018; Zavadskas et al., 2014).

A wide range of MCDM techniques has been applied in structural and infrastructure design, each characterised by a specific decision logic and modelling approach. Among the most commonly used methods are the Analytic Hierarchy Process (AHP) and its fuzzy extension (FAHP), the Analytic Network Process (ANP), TOPSIS, ELECTRE, PROMETHEE, and Goal Programming. These methods differ in the way criteria are structured, weighted, and aggregated, as well as in their capacity to address interdependencies and uncertainty. Table 1 provides a comparative overview of the main MCDM methods applied in structural design, summarising their underlying principles, typical applications, and key references, in order to clarify their respective roles and limitations within early-stage design decision-making.

Table 1 MCDM Methods in Structural Design, offering a synthesized comparison of methods, descriptions, main applications, and references.

Method	Description	Applications in the AEC field	References
AHP	Hierarchical decision-making method based on pairwise comparisons, used to derive relative weights and priority rankings among criteria and alternatives.	Support to early-stage decision-making for problems involving multiple design objectives, such as sustainability-oriented assessments and selection among alternative structural concepts.	(Haddad et al., 2024; Kahraman et al., 2007)
Fuzzy AHP	Extension of AHP that incorporates fuzzy logic to represent uncertainty and imprecision in pairwise comparisons and preference judgements.	Decision problems characterised by qualitative criteria and uncertain information, particularly in early design stages and sustainability-related assessments.	(Kahraman, 2008)
ANP	Network-based decision-making method that generalises AHP by allowing interdependencies and feedback among criteria and alternatives.	Evaluation of complex design problems where criteria are strongly interrelated, such as life-cycle-oriented and resilience-based assessments.	(Kabir et al., 2014)
TOPSIS	Ranking method based on the distance of each alternative from an ideal and a negative-ideal solution in a multi-dimensional criteria space.	Comparison of design alternatives with respect to multiple performance dimensions, often used in preliminary material and system selection.	(Malekly et al., 2018; Saparauskas, 2020)
ELECTRE	Outranking method based on pairwise comparisons that identifies dominance relationships among alternatives without requiring full aggregation of criteria.	Assessment of design alternatives under conflicting criteria, particularly when trade-offs cannot be expressed through a single compensatory index.	(Greco et al., 2016; Roy, 1991)
PROMETHEE	Preference-based outranking method that ranks alternatives using predefined preference functions and partial aggregation of criteria.	Support to decision-making problems involving both quantitative and qualitative criteria, including comparative assessment of design options.	(Brans & Vincke, 1985; Navarro et al., 2020)
Goal Programming	Multi-objective optimisation framework that seeks solutions satisfying multiple goals by minimising deviations from predefined target levels.	Design problems involving competing objectives and explicit performance targets, particularly when minimum or desired levels must be achieved simultaneously.	(Charnes & Cooper, 1961; Romero, 1991)
WSM	Linear aggregation model that combines normalised criteria scores through weighted summation to obtain an overall performance index for each alternative.	Early-stage comparison of alternative design options under multiple criteria, particularly when transparency and interpretability of results are prioritised.	(Belton & Stewart, 2002; Hwang & Yoon, 1981)

The methods summarised in Table 1 differ significantly in terms of decision logic, data requirements, and suitability for early-stage conceptual design. While all of them aim to support decision-making under multiple criteria, their applicability varies depending on the level of information available and the nature of the design problem. Outranking methods such as ELECTRE and PROMETHEE are particularly effective when decision-makers seek to identify dominance relationships among alternatives without full aggregation of criteria. However, their reliance on pairwise comparisons and threshold definitions may limit transparency and interpretability at the conceptual design stage, where design alternatives are still evolving and stakeholder communication is essential.

Hierarchical and network-based approaches, including AHP, Fuzzy AHP, and ANP, offer structured procedures to derive criteria weights and to account for interdependencies. These methods are well suited to problems involving qualitative judgement and uncertainty, but they can become demanding in terms of cognitive effort and consistency requirements when the number of criteria and alternatives increases, as is often the case in early-stage infrastructure design. Simpler aggregation models, such as the Weighted Sum Method, are frequently adopted in conceptual design contexts due to their clarity, flexibility, and ease of interpretation. When criteria are explicitly defined and weighted, linear aggregation allows designers to compare alternative concepts in a transparent manner, while keeping the evaluation framework accessible to non-specialist stakeholders. Although such models require assumptions regarding criteria independence and compensability, these assumptions are often acceptable at the preliminary design stage, provided they are made explicit. For these reasons, aggregation-based approaches play a central role in early-stage conceptual design, where the objective is not to identify a mathematically optimal solution, but to support informed comparison, discussion, and refinement of alternative design options under multiple and competing criteria.

1.4.3 Infrastructure Evaluation Frameworks

In parallel with the increasing complexity of contemporary infrastructure projects, evaluation methods have progressively evolved from single-criterion checks toward structured decision-support systems. Over the last two decades, Multi-Criteria Decision-Making (MCDM) approaches have played a central role in this transition, providing formal mechanisms to compare alternative solutions by simultaneously accounting for heterogeneous and often conflicting criteria. Initially developed within operations research and management sciences, MCDM methods have been widely adopted in the infrastructure domain to support strategic choices

under conditions of uncertainty, long time horizons, and multiple stakeholder perspectives. Within the field of infrastructure assessment, a wide range of evaluation approaches has been developed to support decision-making in the presence of multiple, heterogeneous, and often conflicting criteria. Over the last two decades, these approaches have increasingly relied on Multi-Criteria Decision-Making (MCDM) methods, originally developed within operations research and subsequently adapted to the construction and infrastructure domain to address complex trade-offs between technical, economic, environmental, and qualitative aspects (Kabir et al., 2014; Saaty, 2006; Zavadskas et al., 2014). Review studies highlight how such methods have been widely applied to infrastructure and urban projects, yet with considerable variability in the types of criteria considered and in the underlying evaluation logic, reflecting the absence of a unified assessment paradigm (Radić et al., 2010; Y.-M. Wang et al., 2007; Dodd et al., 2017). This heterogeneity reflects the fact that infrastructure evaluation addresses multiple, only partially overlapping dimensions of project performance. For clarity, existing evaluation approaches are here grouped into three complementary domains, synthesising recurring patterns observed in the literature according to the primary dimension of project quality they address.

- Quality frameworks primarily oriented toward the evaluation of design intent and project coherence, addressing the integration of architectural, structural, functional, and contextual dimensions.
- Sustainability-oriented frameworks primarily focused on long-term environmental, social, and economic performance, typically assessed through life-cycle-based indicators.
- Risk-oriented frameworks primarily concerned with project feasibility and decision-related uncertainty, addressing risks associated with technical complexity, delivery processes, economic variability, and long-term adaptability, rather than hazard-based or code-driven structural safety.

While these domains are not mutually exclusive, each is characterised by a dominant evaluation logic and a specific set of decision priorities. Together, they constitute the contemporary ecosystem of infrastructure evaluation. Nevertheless, their integration into the conceptual design phase remains partial and inconsistent. In structural engineering practice in particular, early-stage evaluation is still largely driven by disciplinary expertise, heuristics, and precedent-based reasoning, with structured cross-domain assessment tools typically introduced only at later stages of the design process. This fragmentation highlights the need for evaluation methods capable of supporting conceptual design decisions in a more systematic,

transparent, and interdisciplinary manner, bridging qualitative and quantitative criteria while remaining compatible with the exploratory nature of early design.

Despite their relevance, these frameworks present important limitations when applied to early-stage footbridge conceptual design. Most quality, sustainability, and risk assessment systems have been developed primarily as evaluation, certification, or management tools and are generally applied once a preferred design solution has already been defined. Their main objective is to assess the performance of a project against predefined criteria rather than to support the comparison of alternative structural concepts during the exploratory phases of design.

As a consequence, they provide only limited support for one of the most critical challenges of conceptual design: selecting among multiple feasible alternatives that satisfy the same functional requirements while exhibiting significantly different structural, environmental, operational, and lifecycle characteristics. In the case of footbridges, designers are often required to compare fundamentally different structural typologies, materials, and construction strategies under conditions of incomplete information and high uncertainty.

Furthermore, existing frameworks typically address quality, sustainability, or risk as separate evaluation domains. They do not provide a unified mechanism for integrating structural performance, robustness, inspectability, maintainability, sustainability, adaptability, and lifecycle considerations within a single decision-support process. This limitation is particularly relevant during conceptual design, where decisions have the greatest influence on long-term project outcomes, but where quantitative information remains limited.

The MCDM framework proposed in this research is intended to address this operational gap. Rather than evaluating a single developed solution, it supports the systematic comparison and ranking of alternative footbridge concepts through a set of integrated performance indicators specifically tailored to the requirements of early-stage structural design.

Quality Frameworks

Frameworks addressing design quality have progressively evolved from architectural discourse toward the broader domain of infrastructure. The Davos Quality System (BAK, 2021), developed as part of the Davos Declaration on Baukultur (2018), stands as one of the most influential initiatives in this field. It proposes eight interdependent themes shown in Figure 6, governance, functionality,

environment, economy, diversity, context, beauty, and sense of place, that together redefine the notion of quality as a synthesis of technical performance, cultural meaning, and spatial identity. In this view, the quality of an infrastructure does not reside solely in its structural efficiency or visual impact, but in the coherence between its form, its governance process, and its contribution to the collective environment.

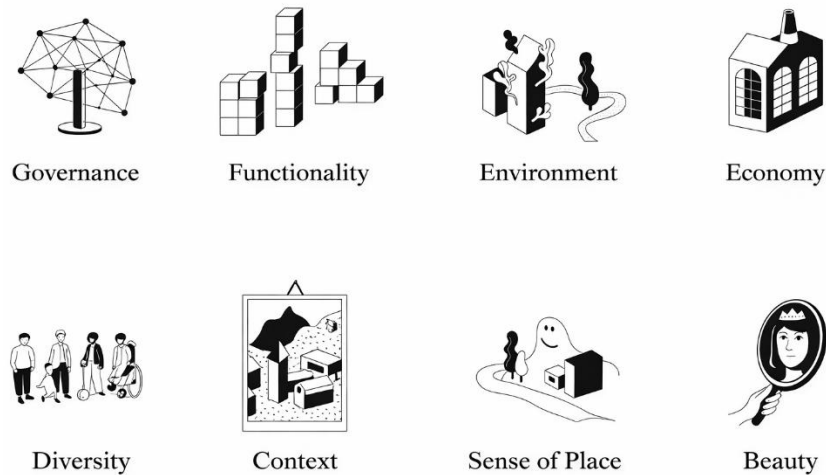


Figure 6 Davos Baukultur Quality System (2021) Manifesto, illustrating the eight quality criteria used to assess the value of the built environment across its entire lifecycle. Image from Swiss Federal Office of Culture / Heyday

Comparable approaches have been adopted in other contexts. In the United Kingdom, the Design Quality Indicator (DQI) developed by the Construction Industry Council introduced a systematic way to assess the spatial, functional, and experiential dimensions of design. Although initially conceived for public buildings, DQI principles, functionality, build quality, and impact, have informed infrastructural assessment, including transport and bridge projects. Similarly, national architecture policies in Ireland, Denmark, and Norway have embedded notions of design quality within public procurement, emphasizing interdisciplinary collaboration and long-term cultural value. The Baukultur Compass, promoted by the Swiss Society of Engineers and Architects (SIA, 2022), extends these ideas by providing practical guidance for evaluating spatial coherence and public benefit in large-scale infrastructure. Across these initiatives, a common paradigm emerges: quality is no longer an aesthetic ambition or a symbolic attribute, but a measure of how infrastructure contributes to environmental integration, social cohesion, and civic identity. Such frameworks do not prescribe design outcomes; rather, they offer a shared vocabulary for negotiating value at the earliest stages of conception. For

structural engineers, they invite a shift from viewing the concept as a purely technical proposal to understanding it as an act of cultural authorship, a deliberate statement about how structures occupy, transform, and enrich their contexts.

Sustainability Frameworks

Sustainability frameworks translate environmental and social ambitions into structured evaluation criteria, enabling performance to be assessed throughout the design process. Among them, the European Commission’s Level(s) framework (European Commission, 2020) provides a set of life-cycle indicators, such as carbon footprint, resource efficiency, adaptability, and comfort, that can be applied to both buildings and infrastructure. While originally conceived for architectural projects, its focus on life-cycle thinking and three levels of assessment based on measurable indicators and it offers a transferable logic for early-stage infrastructural design (Figure 7)

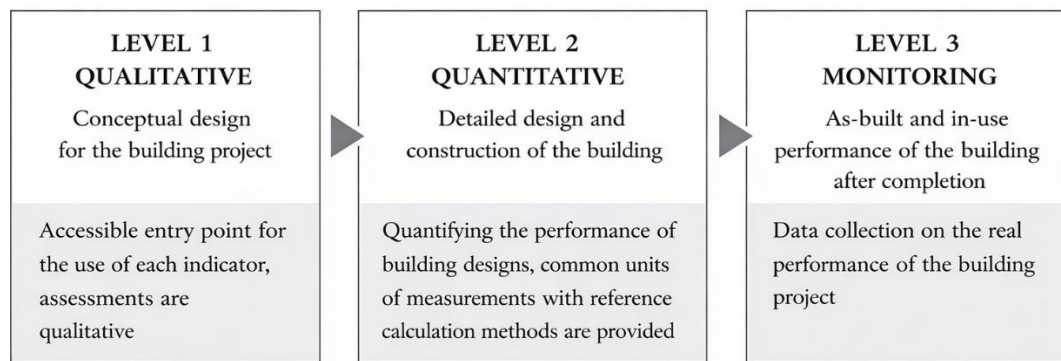


Figure 7 Three-Level(s)structure from conceptual design to performance monitoring.

Complementary systems, such as Envision (Institute for Sustainable Infrastructure, USA), CEEQUAL (UK), Greenroads, and SNBS Infrastructure (Switzerland), further expand sustainability assessment to civil works and transportation projects. These frameworks integrate environmental, social, and governance (ESG) dimensions into performance scoring systems, promoting transparent comparison of alternatives. However, most sustainability frameworks are implemented after the conceptual phase, typically during design development or procurement. Integrating them earlier could enhance design exploration by enabling quantitative feedback on material choices, structural typologies, and spatial strategies. When adapted to early-stage reasoning, these systems can transform sustainability from a compliance goal into a generative design principle,

allowing engineers and architects to explore trade-offs between environmental impact, technical efficiency, and cultural coherence (Table 2).

Table 2 Standards and Certifications for Preliminary Infrastructure Evaluation, outlining key standards, their scope, and relevance to the early design phase.

Standard / Certification	Scope	Relevance to Early Design Phase
ISO 21929-2	Sustainability indicators for civil engineering works	Provides KPIs for sustainable infrastructure planning
ISO 14040/14044	Life Cycle Assessment (LCA) methodology	Supports environmental impact evaluation of early alternatives
ISO 31000	Risk management principles and guidelines	Guides identification and mitigation of project risks
ISO 22301	Business continuity management systems	Assists in preparing for disruptions and ensuring resilience
Envision	Sustainability for infrastructure across quality of life, leadership, and climate	Framework for integrating sustainability at the concept stage
CEEQUAL	Environmental and social performance of infrastructure projects	Encourages early integration of ecological and stakeholder criteria
Greenroads	Sustainability for transportation infrastructure projects	Focus on material use and construction techniques in concept phase
SNBS Infrastructure	Swiss sustainable infrastructure standard for energy and materials	Supports early-stage sustainability planning and evaluation
LEED	Green building certification across energy, water, and materials	Influences design strategies through credits for early decisions
BREEAM	Sustainable design, construction, and operation of buildings	Promotes holistic sustainability assessment from concept design

Risk Analysis Frameworks

The growing complexity of infrastructure projects, extended life spans, and increasing uncertainty in socio-economic, regulatory, and environmental boundary conditions have positioned risk assessment as a central component of infrastructure evaluation. In this context, risk-oriented frameworks primarily support project feasibility and decision-making under uncertainty at the conceptual design stage. Standards such as ISO 31000 (Risk Management) and ISO 22301 (Business Continuity Management) provide structured principles for identifying, analysing, and managing risks associated with technical complexity, organisational interfaces, delivery processes, cost and schedule variability, and long-term adaptability across the infrastructure life cycle.

As design decisions are progressively refined, project-level risk considerations may extend into more technical forms of assessment aimed at verifying the implications of early conceptual choices. In this sense, robustness and collapse-related analyses can be understood as downstream articulations of risk-based reasoning, addressing specific failure scenarios once a structural concept has been

defined (Biondini & Frangopol, 2016; Casas & Frangopol, 2017) Rather than constituting an independent evaluation domain, these analyses translate project-level uncertainty into technical verification tasks at increasing levels of detail.

Emerging guidelines, such as the UNDRR² Principles for Resilient Infrastructure, further emphasise the continuity between risk management and long-term adaptability, linking feasibility, resilience, and sustainability considerations within a unified decision framework. When interpreted in this way, risk analysis shifts from a reactive, hazard-driven exercise to a proactive component of conceptual design, supporting informed decisions on ambition, complexity, and adaptability at the stage where the capacity to influence project outcomes is greatest.

1.5 Gaps in Design Codes, Practices, and Early-Stage Integration

1.5.1 Design Codes and the Scope of Conceptual Design

Despite the increasing recognition of conceptual design as a decisive phase in structural and infrastructural projects, the normative scene governing the built environment continues to provide limited and fragmented guidance for early-stage reasoning. Across disciplines, design codes and standards are primarily conceived to regulate verification, compliance, and performance assessment, rather than to support conceptual synthesis and decision-making. As a result, while the relevance of early design choices is widely acknowledged in research and professional fields, their formal treatment within normative frameworks remains marginal.

In the structural engineering domain, major international codes such as the Eurocodes (EN 1990–1999), the AASHTO LRFD Bridge Design Specifications, and the former British Standard BS 5400 establish comprehensive and robust systems for reliability, serviceability, and resistance verification. These documents define the fundamental principles governing structural safety and performance, yet they largely treat conceptual design as a matter of professional judgment. Guidance related to the early design phase is typically limited to generic recommendations embedded in commentary sections or illustrative examples, without offering explicit methods to structure typological reasoning or to compare alternative concepts. Consequently, the stage of the design process with the greatest influence

² United Nations Office for Disaster Risk Reduction

on structural configuration, material strategy, and construction logic remains weakly formalised from a normative perspective.

Recent evolutions in structural design codes indicate a gradual broadening of scope beyond traditional strength and serviceability checks. Contemporary documents increasingly incorporate concepts such as robustness, durability, inspectability, and maintainability, recognising that structural performance must be sustained over time and under varying operational conditions. References to construction sequence, damage tolerance, redundancy, and life-cycle considerations can now be found, albeit in different forms, within frameworks such as the Eurocodes, the fib Model Code 2020, and related guidance documents.

However, these developments remain firmly embedded within a performance-based and verification-oriented paradigm. Parameters related to robustness, maintenance, and durability are introduced primarily as additional performance requirements to be checked once a structural concept has been selected, rather than as criteria informing the generation and comparison of alternative concepts. As such, while these provisions acknowledge dimensions that intersect with sustainability and risk considerations, they do not provide methodological support for conceptual design decision-making. The integration of broader project objectives into structural codes thus remains indirect and subordinated to post-concept performance verification, rather than constituting a shift toward design-oriented evaluation at the early stage.

Comparable limitations can be observed beyond the strictly structural domain. Architectural and urban design frameworks, such as those promoted through the Davos Declaration on Baukultur and its associated quality systems, explicitly recognise conceptual design as the locus of cultural, spatial, and social value. These frameworks articulate principles related to contextual integration, spatial coherence, and public benefit, yet they remain predominantly qualitative and descriptive. They do not provide operational criteria or decision-support mechanisms that can be readily integrated with engineering-based evaluations of feasibility, performance, or constructability. As a result, architectural quality frameworks tend to operate in parallel to, rather than in conjunction with, technical design codes.

Sustainability-oriented standards further illustrate this fragmentation. International frameworks such as ISO 21929-2, Level(s), Envision, CEEQUAL, and SNBS Infrastructure define increasingly sophisticated sets of environmental,

social, and economic indicators applicable to buildings and infrastructure. These standards formalise life-cycle thinking and provide valuable metrics for assessing long-term performance. However, their application is typically concentrated in later design stages, such as design development, procurement, or certification. At the conceptual stage, they offer limited methodological guidance on how sustainability indicators should inform the generation and comparison of alternative structural and spatial concepts, often reducing their role to post hoc evaluation rather than generative decision support.

Risk-related standards present a similar pattern. Frameworks such as ISO 31000 (Risk Management), ISO 22301 (Business Continuity Management), and project-oriented guidelines developed by organisations such as FIDIC³ and UNDRR provide structured processes for identifying and managing uncertainty across the project life cycle. While these documents acknowledge the importance of early-stage risk awareness, they primarily focus on organisational, procedural, and managerial aspects of risk. Their translation into concrete criteria capable of informing conceptual design choices, such as structural typology, system complexity, or adaptability, remains largely implicit.

Taken together, these observations indicate that the challenge is not the absence of relevant criteria, but their dispersion across domain-specific codes and standards, each developed with a distinct scope and logic. Structural codes prioritise safety and verification, architectural frameworks emphasise qualitative and cultural dimensions, sustainability standards formalise life-cycle performance, and risk frameworks address uncertainty and feasibility. Yet, none of these normative systems provides an integrated structure capable of supporting interdisciplinary conceptual design decisions. This fragmentation defines the normative boundary within which contemporary design practice operates and sets the context for the gaps observed between codes, practice, and early-stage integration, which are discussed in the following sections.

1.5.2 Design Practice and Early-Stage Decision-Making

The consequences of the fragmented normative landscape described in §1.5.1 are clearly reflected in contemporary design practice. In the absence of formalised criteria and decision-support structures for conceptual design, early-stage choices in infrastructure projects remain largely dependent on individual expertise,

³ International Federation of Consulting Engineers

disciplinary heuristics, and precedent-based reasoning. While professional judgement is an essential component of design, its predominance at the conceptual stage results in several systematic limitations.

First, the lack of explicit conceptual design criteria perpetuates inconsistency in design quality across projects. Comparable design challenges may lead to markedly different outcomes depending on the experience, disciplinary background, or individual sensitivity of the design team, rather than on shared and transparent evaluative principles. Second, the absence of structured evaluation frameworks inhibits the systematic comparison of alternative concepts. Although multiple options are often explored informally, their assessment rarely follows explicit, traceable criteria, limiting the capacity to justify design decisions beyond qualitative argumentation.

Furthermore, this situation delays the early integration of sustainability and risk-related objectives. Environmental performance, life-cycle considerations, and project feasibility are increasingly recognised as critical dimensions of infrastructure quality, yet they are typically addressed only after a preferred concept has been selected. At this stage, sustainability assessments and risk analyses tend to function as verification or compliance exercises, rather than as drivers of conceptual exploration. As a result, opportunities to meaningfully influence material strategies, structural typologies, and construction logic at an early stage are often lost.

The reliance on intuition and experience also reinforces disciplinary fragmentation. Architects, structural engineers, and other specialists frequently contribute sequentially or in parallel, each applying domain-specific reasoning without the support of shared evaluation tools. In the absence of common decision frameworks, interdisciplinary coordination relies on negotiation rather than on explicit, criteria-based comparison of alternatives. This limits the profession's capacity to address mentioned contemporary imperatives which inherently require transdisciplinary coordination from the earliest design moments.

Some recent documents and guidelines attempt to respond to these limitations, albeit in a partial and indirect manner. The fib Model Code 2020 explicitly calls for the integration of sustainability and life-cycle performance into conceptual reasoning, acknowledging the strategic importance of early design decisions. Similarly, ISO 21931-1 (2010) encourages the early consideration of environmental performance in building construction, though without providing

methodological depth or decision-support mechanisms. The RIBA Plan of Work (2020) formally recognises conceptual design as a distinct project stage yet does not define structured criteria for evaluating alternative concepts. Likewise, FIDIC's Project Sustainability Management Guidelines (2022) and UNESCO's Historic Urban Landscape Recommendation (2011) emphasise context-based and participatory approaches, while their application to structural and infrastructural conceptual design remains largely indirect.

Taken together, these observations confirm that contemporary design practice operates within a fragmented evaluative environment. While the importance of conceptual design is widely acknowledged, the tools required to support systematic, interdisciplinary decision-making at this stage remain limited. This disconnects between recognised objectives and available methods directly motivates the need for integrated evaluation approaches capable of supporting early-stage design decisions in a transparent, structured, and cross-domain manner.

1.5.3 Implications for Early-Stage Integration and Evaluation

The limited treatment of conceptual design within existing codes and assessment frameworks reflects a deeper cultural and methodological misalignment within engineering practice. Design standards remain largely anchored in a deterministic, post-creative logic, in which conception is implicitly positioned outside the normative domain. Regulation and formalisation intervene primarily once solutions have been selected, whereas the processes through which alternatives are generated, compared, and discarded remain largely unsupported. As discussed throughout this chapter, the conceptual phase is instead the stage at which performance, meaning, feasibility, and long-term value are first negotiated.

The implications of this misalignment extend across disciplinary boundaries. Structural reliability, environmental sustainability, project risk, and contextual quality are addressed within dedicated normative or assessment systems, each developed with specific objectives and scopes. However, their integration at the early design stage remains weak and largely informal. Consequently, decisions with far-reaching consequences for lifecycle performance, adaptability, and cultural integration are frequently taken without explicit criteria or transparent evaluation logic, reinforcing the separation between design intent and performance assessment.

Addressing this condition requires a shift in emphasis from exclusively verification-oriented standards toward complementary, criteria-based approaches capable of supporting conceptual decision-making. Rather than expanding existing codes through additional prescriptive requirements, there is a need for methodologies that enable the simultaneous consideration of structural reliability, sustainability objectives, risk and feasibility constraints, and contextual reasoning. Such approaches must remain compatible with the exploratory and uncertain nature of early design, providing structure and traceability without constraining creative processes.

Bridging this gap demands coordinated efforts between professional bodies, academic research, and international organisations such as fib, ISO, and FIDIC. By formalising the principles of conceptual design (its logic, evaluation criteria, and interdisciplinary methods), the engineering community can move toward a practice in which design excellence is not left to individual intuition or chance, but becomes a measurable, reproducible, and teachable component of structural and infrastructural design.

1.6 Research Need and Thesis Positioning

1.6.1 Existing approaches and their limitations

The review presented in the previous sections demonstrates that a considerable body of knowledge already exists concerning infrastructure quality assessment, sustainability evaluation, resilience engineering, and decision-support methodologies. However, despite the maturity of these individual domains, their application to conceptual-stage structural design remains fragmented and incomplete.

Multi-Criteria Decision-Making (MCDM) methods have become increasingly established within engineering and infrastructure planning. Their ability to support complex decisions involving multiple and often conflicting objectives has led to widespread applications in transportation planning, environmental assessment, sustainability evaluation, and project prioritization. Various methodologies, including AHP, TOPSIS, ELECTRE, PROMETHEE, and hybrid approaches, have demonstrated their effectiveness in structuring decision processes and improving transparency. Nevertheless, most applications focus on the evaluation of already-defined alternatives and are generally applied once the main design decisions have

been made. Their use as operational instruments during the conceptual phase of structural design remains comparatively limited.

A similar situation can be observed in contemporary infrastructure evaluation frameworks. Systems such as Envision, CEEQUAL, Level(s), and the Davos Quality System have significantly expanded the traditional understanding of infrastructure quality by introducing environmental, social, cultural, and governance dimensions. These frameworks represent an important evolution beyond conventional engineering criteria based solely on safety, economy, and durability. However, as discussed in Sections 1.4 and 1.5, their primary purpose remains evaluative rather than generative. They provide structured mechanisms for assessing project performance, benchmarking outcomes, and supporting certification processes, but they offer limited guidance for comparing alternative concepts during the exploratory stages of design.

The same limitation applies to resilience-oriented approaches. During the last two decades, significant advances have been made in the fields of robustness, resilience engineering, risk assessment, and performance-based design. International initiatives such as the UNDRR framework, the Resilience Alliance, and various infrastructure resilience methodologies have broadened the understanding of infrastructure performance beyond simple structural safety. Nevertheless, these approaches are frequently developed as specialized assessment tools and are rarely integrated into comprehensive conceptual-design methodologies capable of supporting early-stage decision-making.

Likewise, growing attention has been devoted to circular economy principles, adaptability, and life-cycle thinking. Contemporary research increasingly recognizes the importance of reuse, reversibility, disassembly, material recovery, and adaptive capacity as essential components of sustainable infrastructure development. Despite this progress, circularity and adaptability are still seldom translated into operational indicators suitable for conceptual structural design. In many cases, these concepts remain qualitative ambitions rather than measurable decision criteria.

As discussed in §1.5, major international design standards such as the Eurocodes, AASHTO LRFD, and the fib Model Codes provide extensive technical prescriptions for analysis, verification, and detailing. However, they offer limited guidance regarding how alternative concepts should be generated, compared, and selected during the earliest phases of design. As a consequence, conceptual design

continues to rely heavily on designer experience, disciplinary traditions, and implicit reasoning processes.

The limitations identified throughout the literature review can be further examined through a comparative positioning of the principal knowledge domains and approaches relevant to conceptual structural design.

Figure 8 illustrates their relative position with respect to two key dimensions: the degree of multidisciplinary integration and their capacity to support conceptual-stage decision-making. Complementarily, Table 3 summarizes the principal sources of knowledge that informed the development of the proposed framework, highlighting both their contributions and the limitations that justify the need for a more integrated conceptual-design methodology.

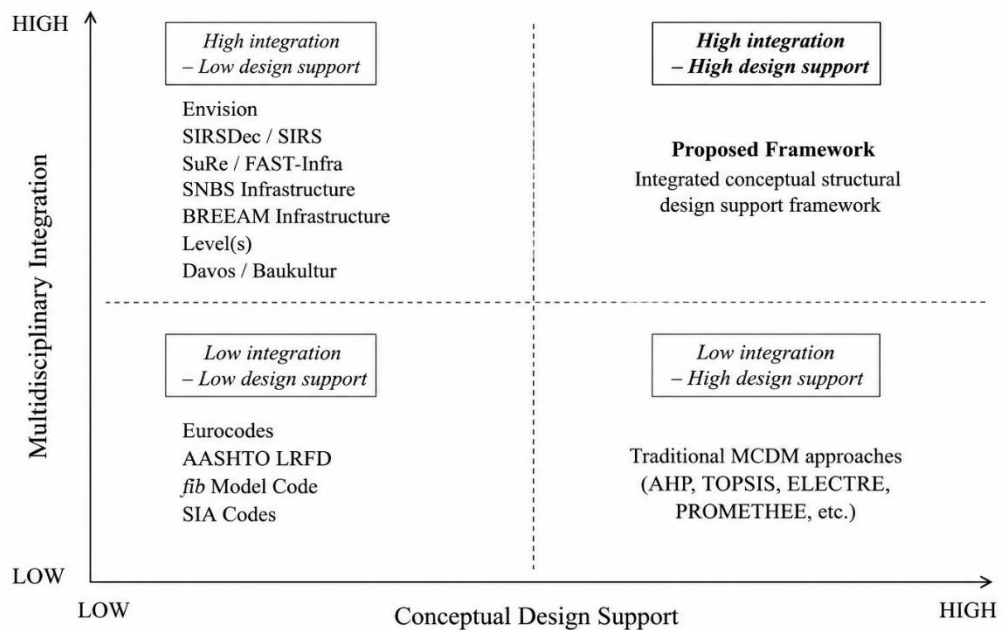


Figure 8 Positioning of existing methodologies and frameworks with respect to multidisciplinary integration and conceptual-design support.

Table 3 Comparative positioning of the principal knowledge domains, methodologies, standards, and assessment frameworks

Knowledge domain	Representative frameworks / approaches	Main contribution inherited by the proposed framework	Main limitation for conceptual structural design
Infrastructure sustainability assessment	Greenroads, Envision, INVEST, SuRe, FAST-Infra, BREEAM Infrastructure, SNBS Infrastructure	Holistic sustainability assessment, infrastructure quality criteria, stakeholder-oriented evaluation	Primarily assessment and certification oriented
Cultural and contextual quality frameworks	Davos Declaration, Baukultur principles	Contextual integration, cultural value, social quality	Limited operational support for concept comparison
Structural design standards	Eurocodes, AASHTO LRFD, fib Model Code, SIA	Structural safety, serviceability, robustness requirements	Focus on verification rather than conceptual decision-making
Multi-Criteria Decision-Making methodologies	AHP, TOPSIS, ELECTRE, PROMETHEE	Comparative evaluation logic and decision-support structure	Not specifically tailored to structural conceptual design
Resilience engineering approaches	Resilience Alliance, UNDRR, risk-based methodologies	Resilience-oriented performance assessment	Often domain-specific and not integrated with design workflows
Robustness and progressive collapse methodologies	ALP, GSA, robustness-oriented design approaches	Basis for the Resistance-to-Collapse Indicator (RI)	Generally applied during verification stages
Circular economy frameworks	Reuse-oriented and circular construction approaches	Circularity assessment principles	Rarely operationalized during conceptual structural design
Adaptability frameworks	Design-for-adaptability approaches	Adaptability and transformation capacity indicators	Predominantly qualitative and difficult to quantify

Taken together, Figure 8 and Table 3 reveal that the knowledge domains and methodologies underpinning contemporary infrastructure design tend to address only specific dimensions of the conceptual-design problem. Design standards provide rigorous technical foundations but offer limited support for conceptual exploration and alternative comparison. Sustainability and infrastructure assessment frameworks adopt a broader and more integrated perspective, yet remain primarily oriented toward evaluation, benchmarking, and certification. Traditional MCDM methodologies provide effective decision-support mechanisms but are generally not tailored to the specific requirements of conceptual structural design. Similarly, resilience, circularity, and adaptability frameworks contribute

valuable domain-specific knowledge but are rarely integrated within a unified conceptual-design methodology.

As a consequence, conceptual structural design remains fragmented across multiple bodies of knowledge, each addressing only part of the decision-making process. This fragmentation highlights the need for a framework capable of combining multidisciplinary integration with explicit support for conceptual-stage reasoning, thereby enabling the structured comparison of alternative structural concepts through a coherent and transparent decision-support methodology.

1.6.2 Positioning of the proposed framework

The review developed in the previous sections reveals a structural and methodological inconsistency within contemporary design practice. While conceptual design is widely acknowledged as the most influential phase in determining the performance, sustainability, and identity of infrastructure projects, it remains the least formalized. In professional practice, this stage is still approached as a matter of intuition or disciplinary tradition, rather than as a structured process guided by explicit reasoning and measurable criteria.

As discussed in §1.5, major international codes, such as the Eurocodes, AASHTO LRFD, and the fib Model Codes, provide extensive technical prescriptions for verification, yet offer limited guidance on how design concepts are conceived and evaluated. The result is a paradox: the phase that has the greatest influence on the life cycle and cultural quality of a project is precisely the one for which no shared framework exists.

At the same time, as shown in §1.4–1.5, the notion of design quality has evolved far beyond traditional definitions of safety, economy, and durability. Contemporary infrastructures must address environmental and social responsibility, resilience, adaptability, and cultural integration. Frameworks such as the Davos Declaration on Baukultur (2018), Level(s) (European Commission, 2020), and Envision have broadened the concept of quality by introducing sustainability, resilience, and social inclusion as explicit dimensions of value. However, these systems remain primarily evaluative: they measure the results of design processes but do not support decision-making during the conceptual phase. This distinction between evaluation and generation reveals a central methodological gap that current standards and design tools fail to bridge.

The first need emerging from this analysis concerns the formalization of conceptual reasoning. Despite decades of discussion (Corres Peiretti et al., 2022; Denton et al., 2012; Hirt & Lebet, 2013), conceptual design remains an implicit and largely undocumented process. There is a pressing necessity to define a methodological

structure capable of describing how early-stage reasoning unfolds and how it may be supported through transparent, repeatable, and communicable methods.

A second need relates to the integration of multidisciplinary criteria within conceptual design. Current practice still tends to separate technical, environmental, economic, and architectural-cultural considerations into distinct evaluation domains, limiting the possibility of addressing them simultaneously during the earliest stages of project development. Yet, as expectations regarding infrastructure quality continue to expand, engineers are increasingly required to balance efficiency, sustainability, resilience, contextual relevance, and long-term value from the outset. This requires a shared decision-making framework capable of accommodating both qualitative and quantitative variables within a coherent analytical structure.

A third gap concerns the relationship between evaluative frameworks and design practice. Systems such as Davos, Level(s), and Envision provide robust post-evaluation tools but remain largely external to the design workflow itself. The challenge is therefore not simply to evaluate quality after decisions have been made, but to reinterpret these frameworks as operative instruments capable of guiding conceptual exploration and supporting the comparison of alternative solutions before detailed design begins.

A fourth need involves the development of decision-support methodologies specifically tailored to structural and bridge design. Multi-Criteria Decision-Making approaches have demonstrated considerable potential in architectural, environmental, and infrastructure assessment contexts. However, their adaptation to conceptual structural design remains limited. Existing models rarely integrate within a single framework the structural, functional, environmental, resilience-related, and cultural dimensions that collectively define quality in bridge and footbridge projects.

Finally, the review highlights an institutional and educational gap. International standards and engineering curricula continue to place strong emphasis on analysis, verification, and detailing, while the conceptual phase remains comparatively underrepresented. This situation perpetuates a reactive design culture that privileges compliance over exploration and limits the development of interdisciplinary reasoning skills. As a consequence, the mechanisms through which conceptual decisions are generated, compared, and justified often remain implicit and difficult to communicate.

Together, these observations outline a clear research agenda: the need to reposition conceptual design as a structured, transparent, and interdisciplinary process supported by explicit reasoning and decision-support methodologies. Within this context, the present research seeks to bridge the gap between evaluation-oriented frameworks and design-oriented methodologies by proposing a coherent framework capable of integrating structural, environmental, social, economic, and cultural dimensions within a common conceptual-design process.

Rather than prescribing design solutions, the proposed framework aims to provide a structured cognitive and procedural environment in which alternative concepts can be generated, compared, and discussed using transparent and traceable criteria. In doing so, it seeks to transform conceptual design from an implicit activity largely dependent on individual experience into a communicable and reproducible decision-making process capable of supporting interdisciplinary collaboration and informed design choices.

1.6.3 Original contributions of the research

Building upon the research needs identified above, this thesis contributes to the advancement of conceptual structural design through four complementary and interconnected contributions. While the proposed framework draws upon existing knowledge from structural engineering, Multi-Criteria Decision-Making (MCDM), resilience engineering, sustainability assessment, and circular design, its originality lies in the way these concepts are integrated, adapted, and operationalized within a coherent methodology specifically developed for conceptual-stage applications.

A fundamental aspect of the proposed approach is its intended role within the design process. Unlike certification systems such as Envision, CEEQUAL, Level(s), or other assessment-oriented frameworks, the proposed methodology is not conceived as a certification, rating, or benchmarking tool. Its primary purpose is to support the generation, comparison, and discussion of alternative design concepts during the earliest phases of project development. The framework therefore operates as a design-support instrument rather than as a compliance or certification mechanism. In this sense, evaluation is not considered an end in itself, but a means to improve conceptual reasoning, facilitate interdisciplinary dialogue, and make design decisions more transparent and traceable.

Within this context, the original contributions of the research can be summarized as follows.

Integration of Structural and Sustainability-Oriented Design Criteria

The first contribution concerns the integration of structural engineering requirements and sustainability-oriented design principles within a unified conceptual-design framework. Existing approaches typically address structural performance, environmental assessment, social value, economic considerations, and contextual quality through separate evaluation processes and often at different

stages of project development. The proposed framework establishes a common decision-making structure capable of simultaneously considering structural, environmental, social, economic, and cultural dimensions during the earliest phases of design.

This integration reflects the growing recognition that infrastructure quality can no longer be evaluated exclusively through technical performance indicators. Instead, contemporary projects require a broader understanding of value that incorporates resilience, sustainability, adaptability, and contextual integration as essential components of design quality.

An Integrated MCDM Framework for Conceptual Structural Design

The second contribution is the development of a Multi-Criteria Decision-Making methodology specifically tailored to conceptual-stage structural design. Although MCDM methods are widely used in infrastructure planning, environmental assessment, and project evaluation, their systematic application to the conceptual phase of bridge and footbridge design remains limited.

The proposed framework adapts established MCDM principles to the specific conditions of early-stage design, where information is incomplete, uncertainty is high, and multiple alternatives must be explored simultaneously. In doing so, it provides a transparent and traceable methodology capable of supporting the comparison of alternative concepts before detailed analysis and verification become possible.

Development of a Probabilistic Resistance-to-Collapse Indicator

The third contribution represents the most technically innovative aspect of the research. The proposed Resistance-to-Collapse Indicator (RI) introduces a probabilistic approach to robustness assessment specifically conceived for conceptual-stage applications.

Unlike traditional conceptual-design methodologies, which generally address robustness through qualitative recommendations or simplified checklists, the RI indicator combines probabilistic hazard occurrence, structural vulnerability, systemic consequences, and recovery considerations within a single assessment metric. By incorporating hazards such as vehicle impact, railway collision, flooding, geological instability, fire, and explosion, the indicator enables resilience-

related considerations to be introduced into conceptual decision-making at a stage where they are typically absent.

This contribution extends the role of resilience assessment from post-design verification toward early-stage design support, thereby strengthening the connection between conceptual reasoning and long-term infrastructure performance.

Operationalization of Circularity and Adaptability for Conceptual Design

The fourth contribution concerns the translation of circularity and adaptability principles into operational decision-support criteria applicable to structural conceptual design.

Although concepts such as reuse, reversibility, disassembly, adaptability, and transformation capacity have become increasingly important within contemporary sustainability discourse, they are rarely incorporated into structured conceptual-design methodologies. In many existing frameworks, these dimensions remain qualitative aspirations rather than measurable design variables.

The proposed framework addresses this limitation by introducing explicit indicators capable of evaluating circularity and adaptability alongside more traditional structural, environmental, and functional criteria. This enables designers to consider long-term transformation potential during concept selection rather than after major design decisions have already been made.

Taken together, these contributions seek to reposition conceptual structural design as a structured process of knowledge creation supported by transparent reasoning and explicit evaluation criteria. The originality of the research therefore lies not in the creation of entirely new evaluation domains, but in the integration, adaptation, and operationalization of concepts that have traditionally been treated separately within engineering practice and research.

Chapter 2

Proposed method

2.1 Introduction and methodological framework

The methodological framework adopted in this research is grounded in the theoretical foundations of Multi Criteria Decision Making (MCDM), a family of approaches that support decision making in the presence of multiple, often conflicting, criteria. As systematically outlined in the comprehensive survey by Greco (2016), MCDM frameworks are widely applied in engineering, infrastructure planning, and systems design, providing structured, transparent procedures for complex problem solving across domains. A key feature of MCDM methods is their iterative and adaptive nature. Rather than being strictly linear, the decision-making process under MCDM evolves over time, incorporating new information, refining preferences, and revisiting alternatives when necessary. This iterative logic is not only beneficial but essential in design and planning contexts, where uncertainty, stakeholder dynamics, and emerging solutions must be systematically managed. As highlighted in empirical applications (Kim et al., 2015), robust decisions often result from repeated refinements rather than from a one-shot evaluation. The framework proposed in this study is structured in five sequential steps, each contributing to a coherent and repeatable decision support process (Figure 9). The first two steps are focused on defining a generalizable structure, identifying decision criteria and modelling the decision space, which can be reused across multiple design problems. These stages represent the foundational layer of the framework and are intended to be predefined in real world applications. In contrast, steps three to five constitute the context specific application phase. Here, the methodology is applied to a specific decision problem: alternatives are evaluated, criteria are weighted, and decision outputs are generated. Crucially, these stages are designed to be iterative. As new data or stakeholder insights emerge, users are expected to revisit earlier stages, adjust inputs, and refine decisions accordingly. This structure reflects current practices in structural engineering, particularly in the design of complex systems such as bridges, where decision-makers must iteratively evaluate alternatives across multiple indicators. As shown by ElMarbaki (2023), MCDM methods enable structured aggregation of technical, economic, and environmental indicators to support robust selection among competing design options.

Overall, the framework achieves a balance between methodological consistency and contextual adaptability., allowing for both consistency in methodology and flexibility in application. Conceived as a decision-support tool for multidisciplinary design teams operating during the conceptual phase, the framework does not seek to prescribe design solutions or optimize a single

performance variable. Instead, the five steps offer a complete methodological cycle that supports structured exploration, comparison, and convergence toward informed design decisions, particularly in complex, multi-stakeholder environments. A detailed description of each of the five steps follows, including methodological rationale, procedural logic, and expected outcomes.

CONCEPTUAL DESIGN SUPPORT TOOL FOR MULTIDISCIPLINARY DESIGN TEAMS

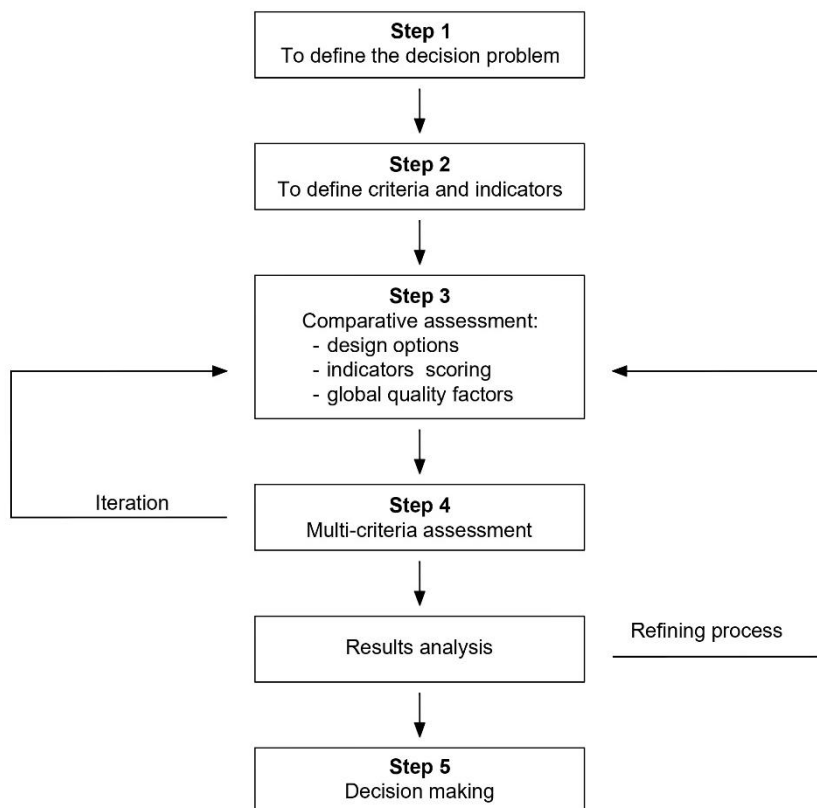


Figure 9 A comprehensive illustration of the structural organization and procedural steps inherent within the proposed framework.

The framework illustrated in Figure 9 is governed by a number of methodological assumptions regarding the treatment of economic considerations and the formalization of the evaluation criteria. These assumptions directly influence the interpretation of the indicators and the intended use of the framework as a conceptual design support tool. Before describing the individual steps of the methodology, they are discussed in the following sections.

2.1.1 Role of Economic Evaluation within the Framework

As discussed in Chapter 1, the concept of infrastructure quality has progressively evolved from traditional engineering objectives centred on function, safety and economy towards a broader and more integrated understanding of value. (Ioannidou, D. et al., 2016). Contemporary infrastructures are increasingly expected to satisfy not only technical and economic requirements, but also environmental, social, cultural, and long-term performance objectives. Within this context, the role of economic evaluation requires specific methodological clarification, particularly because the proposed framework does not include a dedicated economic indicator directly involved in the ranking process.

The present research fully acknowledges the importance of economic evaluation in infrastructure design and strongly supports the principles of Life Cycle Costing (LCC). Unlike traditional approaches based on initial construction cost, LCC recognizes that the economic performance of an infrastructure emerges throughout its entire service life, including maintenance, inspection, operation, adaptation, rehabilitation, and end-of-life scenarios. In this respect, the framework is fully aligned with life-cycle thinking and shares the view that infrastructure decisions should be based on long-term value rather than on initial expenditure alone.

However, the decision not to introduce a dedicated Life Cycle Costing indicator within the proposed framework is intentional and reflects the specific objectives of conceptual design.

The framework was conceived as a decision-support tool for multidisciplinary design teams operating during the earliest stages of project development and, in particular, within design competitions. At this stage, economic feasibility is typically addressed through predefined budget constraints established by the contracting authority. Furthermore, several factors that influence lifecycle costs and long-term economic performance can already be assessed through conceptual indicators addressing structural performance, lifecycle management requirements, environmental quality, and future transformation potential. However, the objective of the framework is not to perform a comprehensive Life Cycle Costing assessment nor to identify the least expensive alternative. Rather, it seeks to compare concepts capable of delivering the highest overall quality and long-term value while remaining compatible with the available resources (Kelly et al., 2014).

This distinction is particularly important because the proposed methodology does not disregard lifecycle economic considerations. On the contrary, it evaluates many of the underlying factors that generate future costs and benefits. The methodological choice is therefore not to exclude economic evaluation, but rather to avoid collapsing multiple dimensions of infrastructure value into a single monetary indicator that could dominate the decision-making process.

More fundamentally, the proposed methodology intentionally seeks to avoid situations in which a single economic indicator exerts a disproportionate influence on the final ranking of alternatives.

The proposed methodology intentionally seeks to avoid situations in which a single economic indicator exerts a disproportionate influence on the final ranking of alternatives. While economic efficiency remains an important objective, conceptual design inherently involves trade-offs between costs and benefits that cannot be adequately represented by a single monetary value (Greco et al., 2016). Resilience, maintainability, inspectability, adaptability, circularity, environmental performance, and contextual quality may require additional investments during the initial phases of a project while simultaneously generating significant benefits over extended periods of time. If these relationships are condensed into a single economic metric, there is a risk that the evaluation process becomes dominated by cost considerations, potentially favouring short-term economic efficiency over long-term infrastructure value.

For this reason, the framework adopts a deliberately disaggregated approach to economic evaluation. Rather than concentrating economic considerations within a dedicated Life Cycle Costing indicator, the methodology evaluates the individual performance dimensions that generate future costs and benefits. The assessment process therefore encourages designers and decision-makers to explicitly examine the benefits associated with maintenance requirements, structural resilience, environmental performance, long-term adaptability and to discuss whether these benefits justify the resources required to achieve them. In this sense, cost-benefit reasoning remains fully embedded within the framework, but it is distributed across multiple performance dimensions rather than being reduced to a single aggregated monetary value.

This approach also reflects an explicit departure from the last 20th century engineering paradigm centred on the triad of safety and economy (Bonenberg & Kapliński, 2018). While these dimensions remain fundamental requirements of any

infrastructure project, contemporary infrastructure quality increasingly depends on additional considerations such as resilience, sustainability, circularity, adaptability, and contextual integration. The framework therefore adopts a broader interpretation of value, seeking to balance these dimensions rather than treating economic optimization as the dominant criterion governing conceptual design decisions.

Economic considerations are therefore interpreted as an inherent property of infrastructure performance rather than as an autonomous evaluation criterion. The framework assumes that long-term economic value emerges from the interaction between structural performance, lifecycle management, environmental quality, future transformation potential. Consequently, economic evaluation is embedded within these performance dimensions and contributes to the assessment of overall infrastructure quality rather than being treated as a separate ranking variable.

The proposed methodology can therefore be interpreted as a value-oriented decision-support framework in which economic implications are integrated across multiple dimensions of infrastructure quality. From this perspective, economic value is not regarded as an independent design objective, but as the outcome of decisions affecting resilience, maintainability, inspectability, sustainability, circularity, adaptability, and overall structural performance throughout the service life of the infrastructure.

2.1.2 Indicator Formalization and Scoring Philosophy

The effectiveness of any Multi-Criteria Decision-Making framework depends not only on the selection of relevant criteria, but also on the way these criteria are formalized and translated into measurable indicators. Within conceptual structural design, this issue is particularly important because the various dimensions contributing to infrastructure quality exhibit different levels of quantifiability. While certain aspects can be assessed through analytical calculations and objective measurements, others are inherently qualitative and are often evaluated through expert judgement, professional experience, or subjective interpretation.

The proposed framework therefore adopts a pragmatic approach to indicator formalization. Rather than forcing all evaluation criteria into a single assessment logic, the methodology recognizes that different dimensions of infrastructure quality require different levels of analytical sophistication. Consequently, the framework combines quantitative, semi-quantitative, and qualitative assessment

procedures according to the nature of the information available during conceptual design.

The proposed framework combines different scoring philosophies according to the characteristics of the criteria being assessed. While some indicators are intentionally formulated through simplified binary structures, others rely on analytical, quantitative, or probabilistic evaluation procedures specifically developed within the present research. The level of formalization adopted for each indicator reflects both the nature of the performance dimension considered and the degree of information that can reasonably be obtained during conceptual design. These procedures seek to transform complex conceptual-design considerations into measurable indicators capable of supporting objective comparisons between alternative solutions. Consequently, the framework does not rely on a single assessment logic but integrates different methodological approaches within a coherent decision-support structure. The specific rationale, formulation, scoring procedures, and limitations associated with each indicator are discussed in detail in the following sections.

Particular methodological effort has been devoted to those performance dimensions for which analytical and quantitative assessment procedures can be developed during conceptual design. This reflects one of the principal objectives of the present research, namely the transformation of selected aspects of structural performance from predominantly qualitative considerations into transparent and measurable decision-support criteria.

Particular attention has also been devoted to ensuring transparency, repeatability, and operational applicability. For this reason, whenever objective quantification is not feasible or would require assumptions exceeding the level of information normally available during conceptual design, simplified scoring structures have been adopted. These structures aim to transform qualitative considerations into explicit evaluation criteria, reducing ambiguity and increasing consistency between different applications of the methodology.

In several cases, binary scoring systems are intentionally employed. This choice should not be interpreted as a methodological simplification imposed by limitations of the framework, but rather as a deliberate strategy aimed at reducing evaluator subjectivity and improving reproducibility. In many existing assessment systems, aspects related to functionality, contextual integration, accessibility, architectural quality, planning coherence, or adaptability-related considerations are

frequently evaluated through expert judgement, qualitative reviews, or jury-based assessments. Although such approaches may be appropriate in specific circumstances, they often reduce the transparency and repeatability of the evaluation process.

The binary structure adopted in the present framework transforms these considerations into explicit and verifiable design checkpoints. Rather than attempting to quantify inherently qualitative characteristics through potentially arbitrary numerical scales, the methodology focuses on determining whether specific design requirements have been addressed or not. In this sense, the binary indicators also operate as a conceptual-design checklist, encouraging multidisciplinary design teams to systematically consider critical structural, environmental, functional, and contextual aspects during the earliest stages of project development.

The adoption of binary scoring inevitably introduces certain limitations. In particular, criteria characterized by gradual or continuous performance improvements may not be fully represented through a simple yes/no assessment, potentially reducing sensitivity when comparing alternatives exhibiting similar characteristics. This limitation is acknowledged and represents a potential area for future methodological refinement. Possible developments may include graded scoring systems, weighted assessment procedures, or fuzzy-based approaches capable of representing intermediate performance levels while preserving the transparency and operational simplicity that constitute fundamental objectives of the framework.

Overall, the proposed scoring philosophy seeks to balance analytical rigor, transparency, repeatability, and practical applicability. The objective is not to maximize methodological complexity, but rather to provide a robust decision-support tool capable of guiding conceptual design decisions under conditions of limited information and significant uncertainty, which are characteristic of the early stages of structural design.

2.2 Step 1: to define the decision problem

This research is positioned within the conceptual design phase of pedestrian bridges, a critical stage in which early design decisions have a thoughtful impact on the structural efficiency, feasibility, and long-term sustainability of the infrastructure. At this stage, design flexibility is at its peak, but decision-making is often hindered by uncertainty and the absence of formal evaluation tools. In response to this gap, the present study introduces a decision, support framework aimed at enabling design teams to systematically assess and compare alternative structural configurations based on objective, quantifiable performance indicators.

In contrast to traditional approaches that frequently rely on subjective judgment or experiential intuition, the proposed methodology is grounded in quantitative criteria that promote consistency, transparency, and replicability in the decision-making process. By structuring the evaluation around predefined structural performance metrics, the framework allows for more rigorous and rational exploration of design alternatives in the early stages of development.

It is essential to clarify that the framework is exclusively concerned with structural aspects and does not incorporate a cost, benefit analysis, construction logistics, or other economic factors typically associated with detailed project planning. These dimensions, while critical to the broader execution of the project, fall under the purview of the contracting authority and are generally addressed in later phases of the design process, particularly in the transition to detailed engineering and procurement.

The tool is particularly designed to support multidisciplinary design teams working in the field of sustainable infrastructure, where multiple, and sometimes conflicting, objectives must be considered in parallel. These include, but are not limited to, structural resilience, environmental impact, and architectural planning aspects. The ability to evaluate trade-offs among these parameters through an integrated and systematic method represents a key advantage of the proposed approach, especially in the context of projects that prioritize long-term performance and ecological responsibility.

In summary, the methodological contribution of this research lies in the development of an objective, structured, and sustainability-aware evaluation tool that can inform and guide early, stage decisions in footbridges design. The framework enhances the clarity and traceability of conceptual choices, facilitates

cross, disciplinary collaboration, and aligns structural engineering practice with broader goals of resilience and sustainability.

2.3 Step 2: to define the common criteria and indicators

As discussed in the Background chapter, the design of contemporary footbridges must meet a set of fundamental requirements ensuring functionality, durability, and integration within the built and natural environment. These can be interpreted through two well, known conceptual frameworks: the Vitruvian triad (1960) (*firmitas*, *utilitas*, *venustas*) and the three pillars of sustainability (Society, Economy, Environment, (Weltkommission für Umwelt und Entwicklung, 2009)). While the sustainability framework has become central in recent infrastructure evaluation, it is often applied only in advanced project phases, reducing its potential to shape strategic early, stage decisions. To address this limitation, the proposed method integrates the Vitruvian triad with the pillars of sustainability into an operational model shown in Figure 10, specifically tailored for the conceptual design phase of pedestrian and cycling bridges. In this reconfiguration, *firmitas* are expanded beyond structural strength to encompass structural resilience, including robustness, inspectability, and maintainability (Violano & Cannaviello, 2022). *Utilitas* is broadened to embed social and planning dimensions, while *venustas* incorporates architectural integration and contextual harmony (Bonenberg & Kapliński, 2018). The resulting framework consists of three macro-themes, each associated with three measurable indicators, enabling an objective, reproducible, and data-driven evaluation:

- **Architecture and Planning:** incorporating social considerations (e.g., accessibility, urban integration, cultural heritage) and economic feasibility aspects, ensuring that the bridge harmonises with its urban or rural context, meets user needs, and complies with planning constraints.
- **Structural Resilience:** encompassing robustness, inspectability, and maintainability, focusing on ensuring safety, reliability, and adaptability under varying and potentially adverse conditions.
- **Environmental Performance:** addressing the environmental dimension of sustainability, with indicators such as Global Warming Potential (GWP), material circularity, and adaptability to future requirements.

In this arrangement, the social dimension of sustainability is integrated into Architecture and Planning, the economic dimension, particularly in terms of Life Cycle Costing (LCC), is distributed across all three macro-themes, and the

environmental dimension is partly reflected in Architecture and Planning (e.g., land use, microclimate effects) but primarily concentrated in the Environmental Performance. By restructuring these classical frameworks into a measurable and early applicable form, the method directly supports design teams, policymakers, and stakeholders in comparing alternative solutions according to quantitative and objective principles, thus operationalising the holistic approach outlined in the previous paragraph.

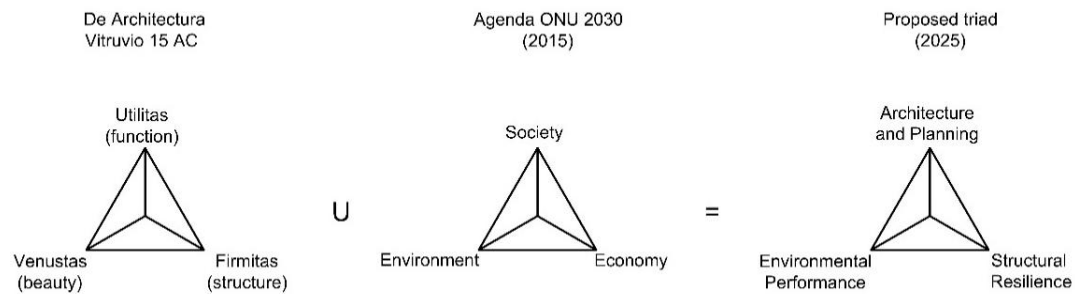


Figure 10 Evolution of the proposed triad according to contemporary macro-themes.

2.3.1 Architecture and planning

The evaluation framework developed in this study to assess the architectural, functional, urban, and operational qualities of pedestrian and cycling bridges is grounded in principles derived from a set of internationally recognized infrastructure sustainability and quality certification systems. These include SNBS, Green Roads, LEED, CEEQUAL, Envision, and BREEAM (BREEAM, 2018; CEEQUAL, 2019; Envision, 2018; Greenroads, 2017; LEED, 2019; SNBS, 2023). Collectively, these systems provide a comprehensive and multidimensional perspective on infrastructure planning, each contributing specific criteria related to design quality, environmental impact, community integration, operational efficiency, and resilience. Each certification system approaches sustainability and performance from unique perspectives, shaped by their regional, cultural, and disciplinary backgrounds. An example is the SNBS, which emphasizes the integration of infrastructure within the natural landscape. It promotes materials and designs that resonate with the surrounding environment. Its guidelines assess the use of local materials, adherence to natural forms, and minimizing visual and ecological disruption, all with the goal of ensuring that constructed structures maintain harmony with the existing context. In contrast, CEEQUAL emphasizes the cultural and historical identity of a place, promoting architectural solutions that

resonate with local heritage. Its indicators assess how materials and styles reflect the historical character of the area, encouraging infrastructure that reinforces the sense of continuity and community identity.

LEED and Envision, on the other hand, link architectural design more closely with energy performance and material sustainability. LEED encourages the selection of low, impact, renewable, or recycled materials to minimize ecological footprints, while Envision integrates resilience and adaptability into its architectural framework. The latter promotes infrastructure that can evolve alongside shifting community needs and environmental conditions, evaluating whether design choices support both long-term usability and aesthetic durability. In terms of urban integration, all systems acknowledge the importance of connectivity, social cohesion, and enhancement of the built environment. SNBS and CEEQUAL prioritize community impact, measuring the extent to which a project enhances public space and encourages social interaction. SNBS includes criteria for green space accessibility, urban cohesion, and community well, being, all aimed at maximizing positive impacts on urban life. CEEQUAL similarly emphasizes regional identity and local character, encouraging stakeholder participation and context, sensitive planning, to transform infrastructure from mere transit space into a meaningful element of urban life. Envision and BREEAM, while equally concerned with integration, take a more operational and functional perspective. Envision promotes multi, modal connectivity, encouraging projects to link with existing transit systems and sustainable mobility networks. BREEAM builds on this with criteria that support land use efficiency, optimal urban density, and the provision of green areas that improve the urban microclimate and contribute to environmental regeneration. These aspects are especially relevant for infrastructure such as pedestrian bridges, which often occupy transitional or residual spaces within urban fabrics. Functionality is another core domain in which all these systems converge.

Although their interpretations vary, all promote principles of efficiency, usability, and safety. Green Roads, for example, places a particular emphasis on operational safety and traffic flow management, proposing indicators that ensure the infrastructure can handle simultaneous use by cyclists and pedestrians without congestion or conflict. It assesses the adequacy of signage, barrier systems, and path geometries, all crucial elements in ensuring a safe and comfortable user experience. LEED addresses functionality from the perspective of energy and resource efficiency. It evaluates whether infrastructure integrates features such as low, consumption lighting, water management systems, or renewable energy

components. LEED's approach ensures that a bridge remains not only functional in terms of movement, but also efficient in its use of resources throughout its operational lifespan. Envision and BREEAM reinforce this perspective. Envision advocates for long-term adaptability and encourages designs that can accommodate future changes in use, population, or technology. BREEAM emphasizes operational management, evaluating the use of monitoring systems, preventive maintenance plans, and resource conservation strategies that sustain the infrastructure's performance over time. Operational quality, especially with regard to durability, resilience, and lifecycle performance, is explicitly addressed in Envision and BREEAM. Envision promotes the development of long-term operation and maintenance plans, ensuring that the infrastructure remains safe and effective throughout its lifespan. Its indicators encourage proactive management strategies, including performance monitoring and risk mitigation, which reduce lifecycle costs and environmental burdens. BREEAM adds an additional layer of climate resilience, assessing whether the project can withstand adverse weather conditions, hydrological risks, and structural stressors. It incorporates criteria for climatic adaptability, emergency preparedness, and resource efficiency during both ordinary operation and crisis scenarios. SNBS and CEEQUAL extend the operational perspective toward community value and social sustainability. In SNBS, operational success is framed as the infrastructure's continued contribution to public welfare, while CEEQUAL promotes long-term environmental compliance and sustainable maintenance as essential to preserving infrastructure value for future generations. These perspectives emphasize that a bridge must not only perform structurally but also contribute enduring value to the community it serves.

Despite their depth, it is important to recognize that the majority of the architectural and urban criteria within these systems are qualitative rather than quantitative. They rely on professional assessments, descriptive narratives, or expert panels, methods that, while rich in insight, are often not suitable for application during the conceptual design phase, where full data is lacking and design decisions are still in flux (Kustova et al., 2024).

To address this limitation, the framework proposed here adopts a deliberately simplified and binary evaluation structure, designed to operate without the need for external specialists or third, party reviewers. It is based on a set of yes/no control questions, grouped into clearly defined categories. This binary checklist is not intended to replace the nuanced assessment methods used in later design stages, but to provide an objective, transparent, and accessible tool for early, phase decision-making. Importantly, this approach is not without precedent. Several of the

certification systems cited above, including LEED, Green Roads, CEEQUAL, Envision, and BREEAM, already utilize binary checklists for key prerequisites and mandatory indicators. LEED, for instance, applies binary logic to certain credit categories where only full compliance, such as in waste management or indoor air quality, is considered valid. Green Roads uses binary criteria to verify minimum thresholds in safety and material sourcing. CEEQUAL's indicators for environmental compliance and mitigation planning, and Envision's checks on climate adaptability and sourcing, similarly function as binary gates. BREEAM, particularly during initial project review stages, assesses the presence or absence of essential design features using yes/no protocols, especially in areas such as energy management and safety.

The rationale for employing a binary format in this research is twofold. First, many of the issues under consideration, such as regulatory compliance, budget availability, or minimum safety standards, are non-negotiable prerequisites that must be verified before the project can proceed. These elements are therefore more appropriately framed as feasibility constraints rather than differentiating performance indicators. Second, a binary format avoids subjective scoring in an early, stage context, ensuring that the evaluation remains consistent and reproducible even with limited information.

This methodological choice aligns with recent literature on adaptive, early, stage quality control in infrastructure design. Nawari (2020) emphasizes the value of simplified, adaptive design review systems capable of validating conceptual alternatives without requiring full project data. Studies of infrastructure planning failures (J. Wang & Yuan, 2017) have also revealed that delays and inefficiencies often stem from the insufficient integration of regulatory, contextual, and feasibility factors during the initial planning phase. By introducing a structured checklist, the present framework helps bridge this gap, ensuring that no critical aspect, be it technical, environmental, or social, is inadvertently neglected.

That said, the inclusion of contextual and social dimensions remains a challenge. While economic and regulatory indicators tend to be well-structured and measurable, many urban, cultural, and participatory variables lack standardized metrics. As noted by Bueno et al. (2015) and Liu et al. (2018) sustainability evaluation systems often handle these dimensions qualitatively or marginally, especially in early design stages. To address this imbalance, the current framework explicitly integrates a category of Context and Society Indicators, promoting a more balanced assessment that considers spatial identity, heritage, and community value

as central planning concerns. Recent research confirms the feasibility of incorporating these dimensions in early, phase assessments, particularly through the use of participatory planning methods, GIS based tools, and computational models (Wuni & Shen, 2019). Accordingly, this study introduces a tripartite structure for feasibility evaluation, composed of three indicator domains as shown in Figure 11 each containing 12 binary control questions as reported in Table 4

- Feasibility Indicator (FI): focuses on regulatory alignment, risk management, and financial viability.
- Context and Society Indicator (CI): examines urban integration, social equity, cultural identity, and spatial continuity.
- Geometry and Function Indicator (GI): evaluates spatial organization, accessibility, traffic flow, and user experience.

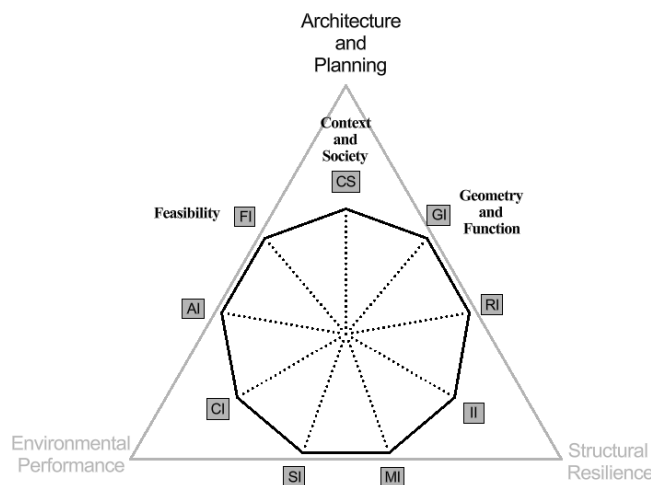


Figure 11 Tripartite structure for architecture and planning macro theme.

Table 4: architectural and planning sub-indicators descriptions and key questions.

Indicator	Sub-indicator	n	Topic	Key question
Feasibility (FI)	Fulfilling the Required Function	1	Official Design Regulations	Does the project meet all official design regulations?
		2	Site, Specific Regulations	Is it in compliance with site, specific or additional competition regulations.
		3	Functional Requirements	Does the project fulfil all required functional aspects?
		4	Virtuous Design Principles	Are design principles beyond minimum requirements considered?
	Budget and Business Plan	5	Budget Up to Dismantling	Is the budget respected up to dismantling?
		6	Construction time schedule	Is the construction time schedule respected?
		7	Risk Analysis	Has a comprehensive risk analysis been conducted?

		8	Business Plan	Is there a detailed business plan for the project?
	Operational Analysis	9	Lifecycle Operational Plan	Does an operational plan cover the project's entire lifecycle?
		10	Monitoring and Functional Plan	Is there a monitoring plan up to dismantling?
		11	Third parties' interfaces and synergies	Are Third parties' interfaces and synergies considered?
		12	Quality Preservation During Construction	Do construction phases ensure quality and functionality of spaces?
Context and society (CS)	Study of the Context	13	Future Development	Does it consider future neighbourhood or city developments?
		14	Social Context Study	Has a study on social context and infrastructure users been conducted?
		15	Environmental and Hydrogeological Study	Are environmental and hydrogeological conditions studied?
		16	Existing Infrastructure Analysis	Are existing infrastructures and analyses considered?
	Built Heritage and Landscape	17	Historical Context	Is historical context and landscape changes information gathered?
		18	Green Space Integration	Are accessible green spaces present, enhancing area quality?
		19	Cultural Landscape and Regional Coherence	Are built heritage and regional specificities acknowledged and actively integrated in the design approach?
		20	Social Cohesion and Identity	Does it enhance social cohesion and identity?
	Dialogue and Quality of the Place	21	Responsible Land Use	Is responsible land use reflected (open spaces, density)?
		22	Public and Private Space Interaction	Are diverse spaces for connection between people present?
		23	User Diversity	Does the project promote user and community diversity?
		24	Community Engagement	Does it foster a sense of belonging and community engagement?
Geometry and function (GI)	Specific Site Requirements	25	Compliance with Site Requirements	Does it meet all specific site requirements?
		26	Defined Project Area Compliance	Is the defined area respected?
		27	Compliance with Stakeholder Requirements	Does it meet stakeholders' requirements?
		28	Health and safety Requirements	Are health and safety requirements met?
	Accessibility and Quality	29	Accessibility for Disabilities	Does the project comply with accessibility standards for people with disabilities and reduced mobility?
		30	Stakeholder Feedback	Has feedback from stakeholders been incorporated?
		31	User Experience Quality	Does it provide a pleasant user experience (e.g., shaded areas)?
		32	Wayfinding and Signage	Is clear signage provided for directions and connections?
	Circulation and External Relations	33	Transport Network and Mobility Integration	Is the project seamlessly integrated with existing and planned transport network to ensure accessibility and connectivity?
		34	Flow analysis	Has a traffic analysis been conducted for peak times?
		35	Smoothness and Safety of Flow	Does the design ensure smooth and safe flows?
		36	Public Transport and Modal Integration	Does it facilitate access to public transport and other modes of transport?

This structure enables a comprehensive yet operational assessment of pedestrian and cycling bridge projects during the conceptual phase. By linking technical, contextual, and functional dimensions within a unified binary framework, it facilitates informed decision-making without compromising objectivity or simplicity.

The framework does not assign definitive ratings or impose threshold values commonly found in investor, or procurement-driven evaluation tools. Rather, it is designed to serve as a risk-oriented diagnostic instrument for designers, enabling them to detect and address potential project weaknesses at the conceptual stage, before these evolve into costly or critical issues during detailed development. In this sense, the framework is positioned not as a compliance-oriented certification tool, but as a design support system that integrates risk awareness into early design processes. As previously stated, the operational logic is based on a binary control checklist, through which each indicator category, Feasibility Indicator (FI), Context and Society Indicator (CI), and Geometry and Function Indicator (GI), is evaluated by verifying the presence or absence of a series of essential criteria. These criteria are structured as binary (yes/no) questions, designed to be unambiguous and actionable. Their purpose is not to offer a granular performance score, but to flag potentially unresolved or problematic dimensions of the project that may require additional attention, investigation, or design revision. This binary outcome does not represent a performance score or a formal pass/fail threshold; rather, it acts as an internal warning mechanism. When the value of an indicator is 0, it triggers a design alert, signalling that a critical dimension of the project has not been fully addressed. These alerts do not serve to reject a project, but to prompt the design team to revisit and resolve essential issues before advancing to more detailed development phases.

By systematically responding to the binary control questions, as shown in Table 4, design teams can quantify the presence of risks and determine whether further studies or modifications are necessary before proceeding. Each of the three indicators (FI, CI, GI) is then calculated using the following proportion:

$$X = \frac{N_s}{N_t} \quad 1$$

Where:

X is the indicator (FI, CS, GI)

Ns is the number of satisfied criteria and Nt is the total number of criteria considered (in this case 12).

This simple yet structured formula does not imply evaluative scoring in the conventional sense. Rather, it functions as a relative measure of design maturity and completeness within each category.

This methodology is supported by current research in early, stage infrastructure risk management, which cautions against premature quantification and rigid evaluation in design phases where uncertainty is still structurally inherent (Lu et al., 2024; Z. Yang et al., 2024). Moreover, it reflects principles of adaptive decision-making, emphasizing flexibility, feedback, and iteration as key to managing design under conditions of complexity and ambiguity (N. Nawari & Ravindran, 2019).

In contrast to models aimed at final certification or investor reporting, the framework's purpose is to assist design teams in asking the right questions at the right time. It provides a means to identify where feasibility, contextual integration, or functional robustness might be lacking, without requiring exhaustive documentation or external validation. In doing so, it enhances the quality and accountability of early design decisions, ensuring that potential obstacles are addressed before the project advances toward detailed planning, stakeholder negotiation, or institutional approval.

In the following, an extensive description of each sub, indicator, main references and key questions are reported.

2.3.1.1 Feasibility Indicator (FI)

Fulfilling the Required Function

1. Fulfilling Official Design Regulations

As explicitly required by most of infrastructure sustainability frameworks such as ENVISION and BREEAM, compliance with all relevant engineering codes and structural standards is a prerequisite for certification. This includes verification of the design against Limit States, ensuring that the infrastructure is safe, functional accessible, and resilient.

2. Fulfilling Site, Specific Regulations

Beyond compliance with national structural codes, infrastructure projects must respond to site-specific regulatory requirements, which may arise from local planning authorities, design competitions, or environmental constraints. This ensures alignment with the physical, ecological, and socio-urban context,

minimizing negative externalities and enhancing contextual integration. Frameworks such as LEED for Neighbourhood Development (LEED-ND) and EU Level(s) promote this alignment by encouraging infrastructure that is compatible with existing urban fabric, supports multi-modal accessibility, and contributes to environmental and social cohesion at the neighbourhood scale.

3. Meeting Project Function Requirements

The project must ensure that the proposed design fully satisfies all intended functional aspects as defined by the program, design brief, or competition requirements. This includes factors such as accessibility for all users, expected pedestrian and cyclist flows, clarity of movement, spatial usability, comfort, and integration with adjacent infrastructure or public spaces. Unlike structural adequacy, which is evaluated separately, this indicator focuses on how well the bridge functions as a space for use, ensuring it can support its role in mobility, connectivity, and public interaction without restrictions or operational compromises. Reference frameworks such as ISO 21542 (2021a), SUMP EU Guidelines(2019) and Envision v3 emphasize that infrastructure must deliver clear, safe, and inclusive functional performance from the earliest design stages.

4. Virtuous Design Principles

In addition to meeting minimum regulatory requirements, the project should demonstrate the adoption of voluntary, value-driven design principles that enhance quality, sustainability, and integration within the physical, social, and ecological context. This includes aligning with best practices from frameworks such as LEED for Neighborhood Development (LEED-ND, 2018), EU Level(s)(2020), or national sustainable design guidelines, which promote context-sensitive, inclusive, and future-ready infrastructure. Examples of virtuous principles include user-centred design, climate responsiveness, passive safety, multimodal integration, and respect for local identity. Incorporating such principles at the conceptual stage contributes to long-term performance, stakeholder satisfaction, and overall design excellence.

Respect of Budget and Business Plan

5. Budget Respect up to Dismantling

The project must include a complete and realistic cost estimate that covers the full life cycle of the infrastructure, including design, construction, maintenance, and dismantling when applicable. Planning for the total cost of ownership ensures

financial feasibility, reduces long-term risk, and demonstrates planning maturity. International standards such as ISO 15686-5 (2023) on life cycle costing, as well as frameworks like Envision v3, recommend that early-stage project evaluations account for end-of-life costs as part of sustainability and financial responsibility.

6. Construction time schedule

The project must include a realistic and clearly defined construction time schedule that reflects the full sequence of activities, from early site works to final commissioning. A robust schedule enables effective coordination, resource optimization, and early identification of potential delays. Frameworks such as ISO 21500(2021b) , PMBOK (2021), ISO 19650(2018b), CEEQUAL, and Envision v3 emphasize the role of detailed time planning as a key factor in delivering quality, minimizing disruption, and ensuring cost and risk control.

7. Risk Analysis

The project must include a structured and documented risk analysis that identifies potential threats affecting cost, time, safety, environmental conditions, and stakeholder dynamics. While this type of analysis is not always produced directly by the design team, it is increasingly required by contracting authorities, design competitions, and international frameworks. Its inclusion from the early design stages improves planning, reduces uncertainty, and increases resilience. Reference standards such as ISO 31000 (2018), ISO 21500(2021b), and sustainability frameworks like Envision and CEEQUAL emphasize the strategic importance of early-stage risk management.

8. Business Plan

A well-structured business plan outlines the long-term operational and financial model of the project, including cost coverage, maintenance strategy, and governance. Although not always prepared by the designer, business planning is often required by clients, infrastructure funding programs, or competition guidelines. Including this component early supports the project's long-term viability and alignment with sustainability criteria. Frameworks such as Envision, SNBS, and CEEQUAL recognize business planning as a key to ensuring infrastructure remains functional, maintainable, and valuable throughout its life cycle.

Operational Analysis (Study of Operation and Functionality Along the Lifecycle)

9. Lifecycle Operational Plan

The project must be supported by a clear and structured operational plan that covers the entire lifecycle of the infrastructure, from commissioning to potential dismantling. This plan should define how the infrastructure will be maintained, monitored, and kept functional over time, including preventive actions, maintenance schedules, and adaptation strategies. Unlike the business plan, which focuses on economic governance, funding, and financial strategy, the operational plan addresses the technical dimension of performance continuity, ensuring that the infrastructure remains safe, usable, and efficient in the long term. Frameworks such as ISO 55000 (2014) on asset management, ISO 15686 (2023) on service life planning, and sustainability certifications like Envision v3 (QL2.3), SNBS Infrastructure, and CEEQUAL emphasize the importance of early lifecycle planning as a foundation for infrastructure resilience and durability.

10. Monitoring and Functional Plan

The project must include a preliminary plan for monitoring its functionality and condition over time. This plan should outline how key parameters related to performance, safety, usability, and contextual integration will be regularly observed, assessed, and verified throughout the infrastructure's lifecycle. While it does not require full technical detailing at the conceptual stage, it must demonstrate that monitoring is foreseen as an integral part of the design intent. The inclusion of this indicator within the domain of Architecture and Planning is intentional. It allows for the early verification that the project is conceived as a system that will remain legible and manageable over time, not only structurally, but also functionally and socially. Monitoring, in this phase, is interpreted broadly, covering aspects such as user flows, accessibility, environmental impact, and public space performance, alongside more traditional operational metrics. Frameworks like Envision v3 (QL1.3), SNBS, and BREEAM Infrastructure promote the integration of such monitoring strategies at the early planning stage, encouraging design teams to anticipate how the infrastructure will be assessed during its use. Although technical monitoring of structural parameters is further developed within the Structural Resilience domain, introducing this theme at the planning level supports a holistic and cross-disciplinary approach. It ensures that the infrastructure is designed to support adaptive management, stakeholder accountability, and performance transparency from the outset.

11. Third Parties' Interfaces and Synergies

The project must demonstrate that it considers interfaces and operational synergies with third parties who are not directly involved in the design process, but whose systems, services, or facilities may be impacted by or integrated into the infrastructure. These include, for example, public utilities, telecommunication networks, energy lines, drainage systems, emergency services, or parallel infrastructure projects that intersect in time or space with the proposed work. This indicator does not assess integration with existing built infrastructure (see indicator 16) nor public transport connections (see indicator 35), but rather the ability of the project to proactively identify coordination needs, reduce conflicts, and explore shared solutions with independent external actors. It addresses the systemic quality of the design, encouraging a shift from isolated project thinking to a network-oriented approach. Standards such as ISO 21500 (project integration), ISO 37101 (2016) (sustainable development in communities), and Envision v3 (LD1.1, QL1.1) underscore the strategic importance of interface management as a tool to increase feasibility, reduce risk, and foster innovation across urban systems.

12. Quality Preservation During Construction

The project must demonstrate that appropriate measures are planned to preserve the quality and functionality of spaces during all construction phases. These include actions to protect design integrity, ensure user safety, reduce disturbance, and maintain aesthetic, environmental, and operational standards throughout the building process. Unlike indicators that address long-term operation, this criterion focuses specifically on the temporary disruptions and spatial challenges inherent to the construction phase. It evaluates whether the project anticipates and mitigates potential negative impacts on accessibility, usability, environmental quality, and public space continuity. Measures may include phased construction strategies, protective site barriers, temporary pathways, noise and dust reduction plans, and stakeholder communication protocols. Frameworks such as SNBS Infrastructure and the Davos Baukultur Quality System (Davos Q) (2018) emphasize that construction is not a neutral process but a visible and lived moment that affects public experience and spatial identity. The Davos Declaration advocates for the preservation of spatial quality during all lifecycle stages, while SNBS promotes the protection of surrounding contexts and the minimization of temporary degradation. These principles are reinforced in Envision v3 (QL2.2, QL2.3), CEEQUAL, and BREEAM Infrastructure, which treat construction-phase quality as a key dimension of sustainable infrastructure.

2.3.1.2 Context and Society Indicator (CS)

Study of the Context

13. Future Development Consideration

The project should demonstrate awareness of potential future developments in the surrounding urban or territorial context. These may include planned transport systems, real estate developments, or urban regeneration strategies that could affect accessibility, visibility, or functionality of the bridge. This indicator focuses on anticipatory planning, which helps ensure that the infrastructure remains relevant and adaptable over time. It avoids future conflicts with evolving land use or policy objectives and encourages infrastructure to be a long-term asset rather than a transient intervention. Frameworks such as SNBS Infrastructure, Envision v3 (LD1.3, QL1.1), and ISO 37101 promote long-term territorial alignment and adaptability. The integration of future-oriented spatial development plans is also a key principle in OECD Guidelines for Urban Policy (2018).

14. Social Context Study

The project should demonstrate a clear understanding of the local social context, including demographic characteristics, user profiles, patterns of mobility, and community dynamics. This assessment supports context-sensitive design choices that align with the values, expectations, and functional needs of the surrounding population. Unlike indicator 20, which addresses social cohesion as a design outcome, this indicator focuses on the preliminary investigation of social characteristics prior to design development. It supports more inclusive infrastructure by identifying potential barriers, underserved user groups, or latent social needs. Social baseline studies are encouraged in frameworks such as Envision v3 (QL1.1), SNBS Infrastructure, and UN-Habitat's Urban Planning for City Leaders (2020), which promote early-stage user analysis as a condition for quality urban integration.

15. Environmental, Hydrogeological Study

The project must consider environmental and hydrogeological factors that could affect the design, construction, or performance of the infrastructure. This includes terrain characteristics, flood risks, soil quality, drainage patterns, and biodiversity considerations. Unlike indicator 12, which focuses on protecting quality during construction, this indicator is specifically about the preliminary

technical and environmental compatibility of the site. It encourages mitigation of potential risks through informed design strategies. This requirement aligns with ISO 14001, ISO 37101, CEEQUAL, and SNBS, all of which demand baseline environmental assessments before infrastructure interventions. Floodplain mapping, ecological assessments, and site surveys are all tools referenced by these systems.

16. Existing Infrastructure Analysis

The project must include technical verification of all infrastructures present in or near the intervention area, including underground networks (e.g., drainage, sewer, gas, water, electricity, telecommunications) and above-ground elements (e.g., aerial lines, pylons, lighting systems). If documentation is not made available by the asset owner or public concessionaire, the design team is responsible for identifying, surveying, and verifying all potential interferences at the earliest project stages. This process ensures compatibility, avoids conflicts, and prevents costly relocations or redesigns during construction. This indicator refers exclusively to technical detection and infrastructure interference analysis. It does not address user access, public space, or spatial integration, which are evaluated in separate indicators. This approach is aligned with international technical standards such as PAS 128(2014), BS 5930 (2015), and guidance provided by Envision v3 (LD3.1) and CEEQUAL Section 2.1, which recommend pre-construction mapping of utility systems as a prerequisite for resilient and conflict-free infrastructure delivery. FIDIC Red Book clauses on site investigation also support this requirement (2017).

Built Heritage and Landscape Qualities

17. Historical Context

The project should begin with a thorough understanding of the site's historical evolution, including past uses, transformations, former infrastructures, and any cultural traces that have shaped the identity of the place. This investigation supports informed design choices, ensuring that the intervention responds to the memory and layered character of the site. This indicator is not about replicating traditional styles or complying with heritage protection rules. Rather, it emphasizes the interpretive role of history during the early design phase. Recognizing how the site has changed over time helps identify spatial patterns, cultural meanings, or symbolic alignments that should guide, rather than constrain, the creative process. The approach follows the principles of UNESCO's Historic Urban Landscape HUL (2011), which advocates for integrating heritage values into urban development, and the Davos

Baukultur Quality System, which highlights historical continuity as a core component of quality in the built environment.

18. Green Space Integration

The project should ensure the presence of accessible green spaces by preserving existing ones or integrating new ones into the design, with the aim of improving environmental quality, urban comfort, and user well-being. Accessibility refers not only to physical proximity but also to actual usability by a wide range of users, regardless of age, ability, or social background. Green areas play a key role in regulating local microclimates, supporting biodiversity, and fostering social cohesion, making public spaces more inclusive and resilient. These benefits are emphasized in international standards such as ISO 37120 (2018c), which includes green space access among key indicators for urban performance, and ISO 37101 (2016), which promotes integrated green infrastructure as part of sustainable community development. A notable example of this principle is embodied in the sponge city model, increasingly adopted in East Asian and European contexts. In such approaches, green infrastructures such as permeable parks, wetlands, and vegetated corridors is designed to absorb, retain, and reuse rainwater, improving flood resilience while providing publicly accessible natural space. This integration of ecological function and spatial accessibility illustrates how green space can support both environmental and social objectives. This indicator evaluates whether the project integrates greenery as part of a functional and accessible spatial system, avoiding residual or merely decorative treatment.

19. Cultural Landscape and Regional Coherence

The project should demonstrate an active integration of regional architectural languages, construction techniques, and landscape identities, ensuring coherence with the local context. Unlike the broader historical dimension addressed in previous indicators, this criterion emphasizes the conscious adoption of local characteristics into the contemporary design process, allowing new infrastructures to harmonize with pre-existing cultural and environmental patterns. This includes, for instance, the reinterpretation of vernacular forms, the use of locally sourced materials, or the preservation of visual continuity with traditional structures and landforms. The indicator is particularly relevant in sensitive or transitional areas, where the project risks disrupting visual, cultural, or ecological balances. Although regulatory requirements regarding heritage conservation are often imposed at national or regional level, a number of international frameworks support the

proactive integration of local identities into contemporary infrastructure. The UNESCO Recommendation on the Historic Urban Landscape (HUL) encourages new developments to incorporate the layering of cultural and natural values as part of design decisions. Similarly, the Davos Baukultur Quality System promotes the cultural sustainability of projects by urging designers to strengthen local identity through contextual and site-responsive design. This indicator does not assess whether historical assets are merely preserved, but whether their presence and the broader regional identity are meaningfully interpreted within the project vision.

20. Social Cohesion and Identity

The project should contribute to social sustainability by enhancing cohesion, inclusion, and collective identity through thoughtful spatial and architectural choices. Social sustainability, as defined by frameworks such as ISO 37101 and the United Nations Sustainable Development Goals (particularly SDG 11), involves ensuring that infrastructure projects promote equity, belonging, and wellbeing across all segments of society. In this perspective, infrastructure is not a neutral element, but a symbolic and functional component of public space that can either support or hinder community life. The indicator focuses on whether the bridge enhances the sense of belonging and shares cultural references within the community it serves. This could be achieved through design elements such as community gathering spaces, references to local culture or history, symbolic materials, or spatial strategies that foster encounter, interaction, and recognition. Projects located in diverse or rapidly changing urban contexts should pay particular attention to cultural pluralism and intergenerational needs, ensuring that the infrastructure does not create division but instead promotes inclusive use and identity continuity. While many sustainability certification systems, such as Envision and CEEQUAL, mention community benefits, they often operationalize social aspects through stakeholder engagement or functional accessibility. This indicator goes further by addressing how spatial and symbolic design decisions can embody and reinforce the social fabric.

Dialogue and Quality of the Place

21. Responsible Land Use

The project should demonstrate responsible and efficient use of land, minimizing the occupation of ecologically sensitive or socially valuable spaces. This includes preserving open areas, limiting soil sealing, and aligning with existing urban density strategies. Responsible land use contributes to environmental and

social sustainability by reducing unnecessary sprawl, protecting local ecosystems, and enhancing urban resilience. Frameworks such as the UN New Urban Agenda and ISO 37123 (2019) advocate for compact, efficient land use that promotes walkability, accessibility, and climate responsiveness. Green infrastructure planning approaches, such as the "sponge city" concept, reinforce this vision by encouraging permeable surfaces, green corridors, and flood-mitigating landscapes in urban infrastructure.

22. Private and Public Spaces

The design should facilitate meaningful interaction between public and private spaces, promoting active edges, permeability, and spatial continuity. This indicator evaluates whether the infrastructure contributes to the vibrancy of public life by integrating spaces for social interaction and enhancing the quality of adjacent areas. Good practice includes transitions between private properties and public circulation areas, visibility between domains, and opportunities for pause, gathering, and informal use. As emphasized in urban design frameworks (Gehl, 2010), spatial interaction fosters safety, social life, and inclusivity in public infrastructures.

23. User Diversity

The project should be designed to reflect the diversity of its potential users, considering differences in age, gender, culture, language, and patterns of use. This indicator evaluates inclusiveness beyond legal accessibility requirements, asking whether the design facilitates comfort and usability for groups such as children, elderly people, families, tourists, and multicultural communities. This dimension is aligned with the broader principles of Design for All, which advocate for environments that are useable by the widest range of people, not only those covered by specific regulations. Unlike Indicator 29, which focuses on accessibility standards for disabilities, this indicator highlights social sustainability and experiential equity. Key references include UN-Habitat's Urban Equality Agenda and ISO 37101 (Sustainable development in communities).

24. Community Engagement

The project should demonstrate that meaningful engagement with local communities has been carried out during the planning and design phases. Community engagement is often initiated and formally managed by the client or public authority, who provides the framework and resources for dialogue. In such cases, the design team is expected to incorporate and reflect the outcomes of this

process in the project. In participatory projects, however, the design team may directly facilitate engagement activities, such as workshops, focus groups, or digital platforms for co-design. In these contexts, the responsibility is shared: the designer does not simply receive input but actively manages the process of interaction, interpretation, and integration of feedback into design solutions. This indicator differs from the Social Context Study (Indicator 14), which is based on research and analysis, and from Social Cohesion (Indicator 20), which evaluates the outcomes of design for community identity. Here, the focus is on the participatory process that creates a direct link between stakeholders and design decisions. Relevant references include ISO 37101 (Sustainable development in communities) and ISO 26000 Guidance on social responsibility (2010), which both highlight the importance of stakeholder involvement. Envision (QL1.1–QL1.3) and CEEQUAL also consider community engagement as a key factor for achieving socially sustainable infrastructure.

2.3.1.3 Geometry and Function Indicator (GI)

Specific Site Requirements Fulfilling (Railways, Rivers, Motorways)

25. Compliance with Site Requirements

The project must comply with all site-specific constraints imposed by physical context, such as clearance requirements over rivers, navigation corridors, flood protection levels, railway safety zones, motorway setbacks, or buffer areas for protected natural sites. These requirements are generally defined by concessionaires or sectoral authorities and represent non-negotiable spatial and safety conditions for feasibility.

26. Defined Project Area Compliance

The project must remain strictly within the boundaries of the designated intervention area, as defined by property lines, right-of-way corridors, competition briefs, or planning permits. Compliance with these limits ensures that the intervention does not expand beyond its assigned footprint, preventing legal disputes, land conflicts, or occupation of adjacent areas. This indicator differs from Responsible Land Use (Indicator 21), which evaluates efficiency of land occupation. Here the focus is solely on respecting the official project perimeter. Relevant references include ISO 21542 Building construction - Accessibility and usability of the built environment, as it defines spatial boundaries for circulation (2021a), ISO 6707-1 Terminology for spatial planning and construction works

(2022), and national or municipal planning codes that regulate construction boundaries and right-of-way constraints.

27. Compliance with Stakeholder Requirements

The project must demonstrate compliance with formal requirements established by competent authorities or institutional stakeholders, such as municipalities, transport operators, or environmental regulators. These requirements may include technical conditions (lighting, clearance, drainage), mobility masterplans, or environmental mitigation measures. This indicator is not about participatory processes (Indicator 24) but about verifying that binding requirements from stakeholders with regulatory or contractual authority are fully integrated. Relevant references include ISO 21500 (Project management — Guidance on project management), ISO 31000 (Risk management — Guidelines), and FIDIC Conditions of Contract, which highlight the role of compliance with employer's requirements and external authority conditions.

28. Health and Safety Requirements

The project must comply with all applicable health and safety regulations to protect users during operation and workers during construction. This includes measures such as safe access routes, guardrails and fall protection systems, anti-slip surfaces, adequate lighting and visibility, and safe interfaces between construction sites and public areas. During the operational phase, safety must extend to all categories of users, ensuring risk-free circulation for pedestrians and cyclists. This indicator is distinct from structural safety (Indicators 1–3), which addresses compliance with engineering codes, and from flow safety (Indicator 34), which concerns the dynamic management of circulation. Here the focus is specifically on compliance with codified health and safety standards aimed at protecting people. Relevant references include: ISO 45001 Occupational health and safety management systems (2018a), ISO 39001 Road traffic safety management systems (2012), EN 13201 Road lighting requirements (2015), EN 1317 Road restraint and barrier systems, applicable to parapets (2010), ILO Guidelines on Occupational Safety and Health in Construction (2005).

Accessibility and Quality

29. Accessibility for People with Disabilities and Reduced Mobility

The project must comply with accessibility regulations while being inspired by the principles of Design for All and Universal Design, ensuring that persons with disabilities or reduced mobility can use the infrastructure safely and autonomously. This includes step-free access, compliant gradients for ramps, tactile paving, handrails, elevators, and accessible signage. This indicator differs from Indicator 23, as it focuses specifically on technical compliance with specific binding standards such as ISO 21542 (2011), the EU Accessibility Act - Directive 2019/882 (2019), and the UN Convention on the Rights of Persons with Disabilities CRPD (2006) .

30. Stakeholder Feedback

The project should demonstrate that structured feedback from relevant stakeholders, such as municipalities, user associations, mobility agencies, or NGOs, has been gathered and considered during the design phase. This is distinct from Indicator 24 (Community Engagement), which refers to participatory processes involving the wider public. Here the focus is on feedback from organized or institutional stakeholders who can provide technical, operational, or user-specific expertise. The objective is to verify whether design iterations have incorporated such input, improving alignment with social, functional, and operational expectations. References include ISO 21500 (Project management), which emphasizes stakeholder analysis and communication, and Envision (QL1.2), which evaluates the integration of stakeholder priorities in project delivery.

31. User Experience Quality

The project should consider the overall comfort, usability, and experiential quality for end users, going beyond minimum safety and accessibility requirements. This includes aspects such as shading and shelter, seating or resting areas, noise and vibration comfort, aesthetic integration, and environmental micro-conditions that enhance the daily use of the infrastructure. This indicator differs from Indicator 29 (Accessibility), which evaluates compliance with accessibility codes, and from Indicator 34 (Flow Smoothness and Safety), which deals with circulation management. Here the concern is the experiential dimension of infrastructure, i.e., whether users find the bridge pleasant, comfortable, and conducive to well-being. References include ISO 37101 (Sustainable development in communities) and the Davos Baukultur Quality System, both of which highlight the quality of experience as a key dimension of sustainable design.

32. Wayfinding and Signage

The project should ensure that wayfinding and signage are clear, intuitive, and accessible to all users, facilitating safe and efficient navigation across the infrastructure. This involves providing legible visual information, tactile and auditory systems for users with disabilities, and strategically placed signage that supports orientation and decision-making. Unlike Indicator 29 (Accessibility), which addresses compliance with technical accessibility standards, this indicator focuses on the cognitive and perceptual dimension of movement, ensuring that users can easily understand and navigate the space. It is also distinct from Indicator 31 (User Experience Quality), which concerns comfort and pleasantness, as here the emphasis is on functional orientation and safety through information systems. Relevant references include ISO 21542 Accessibility and usability of the built environment, ISO 7001 (Graphical symbols — Public information symbols), and the UN Convention on the Rights of Persons with Disabilities, which highlights the importance of multi-sensory communication in public infrastructure. Best practices are also described in the Global Designing Cities Initiative guidelines, which emphasize inclusive signage systems in urban mobility projects.

Circulation and Relation with External Infrastructures

33. Transport Network and Mobility Integration

The project should demonstrate effective integration with current transport systems (pedestrian, cycling, road, and public transport networks) as well as with planned future mobility infrastructures. This ensures that the bridge contributes to accessibility, continuity of movement, and long-term connectivity across the area. In most cases, strategic information on future developments is provided by the client or public authorities through urban plans, mobility masterplans, or transport strategies. The role of the design team is to incorporate these requirements, aligning the project with both present and future mobility systems. This indicator differs from Indicator 16 (Existing Infrastructure Analysis), which is limited to mapping technical utilities and constraints. Here the emphasis is on strategic coherence with transport and mobility networks, ensuring that the infrastructure becomes a functional node in a broader system. Relevant references include ISO 37101 (Sustainable development in communities), the EU Urban Mobility Framework, and the TEN-T Guidelines for multimodal integration.

34. Flow analysis

The project should be supported by a technical usage flow study, which evaluates expected pedestrian and cyclist demand, peak conditions, and circulation

patterns. These analyses are often provided by the client as part of feasibility studies, but in more complex contexts — for example, when several areas or mobility corridors intersect — the design team may be required to conduct or complement them. The aim is to ensure that the infrastructure is dimensioned correctly, preventing congestion and bottlenecks. This indicator differs from Indicator 35, which concerns the experiential outcome of flows, as here the focus is on the existence and strength of the analytical study. Relevant references include PIARC (Pedestrian and Cyclist Infrastructure Guidelines), ISO 14813 (Intelligent Transport Systems Framework for Transport Information), and the EU Urban Mobility Framework.

35. Smoothness and safety flow

The project must guarantee that circulation along the bridge is continuous, comfortable, and safe for all users once the infrastructure is in operation. This indicator is not concerned with compliance to codified health and safety standards, which are addressed elsewhere, nor with the existence of traffic simulations, but with the actual quality of the flows as they are experienced in practice. A well-designed bridge should allow people to move without interruptions or bottlenecks, avoiding situations where cyclists and pedestrians interfere with one another or where spaces narrow and create congestion. The geometry and width of the deck, the clear separation between different user groups, and the intuitive layout of access all play a role in creating a fluid circulation pattern. In addition, the perception of safety is enhanced when environmental conditions are considered, such as protection against wind, adequate lighting at night, or the use of materials that reduce the risk of slipping in wet conditions. A smooth flow is therefore not only a matter of efficiency but also of comfort and reassurance, making the infrastructure inviting and reliable in everyday use. This indicator differs from the technical traffic analysis (Indicator 34), which is about modelling and predicting flows, and from codified health and safety compliance (Indicator 28), which is about minimum regulatory standards. Here the emphasis is on whether the design choices translate into an environment where users can move intuitively, without conflict, and with a sense of comfort and safety in their daily experience.

36. Modal and Public Transport Integration

The project should demonstrate that the new pedestrian and cycling bridge does not act as a stand-alone element but contributes to the wider mobility system by facilitating direct access to public transport and other modal options. This indicator

evaluates the bridge's role as an intermodal connector: does it shorten walking distances to bus or tram stops, improve access to metro stations, link effectively to bike-sharing facilities, or provide connections to park-and-ride areas? In this way, the bridge becomes not just a crossing, but a node that enables seamless transfers between modes and encourages sustainable mobility choices. Unlike Indicator 33 (Integration with Existing and Planned Transport Networks), which focuses on the technical and strategic alignment of the bridge with planning documents, mobility masterplans, and long-term infrastructure strategies, this indicator is oriented toward the practical and experiential relationship between the bridge and the extended modal system. Indicator 33 ensures that the project is consistent with broader mobility frameworks, while Indicator 36 assesses whether it enables users to connect easily and intuitively with other modes in their daily journeys. Relevant references include ISO 37101 (Sustainable development in communities), the EU TEN-T Guidelines for intramodality (2013), and UITP International Association of Public Transport standards (2019), all of which highlight the importance of designing infrastructure as an integral part of a multimodal mobility chain.

2.3.2 Structural resilience

Recent studies have highlighted the growing need to integrate key performance parameters from the earliest design stages to ensure the long-term sustainability, resilience, and durability of bridge infrastructure (Frangopol & Soliman, 2016; Gozzi & Guante Henriquez, 2025b). Traditional design approaches, centred on Ultimate Limit State (ULS) and Serviceability Limit State (SLS) verifications, ensure adequate safety under prescribed loading conditions but are increasingly regarded as insufficient to address the multifaceted challenges posed by ageing infrastructure, climate change, and evolving hazard scenarios. Modern design philosophies therefore call for a broader framework, one that integrates robustness, inspection, and maintenance as essential parameters to be explicitly considered during the conceptual design phase. Incorporating these parameters early enables a shift from a prescriptive to a performance-based and resilience-oriented design paradigm, providing a holistic understanding of structural behaviour throughout the life cycle (Bocchini et al., 2014; Bruneau & Reinhorn, 2007).

In this view, structural resilience is defined as the capacity of a structural system to absorb and adapt to disturbances while maintaining essential functions and recovering rapidly after extreme or unexpected events. This conception of resilience builds upon the interplay of three mutually reinforcing properties: robustness, inspectability, and maintainability, which together determine the system's ability to

resist, detect, and mitigate degradation or damage. These attributes, if incorporated from the conceptual stage, guide design decisions that not only enhance safety and durability but also improve cost efficiency and sustainability over the life span of the structure (Frangopol & Liu, 2007).

Within asset management practice, inspection and maintenance are already institutionalized through frameworks such as Road Infrastructure Asset Management Systems and Sustainable Infrastructure Rating Systems (SIRS), where they are governed by national guidelines and digital management standards. These systems ensure long-term operational safety by defining inspection intervals, deterioration models, and prioritisation strategies for maintenance actions. However, such processes are typically introduced after construction, as reactive measures. This gap highlights the lack of a true design-for-inspection and design-for-maintenance philosophy in structural engineering, an approach that is already standard in mechanical and industrial design, where geometry, accessibility, and modularity are optimised to facilitate future interventions (Bittencourt et al., 2016; Kong & Frangopol, 2003). Transferring this philosophy to bridge design implies conceiving structures that are inherently observable, serviceable, and maintainable throughout their service life, with access systems, monitoring strategies, and material choices embedded in the design concept itself.

Robustness, by contrast, represents a more intrinsic and system-level property. It defines the ability of a structure to withstand local damage or accidental actions without suffering disproportionate collapse relative to the initiating cause (Ghosn et al., 2010; Starossek & Haberland, 2012). According to the CNR-DT 214/2018 (2018), robustness is the capacity of a construction to avoid damage disproportionate to the magnitude of an exceptional or extreme action. The CNR-DT 214/2018 further links this concept to the mitigation of progressive collapse, where a local failure may propagate through the structure if alternative load paths and compartmentalisation are not properly conceived. In its conceptual design guidelines, the CNR-DT 214/2018 emphasises that robustness must be provided through appropriate structural configuration, achieved by redundancy, continuity, ductility, and geometric segmentation, to ensure that the structure can mobilise reserve resistance before collapse. These characteristics are not add-ons but design fundamentals that must be considered from the earliest stages of conception.

Crucially, the CNR-DT 214/2018 also establishes a strong connection between robustness and risk, recognising that the probability of disproportionate collapse depends both on the structural system's resistance and on the site-specific

likelihood of initiating events. It introduces a probabilistic framework for collapse risk analysis, in which the annual probability of collapse $P(C)$ is expressed as the product of conditional probabilities related to the local damage state and the occurrence of the hazard event. This multi-hazard, site-dependent approach acknowledges that robustness cannot be assessed in isolation from its exposure environment. As a result, the robustness concept evolves into a risk-informed measure, an idea that forms the basis of the Collapse Resilience Indicator developed in this study.

Building upon these foundations, the present framework integrates three complementary indicators that together define the structural resilience of pedestrian bridges in the conceptual phase (Figure 12). The first, the Collapse Resistance Indicator (RI), quantifies the structure's robustness and risk-informed capacity to resist disproportionate collapse. It translates the probabilistic reasoning of the CNR-DT 214/2018 into a practical tool for early design, bridging deterministic robustness evaluation and probabilistic risk assessment. The second, the Inspection Indicator (II), evaluates the structure's observability and detectability, assessing how easily potential damage, deterioration, or anomalies can be identified throughout the bridge's service life. It accounts for factors such as accessibility of critical components, visibility, and compatibility with monitoring technologies. Embedding inspectability at the conceptual stage facilitates data-driven asset management and supports resilience through early detection and condition awareness. The third, the Maintenance Indicator (MI), measures the maintainability and sustainability of the structure, addressing the feasibility, frequency, and environmental impact of maintenance actions. It encourages design choices that simplify interventions, extend service life, and reduce life-cycle costs and emissions. As demonstrated in studies by Frangopol & Liu (2007) and Bittencourt et al. (2016), design decisions that promote maintainability have a direct influence on resilience by ensuring functional continuity and minimising downtime after extreme events.

These three indicators are interdependent and must be interpreted collectively. A structure optimised solely for robustness might present limited accessibility for inspection, while a highly inspectable system could entail more frequent maintenance demands. The challenge lies in balancing these dimensions so that the design achieves a resilient equilibrium, one capable of withstanding hazards, remaining observable for condition monitoring, and facilitating efficient interventions. In this integrated view, robustness, inspection, and maintenance form a closed loop: robustness prevents excessive damage; inspection detects deviations

from intended performance; and maintenance restores or enhances that performance over time. The proposed conceptual design framework thus extends beyond the traditional scope of safety verification to encompass the full life cycle of bridge performance. It embodies the shift from strength-based to resilience-based design, aligning with international recommendations such as ISO 2394 (2015a) and the COST Action C26 (2012), which advocate for the integration of risk and robustness considerations in the earliest design stages. By introducing explicit indicators for robustness, inspection, and maintenance, this framework provides designers with operational tools to evaluate and optimise resilience before detailed analyses or construction decisions are made. Each of these three indicators is described in detail in the following sections, where their theoretical formulation and application to conceptual bridge design are presented.

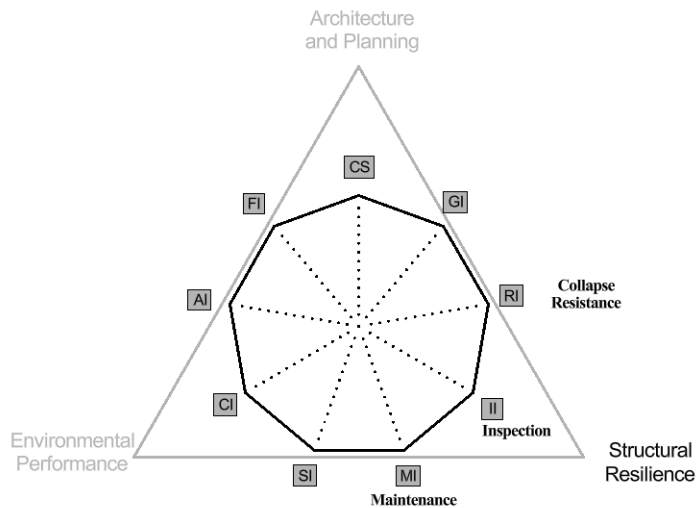


Figure 12 Tripartite structure for structural resilience macro theme.

2.3.2.1 Collapse Resistance Indicator RI

The probabilistic formulation introduced in the CNR-DT 214/2018 provides a comprehensive and risk-informed basis for assessing structural robustness. Moving beyond deterministic definitions based solely on geometry, redundancy, or ductility, the CNR adopts a reliability-based perspective consistent with the probabilistic approach developed by Augusti et al. (1984). In this view, robustness is not treated as an absolute or intrinsic property of a structure but rather as a conditional one, dependent on the probability that specific initiating events may occur and on the system's capacity to limit the resulting damage. Accordingly, Chapter 3 of the CNR formulates the annual probability of disproportionate collapse, denoted as $P(C)$, as the convolution of three conditional probabilities that

describe the sequence of physical processes leading from the occurrence of a hazard to the failure of the entire structure:

$$P(C)=P(C|SL) \cdot P(S|LH) \cdot P(H) \quad 2$$

Where:

- $P(H)$ represents the probability of occurrence of a hazardous event.
- $P(SL | H)$ denotes the probability that such a hazard induces a local damage state.
- $P(C | SL)$ expresses the probability that the resulting local damage propagates into a disproportionate or global collapse.

This structure of conditional probabilities, grounded in the total probability theorem, enables a rigorous separation between three fundamental dimensions of collapse risk: hazard exposure, element vulnerability, and system robustness. It directly aligns with the formulation proposed by Baker et al. (2008) who conceptualized robustness as a probabilistic component of total structural risk, rather than an independent safety property.

In this framework, the probability of collapse $P(C)$ represents a risk-informed measure of robustness, explicitly linking the internal performance of the structure to the external frequency and severity of exceptional events. A structure may therefore be considered mechanically robust but still exhibits a high probability of collapse if the frequency of initiating events $P(H)$ is large, or if critical components have a high vulnerability $P(SL | H)$. Conversely, a configuration exposed to rare hazards or possessing greater internal redundancy will correspond to a lower $P(C)$. Through this reasoning, the CNR reinforces the view, already expressed by Ellingwood (1978) and Asprone et al. (2010), that robustness and risk must be assessed jointly, since structural performance cannot be dissociated from the probabilistic nature of the loads and actions acting upon the system. This probabilistic representation also provides a rational foundation for comparing structural configurations under different hazard environments. Unlike purely deterministic approaches, which rely on predefined load cases or accidental scenarios, the probabilistic formulation accounts for uncertainty in both the occurrence of hazards and the propagation of damage. The result is a framework in which robustness becomes explicitly context-dependent, its adequacy determined by the combined effects of site exposure, structural topology, and the likelihood of initiating events. This perspective aligns closely with the principles of risk-

informed design outlined by Paté-Cornell (1994) and the COST Action TU0601 (2011), in which the aim is not to eliminate uncertainty but to quantify and manage it through informed design decisions. Building upon this foundation, the present work adopts the CNR probabilistic formulation as the theoretical basis for defining the Collapse Resistance Indicator (RI). In this framework, each term of the CNR expression is reinterpreted to reflect the type and quality of information available during conceptual design. Specifically, $P(C|SL)$ is used in this work to represent structural robustness (R), i.e., the capacity of the system to tolerate the removal or impairment of critical elements without leading to disproportionate collapse. $P(SL|H)$ is interpreted as a measure of susceptibility of the structure to a given hazard scenario, quantifying how likely it is that the hazard will trigger a specific structural damage state (SL). Finally, $P(H)$ is defined as a site-specific measure of hazard exposure, reflecting the contextual likelihood of different accidental events relevant to footbridges. Through these reinterpretations, the RI maintains the probabilistic logic and physical meaning of the original CNR expression while adapting it to the limited data and heuristic nature of conceptual design. It thus becomes a practical comparative indicator that connects deterministic robustness reasoning with probabilistic risk assessment, embedding risk-informed robustness directly into the earliest stages of structural conception. Figure 13 summarizes the overall logic of the proposed methodology.

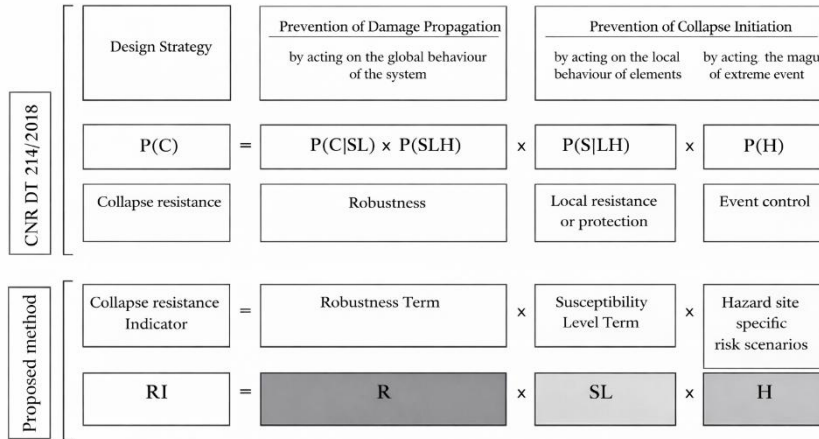


Figure 13 Conceptual framework of the proposed methodology, illustrating the reinterpretation of the CNR probabilistic terms for early-stage design of footbridges.

Then equation 2 becomes:

The following section outlines the numerical procedure adopted to evaluate the three probability terms introduced above, providing a quantitative formulation of R , SL , and H within the proposed framework.

R: robustness term

The probability term $P(C | SL)$, representing structural robustness R , quantifies the ability of the bridge system to prevent local damage from escalating into a disproportionate or global collapse. Its evaluation in this work follows the linear-elastic Alternate Path (AP) method proposed by the GSA (2013) adapted to the conceptual design phase and interpreted through the multi-level robustness framework developed by Bae et al. In the GSA approach, robustness is assessed by removing selected load-bearing components and analysing the residual structural response under static load combinations. The Demand-to-Capacity Ratio (DCR) serves as a numerical proxy for robustness, indicating whether the system can maintain stability and load transfer after a local failure.

The load combination adopted, consistent with GSA (2013), is:

$$G_{LF} = \Omega_N (\gamma_G \cdot DL + \gamma_Q \cdot LL) \quad 4$$

Where:

- DL and LL denote dead and live loads respectively.
- γ_G is the partial safety factor for permanent loads equal to 1.2
- γ_Q is the partial safety factor for variable loads equal to 0.5
- Ω_N is the dynamic increase factor to be applied to elements immediately adjacent to the removed element

In this study Ω_N equal to 1 is adopted for the dynamic increase factor in the load combination used for robustness assessment, consistent with the static equivalent formulation of the Alternate Load Path Method proposed by GSA (2013). While dynamic analyses often apply amplification factors ranging from 1.0 to 2.0 to account for transient effects such as inertia and impact during sudden member removal, the conceptual stage of design prioritizes comparative evaluation over precise dynamic fidelity. The selection of $\Omega_N = 1$ reflects a deliberate simplification that ensures conceptual clarity and computational tractability. This

approach avoids the need for local stiffness and mass modelling, which is often unavailable at early design stages, and prevents the introduction of unjustified variability due to localized amplification of internal forces. Furthermore, since the RI and its conditional component are employed in a comparative framework across alternative structural configurations, applying a uniform dynamic amplification would affect all solutions equally, thus not altering their relative ranking. Therefore, the use of $\Omega_N = 1$ preserves the fairness and scalability of the evaluation. This assumption is consistent with the simplified procedures recommended by GSA (2013) for preliminary analysis and aligns with the multi-level robustness framework proposed by Frangopol and Curley (1987), wherein static linear-elastic methods are deemed sufficient for capturing the redistribution potential of structural systems. Moreover, the approach is compatible with the probabilistic interpretation of robustness outlined in CNR-DT 214/2018, which conceptualizes robustness as a global system property rather than a local dynamic phenomenon. According to Voulpiotis et al.(2021), robustness can be evaluated across three hierarchical levels.

Figure 14) (i) component level, focused on the resistance of individual members; (ii) sub-assembly level, addressing local load redistribution between interconnected elements; and (iii) system level, concerned with the overall integrity and continuity of the structural system. Within this hierarchy, the present framework positions itself at the system level, focusing on the global robustness of the bridge rather than on the local strength of single components. The approach assumes the removal of primary unifilar elements, such as main girders, columns, piers, or critical ties, to simulate localised failure and evaluates whether the remaining system can redistribute internal forces and maintain equilibrium under the prescribed load combination.

Scale of analysis	Description
 System scale	Global structural behaviour and load redistribution mechanisms.
 Component scale	Resistance and failure modes of individual structural members.
 Connection scale	Localised behaviour of joints and interfaces governing force transfer.
 Material scale	Mechanical properties and degradation mechanisms at material level.

Figure 14 Hierarchical levels of a structure (adapted from Voulpiotis et al., 2021).

On regard, Figure 15 shows the basic taxonomy used in this study, with the aim of adopting a uniform and consistent terminology.

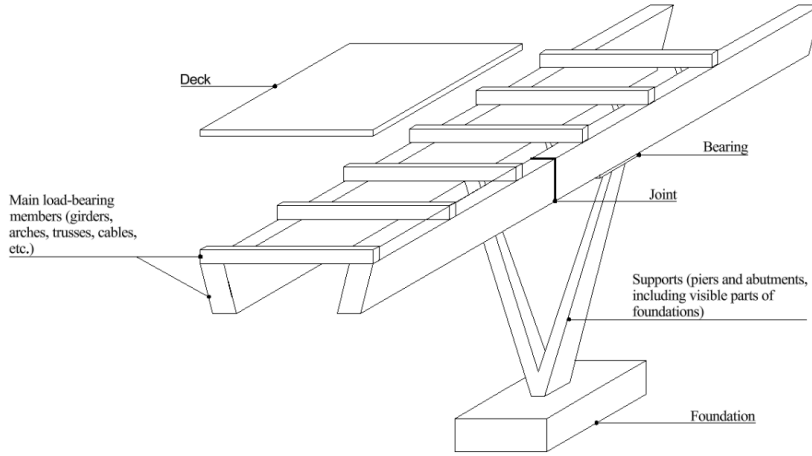


Figure 15 Structural Taxonomy

In this framework, the robustness term is expressed as a percentage of the remaining live load capacity (%LL), as this representation provides an intuitive and comparative measure of the structure's residual load-carrying capacity after local element removal. Expressing robustness in terms of %LL allows the assessment to be directly related to the bridge's service function, namely, its ability to continue carrying live loads after damage, thus linking the probabilistic concept to a physically meaningful engineering quantity that can be easily interpreted during the conceptual design stage (Gozzi et al., 2026). This formulation is consistent with the principles of residual capacity assessment introduced UIC (2009) proposing the residual live load as a key indicator of post-damage performance in bridge evaluation, as well as with the approach adopted in the CNR-DT 213/2015 and the CSLP Guidelines for existing bridges (2022), where the remaining load-carrying capacity represents a primary measure of safety and serviceability under degraded conditions. By adopting %LL as a normalized indicator, the robustness assessment directly connects the probabilistic framework of the CNR-DT 214/2018 with the performance-based logic of bridge assessment standards, ensuring continuity between conceptual design and structural evaluation practice. R formulation is:

$$R = \%LL = \max(0, \min(1, \frac{C-S_{DL}}{S_{LL}})) \quad 5$$

Where:

- C represents the structural capacity (e.g. bending, shear, or axial resistance such as M_r, V_r, N_r, f_{yd})
- S_{DL} is the internal force due to dead load (load increasing factor 1.2)
- S_{LL} is the live-load effect (load increasing factor 0.5)

In the context of this framework, the probabilistic term $P(C | SL)$ assumes values between 0 and 1, representing the degree of robustness of the structural system. The value of $P(C | SL) = 1$ corresponds to a fully robust configuration, in which the structure remains stable and capable of carrying the prescribed design loads even after the removal of a critical component. This condition indicates that the system possesses sufficient redundancy, continuity, and alternative load paths to prevent progressive collapse, in accordance with the robustness principles outlined by GSA (2013) and CNR-DT 214/2018. In this case, the residual live load capacity (%LL) equals or exceeds the reference service load, meaning that the loss of a single element does not compromise the bridge's global equilibrium or serviceability. Conversely, the value of $P(C | SL) = 0$ denotes a non-robust configuration, where the system cannot sustain equilibrium following the removal of a key load-bearing element. In this condition, the residual live load capacity tends to zero, implying that local damage propagates rapidly through the structural system, leading to disproportionate or global collapse. Such a result identifies structural schemes with insufficient redundancy or critical dependency on single elements, providing clear guidance during conceptual design to modify geometry, connectivity, or structural hierarchy to improve robustness. Intermediate values of $P(C | SL)$ between 0 and 1 describe partially robust configurations, where limited load redistribution is achieved, but the structure still exhibits some sensitivity to local failures. These cases are particularly informative in the conceptual phase, as they help identify critical regions or connections where redundancy can be enhanced to achieve an optimal balance between efficiency and robustness.

SL: susceptibility level term

In the proposed framework, the conditional probability term $P(SL | H)$, representing the likelihood that a given hazard H induces a local damage state SL , is reinterpreted as the Structural Susceptibility Level (SL). This parameter expresses the degree to which the structural system is locally protected or, conversely, susceptible to hazard-induced damage. The concept is derived from the probabilistic formulation introduced in the CNR-DT 214/2018, where the local failure state (stato limite locale) defines the transition between local damage and

global collapse. Here, the same logic is applied at the unifilar level of modelling, consistent with the conceptual design phase, where the structure is represented through simplified load-bearing lines and critical nodes rather than detailed sectional or material properties. The Structural Susceptibility Level (SL) is calculated as:

$$SL = 1 - \frac{N_{crit}}{N_{total}} \quad 6$$

Where:

- N_{crit} notes the number of elements identified as critical with respect to the hazard considered (i.e., those that may fail locally if the hazard occurs such as one or more pillars, beams, etc.
- N_{total} is the total number of primary load-bearing elements represented in the unifilar model.

A value of $SL = 1$ corresponds to a configuration in which no critical elements are present, indicating maximum local protection and minimal susceptibility, whereas $SL = 0$ indicates that all primary elements are critical, corresponding to maximum local susceptibility. Intermediate values capture partial exposure conditions and enable a comparative evaluation of conceptual configurations in terms of their inherent ability to confine damage locally. Within this framework, the Structural Susceptibility Level SL does not represent a measure of structural strength or classical mechanical redundancy, but a topology-based indicator of how widely a critical scenario may affect the primary load-bearing system. Higher values of the ratio N_{crit}/N_{total} indicate lower robustness and greater susceptibility to collapse, as a larger fraction of elements participates in the critical mechanism, whereas lower ratios correspond to configurations in which damage can be confined to a limited number of components. Expressing $P(SL | H)$ through the Structural Susceptibility Level provides a normalised and intuitive metric for evaluating how geometry, load-path distribution, and topological redundancy effects influence the local response of the structure to hazard effects. At the unifilar modelling level, this approach captures the essential topological characteristics governing susceptibility, such as the number and distribution of primary members, their exposure, and connectivity, without requiring detailed material or sectional properties. The relevance of the number and role of critical elements in governing collapse susceptibility is well established in the progressive collapse literature. Farahani et al.(2018) employed sensitivity analysis to identify critical structural elements and demonstrated that system vulnerability increases when a larger set of primary

members exhibits high sensitivity to local damage scenarios. Similar conclusions are drawn in recent contributions to the ASCE Journal of Structural Engineering (Fiorillo & Ghosn, 2022) where robustness against disproportionate collapse is shown to depend strongly on the number, location, and interaction of critical components rather than on the properties of isolated elements alone. Consistently, proportional formulations have been adopted in robustness and resilience studies, where system performance is expressed as the ratio between unaffected and total structural components (Fascetti et al., 2015) or as the fraction of vulnerable elements exposed to initiating events (Castaldo et al., 2020). The proposed definition is fully consistent with the probabilistic risk-based formulation of local limit states in CNR-DT 214/2018 and compatible with bridge vulnerability assessment frameworks developed by Frangopol & Liu (2007) and Casas et al. (2007).

H: hazard site specific risk scenarios term

In the probabilistic framework adopted for the Collapse Resilience Indicator, the term H represents the probability of occurrence of an initiating hazard event, that is, the likelihood that an external or internal action capable of triggering local or global damage occurs within the structure's reference period. This probability captures the initiating stage of the risk chain, integrating both environmental exposure and human-related uncertainties that may affect structural performance over time. In quantitative risk-based engineering, hazards are classified according to their origin and degree of controllability, resulting in three broad categories (American Society of Civil Engineers, 2022; Consiglio Nazionale delle Ricerche, 2018; International Organization for Standardization, 2015b)

- Category 1 – Natural or unintentional hazards.

This class includes natural phenomena and unintentional human-induced events, such as earthquakes, floods, landslides, extreme winds, explosions, or accidental fires. Their probability of occurrence is primarily site-specific, depending on local geography, environmental conditions, and regional hazard exposure. These probabilities can be quantified through probabilistic hazard maps, historical records, or return-period analyses.

- Category 2 – Intentional human actions.

This class includes deliberate events such as vandalism, sabotage, or terrorism. Unlike natural or accidental hazards, their probability is not tied to the physical site but to contextual factors, including accessibility, symbolic relevance, and

socio-political exposure. These hazards are often assessed through scenario-based approaches and security-informed probabilistic frameworks.

Category 3 – Process-related or systemic hazards.

This category covers failures arising from conceptual, design, or execution errors, including inadequate detailing, quality control deficiencies, or procedural inconsistencies. Although not random in a physical sense, they are treated as stochastic events within reliability theory, with probabilities associated with quality assurance and management processes.

This taxonomy allows the hazard probability term $P(H)$ to encompass both external physical phenomena and human or procedural factors.

However, within the scope of this study, focused on the conceptual design of pedestrian bridges, only Category 1 hazards, corresponding to natural and unintentional human-induced events, are considered determinant for comparative evaluation. These are the only hazard types whose probability meaningfully depends on site exposure and can therefore influence conceptual design choices. Category 2 hazards are acknowledged but excluded from formulation, as their occurrence is largely context-dependent and independent of design configuration, while Category 3 hazards are omitted since they reflect process quality rather than structural behaviour.

The probability term H is computed using the Poisson probabilistic model, which assumes that hazard events occur independently and at a constant mean rate over time. This model, widely adopted in reliability-based risk assessment (Cornell, 1968; Stewart, 2010; Vrouwenvelder, 2000; Woo, 2011), provides a rigorous yet practical way to express hazard probability from measurable frequency data or return periods. It enables comparability across hazard types and temporal consistency for different design lives, allowing diverse natural and accidental phenomena, such as seismic, hydrological, meteorological, and geotechnical hazards, to be represented on a unified probabilistic scale. The probability that at least one event occurs within the reference period T is given by:

$$H = 1 - \exp(-\lambda T) \quad 7$$

Where λ represents the mean annual frequency of occurrence of the hazard derived from statistical or observational datasets; for anthropogenic hazards, it represents a contextual average obtained from reference incident databases. In this framework, the computed H values quantitatively express the site-specific hazard exposure of each conceptual bridge configuration. Among the various hazard

scenarios potentially affecting pedestrian bridges, certain types are more frequent and widely recognised in the literature and design practice as critical for resilience-oriented assessment. These include both environmental and accidental sources of risk, which may act independently or in combination depending on site conditions and bridge typology. The most representative hazard scenarios considered in this study are:

1. Overpassing Roads – vehicle collision or impact from road traffic beneath the bridge
2. Overpassing Railways – collision, derailment, or dynamic loading induced by train transit.
3. River's crossing – hydraulic and hydrological actions such as flooding, debris flow, or scour phenomena.
4. Geological Risk Area – local instabilities such as landslides, rockfalls, or soil movements that may affect abutments or piers.
5. Fire Risk Area – accidental fire events related to nearby traffic or infrastructure services.
6. Explosion Risk Area – unintentional explosions originating from nearby industrial, transport, or pipeline activities.

These hazard types correspond to the most commonly recognized scenarios for bridge systems, as documented in international guidelines and recent research (American Society of Civil Engineers, 2016, 2016; Bangash & Bangash, 2006; European Committee for Standardization, 2006; Mazzolani, 2010; Stewart et al., 2006). Each of these categories is associated with a distinct occurrence frequency λ , reflecting both the nature of the hazard and the exposure of the bridge within its operational environment.

To be noted that seismic actions are not included in the present hazard framework. This exclusion is justified by two reasons. First, seismic design is mandatory for all footbridges under the applicable national regulations, meaning that seismic resistance does not depend on conceptual alternatives but is ensured by compliance with prescriptive seismic provisions. Second, seismic zonation maps operate on territorial grids significantly larger than individual project areas; therefore, for a single footbridge site, all conceptual solutions are subjected to the same seismic input. Since the objective of the framework is to compare alternative conceptual configurations for the same project, only hazards whose frequency and

exposure vary with geometry, siting, and functional context are considered relevant. Consequently, seismic action does not contribute to the differentiation between conceptual alternatives and is not treated in this robustness-oriented probabilistic screening.

The adopted λ values for these Category 1 hazards are summarised in the following tables, which report the representative annual frequencies selected for the comparative evaluation of structural resilience. For each hazard type, a dedicated subsection provides the rationale, data sources, and calculation procedure used to determine the corresponding λ value, ensuring methodological transparency and consistency within the overall probabilistic framework. The annual occurrence rates (λ) adopted in this framework represent a structured synthesis of multiple data sources, including European standards, technical reports, empirical datasets, and peer-reviewed literature. While some λ values are directly traceable to official databases or technical documents (Federal Highway Administration, 2024; International Union of Railways, 2015; Joint Research Centre, 2009) others are derived or adjusted from incident rate formulations and accident frequency models available in technical and scientific literature. In addition, for each hazard class, the associated critical structural elements are explicitly identified. These elements represent the most vulnerable or directly affected components under the corresponding hazard scenario and are therefore the ones removed or impaired in the robustness assessment linked to the term SL. Establishing this consistent linkage between hazard exposure and structural configuration ensures that the probabilistic representation of H remains physically meaningful and coherent within the broader resilience evaluation.

For instance, in the case of vehicle impact or train collision hazards, bridge piers or supports located within the potential collision zone are designated as critical elements; for hydrological or geological hazards, foundations and abutments exposed to erosion, scour, or ground instability are considered critical; while for seismic or explosion scenarios, primary load-carrying members such as decks or main girders are identified as the components most likely to experience initiating damage. In conceptual design, pedestrian bridges may be simultaneously exposed to more than one potential hazard scenario, for instance, a crossing located above both a roadway and a river may be subjected to vehicle impact and flood hazards. However, at this stage, the objective of the probabilistic evaluation is not to compute the cumulative probability of occurrence of all possible events, but rather to identify the dominant or most representative hazard condition influencing the design configuration. Accordingly, for each bridge context, only the hazards that

are physically plausible and relevant to the site conditions are considered active. Among these, the hazard associated with the highest or most representative probability of occurrence is selected as the reference condition for the comparative evaluation within the Collapse Resistance Indicator. This simplification aligns with the early-stage nature of conceptual design, where the available information is typically limited to general site data and contextual parameters, and where the focus lies on the relative resilience of alternative solutions rather than on absolute risk quantification. This “dominant hazard” approach ensures that the analysis remains consistent, transparent, and scalable, while avoiding the introduction of unnecessary uncertainty linked to the combination of poorly constrained probabilities. Consequently, the selected H for each design alternative reflects the most critical and credible hazard exposure for the specific bridge context, whether seismic, hydraulic, vehicular, or environmental, thus ensuring comparability across different conceptual configurations while maintaining methodological simplicity and physical coherence.

1-Overpassing Roads: vehicle collision or impact from road traffic beneath the bridge

For pedestrian bridges crossing over road infrastructure, the most relevant accidental hazard is the impact of road vehicles against structural elements, such as piers or columns located beneath or adjacent to the carriageway. This initiating event is explicitly addressed in major international standards such as EN 1991-1-7:2006, EN 1990:2023, and fib Bulletin 80 (2016), which identify accidental vehicle impact as one of the principal hazards for bridges overpassing roadways. The hazard term H represents the probability of occurrence of such an impact event over reference design life and is quantified through an annual frequency parameter λ , derived from accident statistics and probabilistic formulations found in the technical literature (JRC Report EUR 23964 EN, 2009; FHWA HIF-24-051, 2024; PIARC Technical Committee 1.3, 2015). To identify whether structural components are exposed to this hazard, a threshold distance of 6.0 meters from the edge of the traffic lane is adopted uniformly for all design cases considered in the framework (1a, 1b, and 1c). This value reflects a balanced and conservative assumption that encompasses a wide range of conditions, from fully protected structures to those lacking specific impact mitigation measures. While European standards such as EN 1991-1-7:2006 (§4.3.1) and fib Bulletin 80 (2016) define a conventional impact zone of 5.0 meters, several international guidelines suggest larger lateral influence areas. In particular, the AASHTO LRFD Bridge Design Specifications and the FHWA Roadside Design Guide (2020) recommend clear

zones extending up to 9.0 meters in the absence of barriers, especially on high-speed or high-volume roads. By adopting a uniform threshold of 6.0 meters, this study aims to balance regulatory compliance, practical generalization, and conceptual simplicity. The threshold ensures that critical structural elements potentially exposed to vehicular collision are consistently captured, regardless of the specific design condition, while maintaining the operational simplicity of a single-distance criterion within the framework. To formalise the hazard quantification, a classification table is developed that cross-references.

Design condition of the bridge structure:

- Case 1a – Designed for impact according to current regulations, with safety barriers and mitigation provisions.
- Case 1b – Designed for impact according to regulations, but without safety barriers or provisions.
- Case 1c – Not designed for impact, and lacking both safety features and regulatory compliance.

Road type, based on functional classification and traffic intensity:

- Highway
- Statal
- Urban
- Local

The assigned values of λ are derived from national and international accident databases and design references (JRC Report EUR 23964 EN, 2009; fib Bulletin 80, 2016; FHWA HIF-24-051, 2024). These values define the hazard exposure term H_{used} in the Collapse Resistance Indicator (RI), allowing a risk-informed comparison across different conceptual configurations.

2-Overpassing Railways: collision, derailment, or dynamic loading induced by train transit

For bridge configurations crossing over railway infrastructure, the most relevant accidental hazard scenario is the impact or derailment of trains against structural elements located in proximity to the tracks. This type of initiating event is formally recognized in several international and national standards as a credible

source of accidental action with potential to compromise structural stability (EN 1991-1-7:2006, §4.3.1 and Annex C; SIA 261/1:2014; NTC 2018). Within the present framework, the hazard term H quantifies the likelihood that such an event will occur within the reference design life of the structure and is expressed via an annual occurrence rate λ derived from statistical studies, operational databases, and probabilistic models of railway impact events (UIC 777-2, 2015; fib Bulletin 80, 2016; Stewart et al., 2006).

In analogy to the procedure adopted for road overpasses, the hazard level is differentiated by railway typology, considering High-Speed/High-Capacity, Conventional, Urban/Suburban, and Freight lines, and by the presence or absence of regulatory design provisions and protective measures. Specifically, the assessment distinguishes three conceptual cases:

- Case 2a – Designed for impact according to current regulation and equipped with safety barriers and mitigation provisions.
- Case 2b – Designed for impact according to current regulation but lacking safety barriers or mitigation provisions.
- Case 2c – Not designed for impact and lacking both safety features and regulatory compliance.

Each configuration reflects a different degree of vulnerability to impact scenarios, influencing both the frequency of hazard occurrence and the exposure of critical structural elements. In this framework, structural elements located within 6 meters from the edge of the nearest track are considered exposed to potential impact from train derailments or lateral deviations. This threshold is supported by multiple international studies and engineering guidelines that define the danger zone or vehicle deviation envelope based on derailment dynamics, train type, and infrastructure geometry. Notably, guidelines such as UIC Code 777-2, AREMA (USA), and Network Rail UK (NR/GN/CIV/025) establish that in high-risk contexts, such as freight corridors or high-speed rail, vehicles may travel laterally beyond the track alignment by several meters upon derailment. A 6-meter distance thus represents a conservative yet internationally relevant approximation of the lateral hazard corridor, capturing the residual dynamic path of derailed vehicles in most operational scenarios. This value allows for a clear binary classification of critical versus protected elements during the conceptual design stage and is consistent with accepted derailment risk envelopes used in railway bridge protection literature (e.g., Krauthammer, 2008; Liu et al., 2016; Stewart &

Netherton, 2010). Furthermore, it provides a practically scalable criterion applicable across different railway typologies, urban, conventional, or high-speed, without resorting to oversimplified assumptions or site-specific prescriptions. In this context, the 6-meter threshold ensures that resilience evaluations remain comparable across bridge typologies while acknowledging the probabilistic nature of train deviation hazards.

3- Rivers Crossing: hydraulic and hydrological actions such as flooding

For footbridges crossing rivers or streams, flooding represents a context-dependent accidental action that may induce loss of stability through scour, buoyancy forces, increased hydrodynamic pressure or impact from floating debris. These mechanisms are widely recognized in international standards as critical actions for structural components located within or adjacent to active watercourses (EN 1991-1-7:2006; EN 1991-1-4:2005; EN 1997-1:2004; ISO 21650:2007; fib Bulletin 80, 2016). Within the present framework, only those flood hazards that depend directly on the spatial position of piers or foundations relative to the riverbed are retained, consistent with the early-stage hazard screening principles of EN 1990:2023 (Annex C). Hydrological hazard is typically characterized through return periods (T_r) derived from regional flood-frequency analyses and hydraulic studies. These return periods represent the statistical frequency with which a given discharge or water level is exceeded and constitute the primary probabilistic descriptor of flooding in engineering practice. To maintain consistency with the probabilistic treatment adopted for other accidental actions, the annual exceedance probability associated with a flood event of return period T_r is defined as:

$$\lambda = \frac{1}{T_r} \quad 8$$

This relationship is routinely employed in hydraulic engineering and appears explicitly in international guidance for reliability-oriented geotechnical and hydraulic design (ISO 2394:2015; USACE Flood Risk Management Guidelines; FEMA Flood Hazard Mapping Program; CIRIA C753). Within the present framework, the λ values obtained from T_r serve as the hazard term $P(H)$, expressing the annual frequency with which a flood of given magnitude reaches the elevation of the structural element.

A distinction is made between alternatives that comply with flood-resistance design provisions (e.g., foundations placed outside the riverbed, piers elevated above design flood levels, scour-resistant detailing) and alternatives that do not

incorporate any adaptation to the local hydraulic regime. This distinction parallels the approach used for geological and fire hazards:

- Case 3a – when the alternative is designed according to flood provisions the hazard is represented by reduced residual frequencies, reflecting the lower likelihood that a flood event leads to structural failure.
- Case 3b – when the alternative is not designed according to flood provisions ($T_r = 200$ years for CC2 footbridges) full hazard frequencies as per equation 7 are adopted.

Residual frequencies are defined following ISO 2394 and JCSS recommendations on risk reduction through code-compliant mitigation, then, the effective annual occurrence rate is defined as:

$$\lambda_{residual} = r \cdot \lambda_{full} \quad 9$$

with $r=0.1$, corresponding to an order-of-magnitude reduction in the likelihood that an instability event leads to structural failure after mitigation.

In Table 5, the annual occurrence rates λ associated with flooding are derived from the return periods T_R conventionally used in hydraulic engineering to characterise design floods. These return periods do not originate from the present framework but are imported from national hydraulic standards, river-basin authorities and site-specific flood-frequency analyses, which typically prescribe design events in the range of 50–500 years depending on the importance class of the structure and on the characteristics of the watercourse.

4- Geological risk area: rapid and localized ground-failure mechanisms

At the conceptual design stage, only those geological hazards that are directly linked to the spatial location of the footbridge and to the geomorphological characteristics of the site are retained. This selection is consistent with the early-stage risk identification principles established in EN 1990:2023 (Annex C – Accidental and Robustness Design), EN 1997-1 (Geotechnical Design), ISO 2394:2015 and the screening methodologies adopted in the JCSS Probabilistic Model Code (2008). In line with these documents, the framework considers only rapid and localized ground-failure mechanisms that may lead to partial or total loss of structural support of abutments or piers, such as shallow and deep-seated landslides, rockfall, block detachment, sinkholes and local subsidence. Slowly developing geotechnical effects (e.g., uniform settlement, long-term consolidation) are not included, as they are addressed through ordinary geotechnical design and

do not represent accidental actions in the robustness sense. A crucial distinction must be made between:

- hazard exposure imposed by the site, which depends solely on the position of foundations with respect to geological hazard zonation.
- design response to that exposure, which varies between conceptual alternatives and must therefore be reflected in the comparative evaluation.

At the global scale, geological hazard maps adopt semi-probabilistic zonation methodologies that assign instability levels through a combined evaluation of historical event inventories, geomorphological susceptibility, triggering conditions and expert judgement. Despite regional differences, national and international guidelines (e.g., ISO 2394:2015; JCSS Probabilistic Model Code 2008; USGS Landslide Hazard Guidelines; Natural Hazard Partnership UK; Geoscience Australia; Canadian Geological Survey) converge on the use of three broad hazard categories, each associated with indicative return-period ranges used for risk screening and land-use planning. Across these systems, typical return periods are:

- E1: low hazard (Return period $T_r=300$ years),
- E2: medium hazard (Return period $T_r=100$ years),
- E3: high hazard (Return period $T_r=\text{years}$).

These full-hazard annual occurrence rates are assigned to:

- Case 4b – Not designed according to geological hazard maps, which refers to situations where foundations or abutments fall within a mapped hazard zone without specific adaptive measures or relocation. In this condition, the geomorphological hazard acts with its full frequency, as defined by the zonation.
- Case 4a – Designed according to geological hazard maps, which is when a conceptual alternative explicitly incorporates the information provided by geological hazard maps, for example by relocating the abutments outside the most unstable areas, selecting geotechnically stable ground, or adopting stabilisation measures. Here the probability that a mapped event results in structural loss of support is significantly reduced and the full hazard frequency associated with a given class is reduced by a residual factor according to equation. This yields residual frequencies for each hazard level (E1–E3), maintaining the probabilistic

logic of the framework while avoiding artificial suppression of low-probability events. As in the other hazard categories, critical elements for the assessment of SL are those structural components whose performance is directly affected by the hazard mechanism, namely abutments, foundations and piers.

5-Fire risk area: accidental fire events related to nearby traffic or industrial activities

At the conceptual design stage, only those fire-triggering hazards that are directly linked to the spatial configuration, siting, and functional context of the footbridge are retained. This selection is consistent with the principles of early-stage risk identification established in EN 1990:2023 (Annex C – Accidental and Robustness Design), EN 1991-1-2 (Fire Actions), EN 1991-1-7 (Accidental Actions), as well as with probabilistic screening methodologies recommended in ISO 2394:2015, the JCSS Probabilistic Model Code (2008), fib Bulletin 80 (2016), and FEMA 426 (2003). A crucial distinction must be made between impact-induced accidental events and fire-only accidental events. In the proposed framework, vehicle or train impacts (collision with deck, piers or supports) are already included and treated in a separate hazard category. Therefore, the present fire-related hazard class considers only ignition scenarios that occur in the absence of impact. This approach is fully aligned with the definition of independent accidental actions in EN 1991-1-2 (§2), which recognises that fire may arise without mechanical interaction, and avoids double counting of coupled hazards such as “collision + fire”. Within this definition, only the following fire-only hazards are retained because they depend directly on the relative position of the bridge with respect to surrounding infrastructure and can be identified through contextual information available at conceptual level, without requiring detailed thermal or structural modelling:

- Case 5a – EN 1991-1-2 explicitly recognises vehicle fires as accidental actions, and analogous principles apply to railway rolling stock as documented in fire-safety literature (BS 6853; UIC Guidelines; NFPA 130). Bridge-fire studies (Garlock et al., 2012; Wright et al., 2013) show that spontaneous ignition, caused by engine or brake overheating, electrical faults, fuel leaks or thermal runaway, may occur without any preceding collision. The annual occurrence rates $\lambda_{\sigma_a, \text{road}}$ and $\lambda_{\sigma_a, \text{rail}}$ are defined from published statistics on fire-only ignition events in road and railway traffic: road values derive from NFPA/NFIRS vehicle-fire datasets and international bridge-fire studies, whereas railway values are estimated from NFPA 130, UIC fire-safety guidance and NRC analyses of rolling-stock

fires. These λ values represent order-of-magnitude annual frequencies of spontaneous ignition without impact and are assigned separately for road and rail in accordance with their respective incident rates.

- Case 5b – Industrial-adjacent fires, arising from nearby facilities, fuel-storage areas or processing plants, are consistent with the accidental fire scenarios listed in EN 1991-1-2 and in the SEVESO III Directive (2012/18/EU). In the present framework, these ignition sources are grouped into three categories, pool fires, jet fires and electrical/utility fires, each characterised by distinct ignition mechanisms and thermal intensities, and associated with specific annual occurrence rates λ derived from international industrial fire-safety references (NFPA 30; NFPA 59A; API 521; SFPE Handbook; SEVESO technical guidance).

Although no Eurocode prescribes a single threshold distance for fire exposure, international fire-safety literature (Garlock et al., 2012; Wright et al., 2013; NFPA 130; UIC Guidelines) consistently indicates that structural elements can be thermally affected by open-air vehicle or train fires when located within approximately 5–8 m from the potential ignition source. Within this distance range, radiative heat fluxes typically exceed the 15–20 kW/m² threshold defined in EN 1991-1-2 for significant thermal action. A similar conclusion emerges from industrial fire-safety guidelines (NFPA 30; NFPA 59A; API 521; SFPE Handbook), which show that pool fires and jet fires generated in industrial facilities may produce comparable or higher heat fluxes, with critical thermal effects occurring within 5–8 m of the ignition source. Beyond this range, radiative heat transfer generally drops below the EN 1991-1-2 threshold for structural relevance. In the present framework, the fire-exposure zone is idealised as a sphere of radius 8 m centred on the potential ignition source. Any primary structural element of the footbridge whose centroid lies within this 8 m spherical domain is considered exposed to the fire-only hazard and can be selected as a critical element for the definition of SL. The same criterion is applied consistently to ignition sources associated with road traffic (carriageway level), railway traffic (top-of-rail level), and industrial facilities (e.g., fuel storage tanks, process equipment, utility installations).

6-Explosion risk area: accidental explosive events related to traffic or industrial activities

At the conceptual design stage, only those explosion-triggering hazards that are directly linked to the spatial configuration, siting, and functional context of the footbridge are retained. This approach follows the same early-stage risk-screening

principles adopted for fire hazards and is consistent with EN 1990:2023 (Annex C – Accidental and Robustness Design), EN 1991-1-7 (Accidental Actions), ISO 2394:2015, the JCSS Probabilistic Model Code (2008), and explosion-risk methodologies used in SEVESO III, NFPA 68/69, and API RP 752–754. As for fire-only scenarios, a crucial distinction must be introduced: impact-induced events are treated in a separate hazard class, and explosion hazards considered here correspond exclusively to non-contact explosion scenarios, where structural damage derives from pressure waves, blast-induced impulses, or high-rate dynamic effects without any direct mechanical impact (e.g., no collision preceding the blast). This avoids double counting of coupled events such as “collision + leakage + explosion”. Within this definition, explosion hazards are retained only if they can be identified through contextual, geometric, and functional information available at conceptual stage, without requiring detailed blast modelling. Two main families of scenarios are therefore considered:

- Case 6a – Traffic-related explosions (road or railway) corresponding to accidental blast events involving vehicles or railway rolling stock transporting flammable, explosive, or pressurised materials, in accordance with the hazardous-material classifications of ADR/RID. Typical mechanisms include BLEVE (Boiling Liquid Expanding Vapour Explosion), vapour cloud explosions (VCE) following delayed ignition of flammable vapours, fuel-tank explosions, and gas explosions in pressurised systems. The qualitative occurrence rates for road and rail are defined separately based on published statistics and international blast-safety literature (NFPA, PHMSA, ADR/RID datasets, UIC, NRC), reflecting the different frequencies of explosions associated with road and rail transport of hazardous materials.
- Case 6b – Industrial-adjacent explosions arising from nearby storage facilities, process plants, or pressurised systems, consistent with the accidental explosion scenarios addressed in EN 1991-1-7, the SEVESO III Directive (2012/18/EU), NFPA 68/69, and API RP 752–754. Following SEVESO and API classifications, industrial explosions are grouped into three conceptual families:
 - Vapour Cloud Explosions (VCE) from delayed ignition of flammable vapours.
 - Gas explosions / BLEVEs caused by catastrophic failure of pressurised gas vessels (LPG, LNG, hydrogen).

- Dust or utility explosions, typically associated with industrial equipment handling powders or electrical installations.

Each category is associated with distinct ignition mechanisms and blast-intensity profiles. The corresponding qualitative occurrence rates are assigned based on international industrial explosion-safety references (NFPA, API, TNO Yellow Book, SFPE Handbook). Although the propagation of explosion effects depends on fuel type, congestion and confinement conditions, early-stage blast-screening methodologies (EN 1991-1-7; SEVESO III; TNO *Yellow Book*; API RP 752) commonly rely on geometric stand-off distances to determine whether a structure may experience structurally relevant overpressures. Unconfined vapour cloud explosions (VCE) and BLEVEs may generate damaging overpressures ($> 5\text{--}10\text{ kPa}$) within approximately 10–20 m from the source in open-air conditions. Accordingly, within the proposed conceptual framework, the blast-exposure zone is idealised as a sphere of radius 15 m centred on the potential explosion source (carriageway, top-of-rail, industrial vessel or process unit). Any primary structural element whose centroid lies within this 15 m spherical blast domain is considered exposed to the explosion hazard and may be selected as the critical element for the definition of SL.

Table 5 summarizes frequency of occurrence of the hazards λ for each situation mentioned above.

Table 5 Summary of frequency of occurrence of the hazards λ is reported.

Scenario	Description	λ	Source Type	References
I	Overpassing Roads			
	Event: impact (distance $\leq 6\text{m}$)			
	Critical elements: pillars			
1a	Designed for impact according to current regulation and safety barriers and provisions			
1a1	Highway	0.000001	standard-based	EN 1991-1-7:2006; JRC EUR 23964 EN (2009)
1a2	Statal	0.000003	standard-based	
1a3	Urban	0.000010	standard-based	
1a4	Local	0.000030	standard-based	
1b	Designed for impact according to current regulation no safety barriers and no provisions			
1b1	Highway	0.000003	literature-estimate	EN 1990:2023 Annex C; JRC EUR 23964 EN (2009); FHWA HIF-24-051 (20Intable 24)
1b2	Statal	0.000010	literature-estimate	
1b3	Urban	0.000030	literature-estimate	
1b4	Local	0.000100	literature-estimate	
1c	Not designed for impact according to current regulation no safety barriers no provisions			
1c1	Highway	0.000100	empirical	FHWA HIF-24-051 (2024); PIARC (2015); fib Bulletin 80 (2016)
1c2	Statal	0.000300	empirical	
1c3	Urban	0.000500	empirical	
1c4	Local	0.001000	empirical	

2	Overpassing Railways			
	Event: impact (distance $\leq 6\text{m}$)			
	Critical elements: pillars			
2a	Designed for impact according to current regulation and safety barriers and provisions			
2a1	High-Speed/High-Capacity (HS/HC) (>200 km/h)	0.0000001	standard-based	UIC 777-2 (2015); fib Bulletin 80 (2016); Stewart et al. (2006)
2a2	Conventional lines(120–160km/h)	0.000001	standard-based	
2a3	Urban-Suburban (60–120km/h)	0.000002	standard-based	
2a4	Freight lines(<60km/h)	0.000003	standard-based	
2b	Designed for impact according to current regulation no safety barriers and no provisions			
2b1	High-Speed/High-Capacity (HS/HC) (>200 km/h)	0.0000015	literature-estimate	fib Bulletin 80 (2016); Liu et al. UIC 777-2 (2015); Liu et al.
2b2	Conventional lines(120–160km/h)	0.000003	literature-estimate	
2b3	Urban-Suburban (60–120km/h)	0.000005	assumed	
2b4	Freight lines(<60km/h)	0.001	assumed	
2c	Not designed for impact according to current regulation no safety barriers no provisions			
2c1	High-Speed/High-Capacity (HS/HC) (>200 km/h)	1.000000	empirical	fib Bulletin 80 (2016); AREMA Manual
2c2	Conventional lines(120–160km/h)	0.001998	empirical	
2c3	Urban-Suburban (60–120km/h)	0.004988	empirical	
2c4	Freight lines(<60km/h)	0.009950	empirical	
3	Rivers crossing			
	Event: flooding			
	Critical elements: pillars within the riverbed			
3a	Designed according to flooding norms			
3a1	Tr 50years event	0.002000	probabilistic-model	EN 1991-1-6; EN 1991-1-7; EN 1997-1; ISO 2394:2015; USACE Flood Risk Guidelines; FEMA Flood Hazard Mapping; CIRIA C753
3a2	Tr 100years event	0.001000	probabilistic-model	
3a3	Tr 200years event	0.000500	probabilistic-model	
3a4	Tr 500years event	0.000200	probabilistic-model	
3b	Not designed according to flooding norms			
3b1	Tr 50years event	0.020000	probabilistic-model	EN 1991-1-6; EN 1991-1-7; EN 1997-1; ISO 2394:2015; USACE Flood Risk Guidelines; FEMA Flood Hazard Mapping; CIRIA C753
3b2	Tr 100years event	0.010000	probabilistic-model	
3b3	Tr 200years event	0.005000	probabilistic-model	
3b4	Tr 500years event	0.002000	probabilistic-model	
4	Geological risk			
	Event: geological instability			
	Critical elements: pillars and foundations			
4a	Designed according to geological hazard maps			
4a1	E1 Tr 300 years	0.000333333	probabilistic-model	EN 1997-1; EN 1990:2023 Annex C; ISO 2394; national geological hazard maps
4a2	E2 Tr 100 years	0.001	probabilistic-model	
4a3	E3 Tr 30 years	0.003333333	probabilistic-model	
4b	Not designed according to geological hazard maps			
4b1	E1 Tr 300 years	0.003333333	probabilistic-model	EN 1997-1; EN 1990:2023 Annex C; ISO 2394; national geological hazard maps
4b2	E2 Tr 100 years	0.01	probabilistic-model	
4b3	E3 Tr 30 years	0.033333333	probabilistic-model	
5	Fire Risk Area			
	Event: accidental fire (distance $\leq 8\text{ m}$, spherical radius)			
	Critical elements: within 8 m spherical fire-exposure zone			
5a	Traffic			
5a1	Road	0.000010	literature-estimate	NFPA Vehicle Fires (Ahrens, 2020); NFIRS bridge/trestle fires; NCHRP 12-85 Guide; Kodur & Naser (2013); Khan et al. (2021)

5a2	Rail	0.000005	literature-estimate	NRC (2011) severe freight-train fire frequency; NFPA 130; UIC fire-safety guidance
5b	Industrial activities			
5b1	Pool fires	0.00001	literature-estimate	EN 1991-1-2; SEVESO III; NFPA 30; API 521; SFPE Handbook
5b2	Jet fires	0.000001	literature-estimate	SEVESO III; NFPA 59A; API 521; SFPE Industrial Fire Chapter
5b3	Electrical/utility fires	0.00005	empirical	NFPA 70B; IEEE transformer failure statistics; SFPE Handbook
6	Explosion Risk Area			
	Event: accidental explosion (distance ≤ 15 m, spherical radius)			
	Critical elements: within 15 m spherical explosion-exposure zone			
6a	Traffic			
6a1	Road	0.000001	literature-estimate	EN 1991-1-7; ADR/RID data; NFPA; PHMSA; TNO Yellow Book
6a2	Rail	0.0000005	literature-estimate	EN 1991-1-7; UIC hazmat statistics; NFPA 130; NRC railway incident analyses
6b	Industrial activities			
6b1	Pool fires	0.000010	literature-estimate	SEVESO III; API RP 752–754; TNO Yellow Book; SFPE Handbook
6b2	Jet fires	0.000001	literature-estimate	NFPA 59A; API 521; SEVESO III; SFPE Industrial Explosion Chapter
6b3	Electrical/utility fires	0.000050	empirical	NFPA 652/654; IEEE explosion statistics; SFPE Handbook

Single and multi-hazard approach

In the conceptual design phase, the selection of the dominant hazard is driven exclusively by the frequency of occurrence of potential initiating events, rather than by their structural or functional consequences. This choice reflects the level of information available at this early stage, where only the contextual exposure, defined by the bridge location, surrounding infrastructure, and environmental conditions, can be reliably assessed. Accordingly, hazards are not combined within the probabilistic formulation; instead, only the most frequent and site-relevant hazard is explicitly considered in the computation of the Collapse Resistance Indicator. This assumption is consistent with the principles of conceptual-level risk screening adopted in performance-based and resilience-oriented design frameworks (Baker et al., 2008; Frangopol & Soliman, 2016; JCSS, 2008; ISO 2394:2015), that recommend identifying a single governing accidental scenario for comparative assessment. Within this methodology, other low-frequency hazards are treated qualitatively as residual risks that may inform later stages of detailed design or operational planning, but do not contribute quantitatively to the early-stage resilience evaluation. This constitutes a single-hazard approach, in which only one dominant accidental scenario is analysed at a time. Such a simplification is considered appropriate for the conceptual design phase, where hazard interactions cannot yet be quantified, and the objective is to compare alternative structural configurations under the most probable initiating event.

Application example 1

In this study, the proposed method is applied to perform a comparative assessment among three conceptual design solutions for a pedestrian bridge crossing over an urban road. The objective is to evaluate the Collapse Resistance Indicator of alternative configurations subjected to the same dominant hazard scenario, represented by accidental vehicle impact. Although the three bridge configurations share the same material (steel), deck width, live loads, and imposed loads, they differ in both self-weight and geometric arrangement, which influence their respective exposure to the impact hazard. In the first configuration, all supporting elements are located beyond the 6 m safety clearance and therefore are not directly exposed to potential vehicle impact. In contrast, the second and third configurations include respectively one pier positioned within 6 m of the roadway edge and two piers, representing critical elements in the context of the Overpassing Roads hazard scenario. This variation in structural layout allows the probabilistic framework to capture how differences in geometry and exposure affect the overall collapse resistance of the system. The following static schemes illustrate the three configurations considered in the analysis.

Dominant scenario: Overpassing Roads/Urban 1a ($\lambda=10^{-5}$).

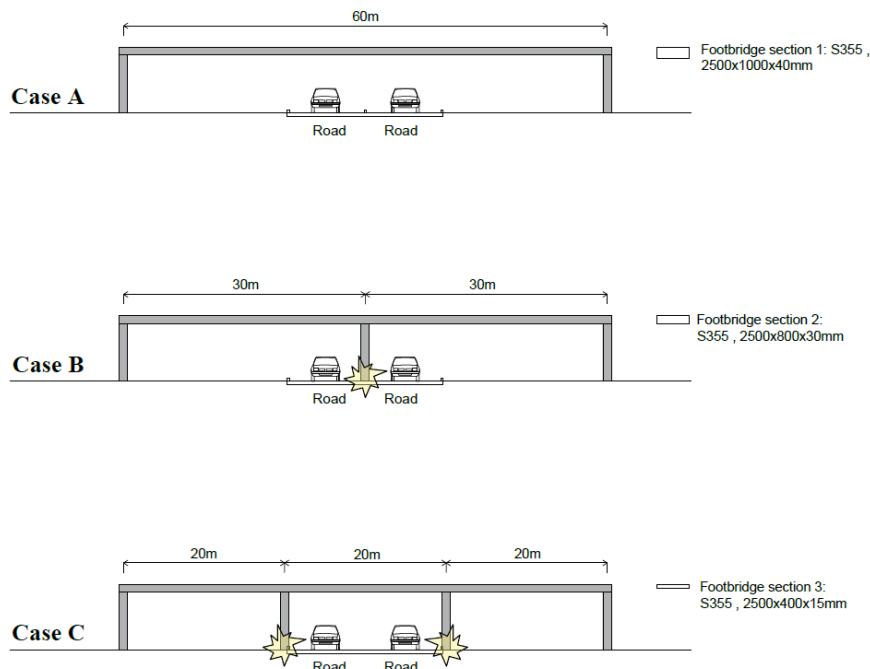


Figure 16 Application example 1: Schematic representation of the hazard identification and classification process adopted for assessment.

Table 6 Application example 1: collapse resistance indicator calculation

CASE A			CASE B			CASE C		
Element removal	0		Element removal	1 column		Element removal	2 columns	
qGSA	49.18	KN/m	qGSA	40.21	KN/m	qGSA	30.01	KN/m
MmaxGS A	30955.66	kNm	MmaxGS A	18095.62	kNm	MmaxGS A	13504.78	kNm
sigma	329.11	N/mm2	sigma	411.49	N/mm2	sigma	1309.94	N/mm2
%*LL	1.0000000	-	%*LL	0.3000000	-	%*LL	0.0000000	-
Ncrit	0.0000000	-	Ncrit	1.0000000	-	Ncrit	2.0000000	-
Ntot	3.0000000	-	Ntot	5.0000000	-	Ntot	7.0000000	-
R	1.0000000	-	R	0.3000000	-	R	0.0000000	-
H	1.0000000	-	H	0.9995001	-	H	0.9990005	-
SL	1.0000000	-	SL	0.8000000	-	SL	0.7142857	-
RI	1.000	-	RI	0.240	-	RI	0.000	-

Although, in principle, the probability of simultaneous impact by two vehicles differs from that of a single-vehicle collision, such combined events are characterized by extremely low occurrence frequencies. According to probabilistic accident models and statistical analyses reported in JRC Report EUR 23964 EN (2009) and fib Bulletin 80 (2016), the likelihood of two independent vehicles colliding with the same bridge element at the same time is several orders of magnitude smaller than that of a single impact event. For this reason, concurrent or multi-vehicle collisions are not explicitly considered in the present framework. The hazard term H is therefore defined based solely on the annual rate of single-vehicle impacts, which adequately represents the realistic exposure level for conceptual design purposes. Although the probabilistic framework formally treats each hazard scenario as independent, an implicit relationship may exist between the hazard exposure term H and the robustness term R . This relationship stems from the structural configuration itself: a bridge concept that demonstrates high robustness under one hazard type may prove more vulnerable under another. For instance, in Case A, where no vehicle impact risk is present, the structure is not exposed to the dominant accidental action but could be more sensitive to residual hazards such as fire or explosion. In such a case, the same geometric and static features that provide robustness against impact, such as the absence of substructure elements near the carriageway, could increase susceptibility to other types of localised damage. This interplay between hazard exposure and structural robustness, although not explicitly modelled in the present formulation, highlights the importance of

considering multiple hazard sensitivities when interpreting the comparative results. It also suggests that future developments of the proposed framework could extend the current single-hazard approach toward a multi-hazard resilience.

Application example 2

In this study, the proposed method is applied to perform a comparative assessment among three conceptual design solutions for a pedestrian bridge crossing over an urban road (case 1a statal) and railway (case 2b suburban). The objective is to evaluate the Collapse Resistance Indicator of alternative configurations subjected to the same dominant hazard scenario, represented by accidental train impact ($\max \lambda$):

- Urban road (case 1a statal) $\lambda = 0.00000300$
- Railway (case 2b suburban) $\lambda = 0.00000500$

Dominant scenario: Overpassing Railway (case 2b suburban) ($\lambda=10^{-5}$).

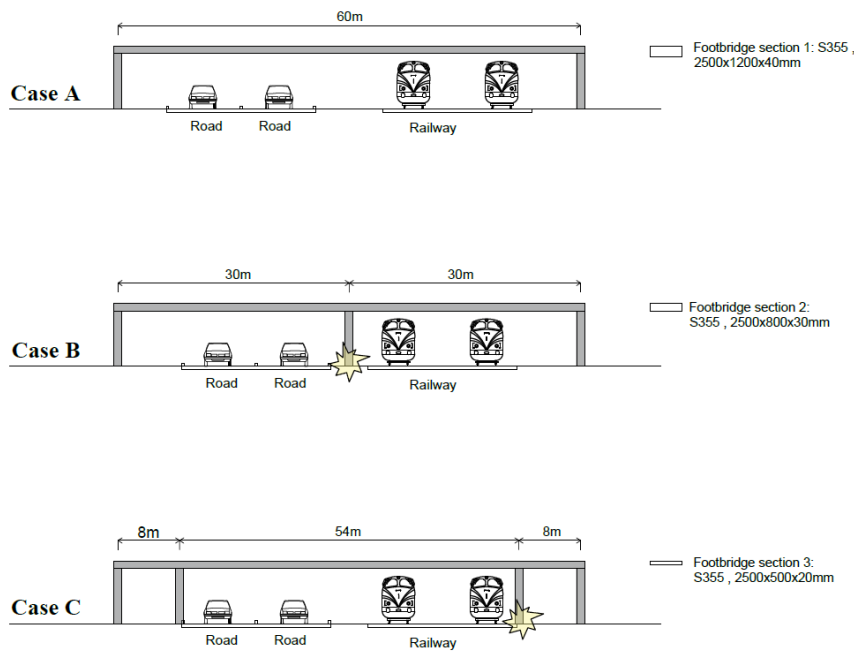


Figure 17 Application example 2: Schematic representation of the hazard identification and classification process adopted for assessment.

Table 7 Application example 2: collapse resistance indicator calculation

CASE A			CASE B			CASE C		
Element removal	0		Element removal	1 column		Element removal	1 column	
qGSA	49.18	KN/m	qGSA	40.21	KN/m	qGSA	33.05	KN/m
MmaxGS A	30955.66	kNm	MmaxGS A	18095.62	kNm	MmaxGS A	8031.95	kNm
sigma	329.11	N/mm ²	sigma	411.49	N/mm ²	sigma	461.32	N/mm ²
%*LL	1.0000000	-	%*LL	0.3000000	-	%*LL	0.1000000	-
Ncrit	0.0000000	-	Ncrit	1.0000000	-	Ncrit	1.0000000	-
Ntot	3.0000000	-	Ntot	3.0000000	-	Ntot	5.0000000	-
R	1.0000000	-	R	0.3000000	-	R	0.1000000	-
H	1.0000000	-	H	0.9995001	-	H	0.9995001	-
SL	1.0000000	-	SL	0.6666667	-	SL	0.8000000	-
RI	1.000	-	RI	0.200	-	RI	0.080	-

In the first configuration, all supporting elements are located beyond the 6 m safety clearance and therefore are not directly exposed to potential vehicle or train impact. In contrast, the second configuration include middle pier positioned within 6 m representing critical element. In third configuration two intermediate piers can be involved in vehicle and train impact. Considering that the approach is single hazard it is necessary to define dominant scenario according to the higher λ from Table 5.

Application example 3

In this study, the proposed method is applied to perform a comparative assessment among three conceptual design solutions for a pedestrian bridge near by Explosion Risk Area (electric utilities 6b) and crossing over an urban road (case 1a statal). The objective is to evaluate the Collapse Resistance Indicator of alternative configurations subjected to the same dominant hazard scenario, represented by electrical line explosion:

- Urban road (case 1a statal) $\lambda = 0.00000300$
- Explosion Risk Area (electric utilities 6b) $\lambda = 0.00005000$

Dominant scenario: Explosion Risk Area (electric utilities 6b) $\lambda = 0.000050$

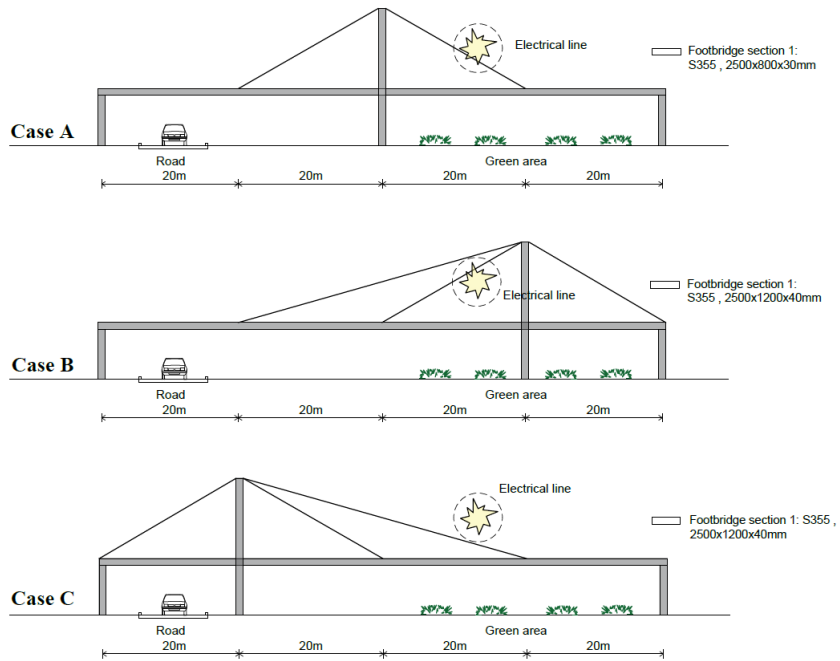


Figure 18 Application example 3: Schematic representation of the hazard identification and classification process adopted for assessment.

Table 8 Application example 3: collapse resistance indicator calculation

CASE A			CASE B			CASE C		
Element removal	1cable		Element removal	2cables+mid pillars		Element removal	0	
gas	27.53	KN/m	qGSA	24.23	KN/m	qGSA	31.73	KN/m
MmaxGSA	7312.76	kNm	MmaxGSA	77550.34	kNm	MmaxGSA	7711.48	kNm
sigma	350.29	N/mm ²	sigma	3714.81	N/mm ²	sigma	369.39	N/mm ²
%*LL	0.4400000	-	%*LL	0.0000000	-	%*LL	1.0000000	-
Ncrit	1.0000000	-	Ncrit	3.0000000	-	Ncrit	0.0000000	-
Ntot	3.0000000	-	Ntot	5.0000000	-	Ntot	5.0000000	-
R	0.4400000	-	R	0.0000000	-	R	1.0000000	-
H	0.9950125	-	H	0.9950125	-	H	0.9950125	-
SL	0.6666667	-	SL	0.4000000	-	SL	1.0000000	-
RI	0.292	-	RI	0.000	-	RI	0.995	-

2.3.2.2 Maintainability Indicator MI

Maintainability plays a crucial role in the long-term performance evaluation of civil infrastructure, particularly when assessing the feasibility and efficiency of ordinary (routine) maintenance activities throughout a structure's service life. Although these interventions are typically non-structural and scheduled, they are essential for preserving the functionality, safety, and usability of built assets over time. A substantial body of literature has addressed the estimation of maintenance needs during the design phase, with early approaches primarily focusing on design-dependent factors. In recent years, more integrated methodologies have emerged that combine construction costs with long-term maintenance projections, enabling designers to account for maintainability within a broader lifecycle perspective (Frangopol & Liu, 2007; Liu et al., 2022). These studies highlight the importance of evaluating design decisions not only in terms of initial investment but also in relation to the expected operational and maintenance costs over the service life of the structure. Contemporary structural codes and guidelines increasingly recognize maintenance planning as an integral part of structural design, to be addressed from the earliest stages of concept development. In line with this evolution, and within this research, the MI is therefore adopted as a conceptual-design indicator that complements, rather than substitutes, detailed LCC analyses, and is used primarily for the structured comparison of design alternatives in the early stages.

This metric draws directly from the ERIC framework (Eliminate, Reduce, Inform, Control) summarized in Figure 19 as advocated by institutions such as the Institution of Structural (Carpenter, 2010; Setola et al., 2017) and adapted to the conceptual design phase.

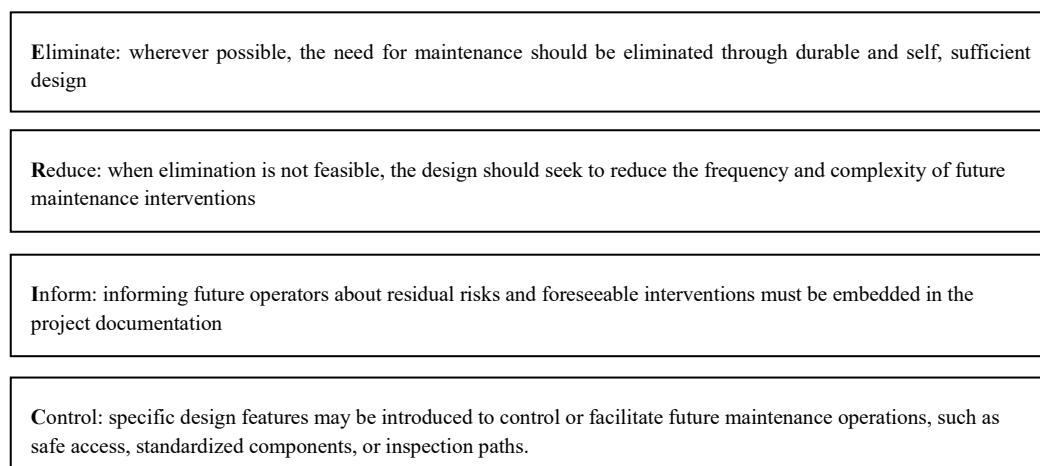


Figure 19 ERIC framework (Eliminate–Reduce–Inform–Control). Conceptual framework outlining hierarchical strategies to address maintenance requirements through design.

In this perspective, maintenance is not treated as an ex-post operational issue, but as a direct consequence of early design decisions, which can be evaluated through design-level parameters.

In the literature, the effect of maintenance on bridge design at the preliminary stage is typically assessed through simplified approaches, consistent with the limited level of information available during conceptual design. The objective is not to predict future maintenance actions in detail, but to enable a comparative evaluation of alternative design solutions.

A first approach is represented by preliminary Lifecycle Cost Analyses (LCCA), as promoted by organizations such as the Federal Highway Administration, where maintenance is modelled using standardized intervention scenarios, typical inspection intervals, and simplified deterioration assumptions. These methods support early decision-making by capturing the long-term implications of design choices without requiring detailed operational data (Federal Highway Administration, 2019).

A second line of research refers to service life planning frameworks, particularly those developed within ISO 15686-7 (2017b) in which maintainability is linked to design-related attributes such as accessibility, durability of materials, protection strategies, and ease of replacement. In this context, maintenance performance is evaluated through qualitative or semi-quantitative criteria rather than detailed cost modelling.

A further approach makes use of maintainability indicators or scoring systems, in which salient design attributes are operationalized into normalized indices. Such metrics facilitate the structured comparison of conceptual alternatives within multi-criteria decision-making frameworks, while rendering maintenance-related effects explicit and analytically traceable (Frangopol & Liu, 2007).

In parallel, contributions in conceptual and sustainability-oriented structural design emphasize that maintainability is largely a direct outcome of the structural concept itself. In this perspective, clarity of the load-bearing system, reduction of unnecessary complexity, prefabrication, and reversibility inherently limit long-term maintenance demand, providing the conceptual foundation upon which indicator-based assessments can be constructed (Billington, 1983). Taken together, these approaches suggest that maintainability can be both generated by conceptual

structural choices and evaluated through simplified indicators, particularly in the preliminary design phase. While full lifecycle cost models provide detailed estimations of future maintenance expenditures, they require extensive input-data and modelling effort, which are generally not available or justified at the conceptual design stage. Conversely, purely qualitative or conceptual approaches, although valuable in defining design principles, do not allow a direct quantification of maintenance implications.

Estimating maintenance costs at this point in the process is inherently challenging, due to limited data availability and the disproportionate effort required for accurate long-term forecasting. To address this limitation, maintenance costs are estimated through a parametric model in which they are expressed as a proportion of the IC and modulated by design-related maintainability factors. Rather than assuming a fixed percentage, the model defines the maintenance ratio as a function of both structural characteristics and the extent to which maintenance-oriented strategies are embedded in the design. On this basis, the Maintainability Indicator is defined as follows:

$$MI = \frac{L}{\alpha IC} \quad 10$$

Where:

- L is the expended life
- MI refers to the projected cost of ordinary maintenance over the service life L in years.
- coefficient α is a corrective factor derived from the ERIC framework defined as:

$$\alpha = \alpha_0 \cdot f_{ERIC} \quad 11$$

In the specific context of footbridges, the framework is applied to assess long-term maintainability and durability of structures through the following principles:

- Eliminate the need for maintenance by design choices (e.g., using integral bridges that avoid bearings and joints),
- Reduce future maintenance by selecting long, life materials and simplifying access (e.g., galvanized components, permanent access fixtures),
- Inform stakeholders by providing clear documentation, digital records, and accessible inspection information,

- Control residual risks via features such as maintenance galleries, inspection hatches, and remote monitoring systems.

Each project is evaluated against these ERIC principles using a weighted scoring system, resulting in a dimensionless corrective factor $f_{ERIC} \in [0,1]$, which modifies the baseline maintenance ratio α_0 specific to the structural typology, material and operational complexity. This enables the integration of preventive design strategies and contextual parameters (e.g., exposure class, accessibility, inspection feasibility) directly into the estimation of long-term maintenance burdens. The application of ERIC within structural engineering is further supported by design guidance such as *Designing for maintenance* (The Institution of Structural Engineers, 2026) which illustrates how safety, maintainability, and lifecycle cost considerations can be embedded from the early stages of design through systematic adherence to these principles.

The baseline maintenance ratio α_0 were derived through the combined analysis of (i) a set of real bridge case studies and (ii) relevant standards, guidelines, and lifecycle cost literature. In particular, the coefficient $\alpha_{0,b}$ was computed from a dataset of real pedestrian and cycle bridges (Table 9), realized across diverse geographic, climatic, and operational contexts. The data used in the analysis was obtained from technical reports, municipal documentation, asset-management records, and peer-reviewed publications. In some cases, explicit annual maintenance costs were not directly reported; in such situations, values were reconstructed through proxy estimation based on documented budget ranges, inspection and maintenance cycles, or typological analogies contained in the same sources. Across the dataset, the resulting ratios consistently fall within 0.3–0.8% of the initial construction cost, a range that is coherent with indicative maintenance-expenditure ratios reported in bridge asset-management literature and lifecycle cost guidelines for pedestrian and small- to medium-span bridges (*Bridge Preservation Guide: Maintaining a State of Good Repair Using Cost-Effective Investment Strategies*, 2011; *ISO 15686-5:2023*, Comité technique 4.3 - Ponts routiers & Technical Committee 4.3 - Road Bridges, 2016).

On this basis, α_0 is adopted as a deterministic baseline proxy, obtained from the synthesis of the case-study evidence and the indicative reference ranges reported in standards and guidelines. No explicit statistical modelling of variability is implemented, since the indicator is conceived for conceptual-design applications. For each combination of structural scheme and main structural material, the reference α_0 values to be used in the Maintainability Indicator are reported in Table

10. To be noted that, the adoption of α_0 as a deterministic baseline proxy implies that context-specific variability is not explicitly modelled. This simplification is considered consistent with the limited level of information available at the conceptual design stage, where the objective is comparative rather than predictive accuracy.

Table 9: Bridge dataset for baseline maintenance ratio definition

#	Footbridge	Structural Scheme	Main structural Material	Annual Maintenance α_{0b} (% of IC)	Reference/Definition Method
1	Okinawa Road Park Bridge – Okinawa, Japan	Continuous Beam	FRP	0.12	Third International Conference on FRP Composites in Civil Engineering (CICE 2006) December 13-15 2006, Miami, Florida, USA A Case Study of Life Cycle Cost based on a Real FRP Bridge
2	Okinawa Road Park Bridge – Okinawa, Japan	Single Beam	PC	0.22	Third International Conference on FRP Composites in Civil Engineering (CICE 2006) December 13-15 2006, Miami, Florida, USA A Case Study of Life Cycle Cost based on a Real FRP Bridge
3	Vilafant Footbridge – Catalonia, Spain –	Continuous beam	FRP + Steel	0.4	SCI / Steel Construction Institute – PDF “ <i>Bridges Built with Advanced Materials</i> ”
4	Peace Bridge – Calgary, Canada	Tubular Truss	Steel	0.7	City of Calgary, Bridge Maint. Summary (2019)
5	Passerelle Simone-de-Beauvoir – Paris, France	Arch / Continuous	Steel	0.5	Ville de Paris Report (2015)/ AFGC – “ <i>Passerelle Simone de Beauvoir à Paris</i> ” “ <i>Maintenance et vie de l’ouvrage</i> ”
6	Ponte della Musica – Rome, Italy	Arch	Steel	0.6	ANAS Technical Note (2018)
7	Te Rewa Rewa Bridge – New Plymouth, NZ	Arch	Steel	0.5	NZTA Bridge Inspection Manual (2013) NPDC (New Plymouth District Council) – “Te Rewa Rewa Bridge repaint” e “Coastal queen gets a face-lift”:
8	Sundial Bridge – Redding, USA – 2004	Cable-Stayed	Steel	0.5	City of Redding Infrastructure Report (2019)
9	Henderson Waves Bridge – Singapore –	Continuous beam	Steel + Timber	0.8	BCA Singapore (2018) <i>Ingenia</i> – “ <i>Walking on Waves</i> ”
10	Scale Lane Footbridge – Hull, England –	Swing / Curved Girder	Steel	0.7	Hull City Council (2017)
11	Streicker Bridge – Princeton Univ., USA –	Cable / Multi-Span	Steel + Concrete	0.6	Glisic & Adriaenssens, “ <i>Streicker Bridge: Initial evaluation of lifecycle cost benefits of various structural health monitoring approaches</i> ” (IABMAS 2010)
12	Skellefteå, Sweden	Simple beam	Timber	0.17	CHALMERS Civil and Environmental Engineering, Master’s Thesis 2015:148
13	Ludvika, Sweden	Truss	Steel	0.18	CHALMERS Civil and Environmental Engineering, Master’s Thesis 2015:148
14	Millennium Bridge – London, UK – 2000	Suspended	Stell	0.6	City of London 2025 Report

15	Road Bridge over the Averser Rhine near Innerferrera	Arch	Timber	0.6	(Gerold, 2006)
16	Crestawald Bridge to the Military Depot at Sufers (Switzerland)	Arch	Timber	0.6	(Gerold, 2006)
17	Gjemnessund Bridge – Norway – 1992	Cable-Stayed	Steel	0.4	Gjemnessund, <i>last main inspection 2015, basic inspections.</i>

Table 10 Maintenance ratio based on structural scheme and material

Structural Scheme/Material	α_0 (%)
Tubular Truss Galvanized/ Painted Steel	0.55
Simple Beam Galvanized/ Painted Steel	0.45
Continuous Beam Galvanized/ Painted Steel	0.50
Suspended Galvanized/ Painted Steel	0.60
Arch Galvanized/ Painted Steel	0.50
Truss Galvanized/ Painted Steel	0.55
Simple Beam Frp	0.35
Continuous Beam Frp	0.40
Simple Beam Reinforced Concrete	0.45
Continuous Beam / Box Reinforced Concrete	0.50
Slab Reinforced Concrete	0.40
Arch Reinforced Concrete	0.45
Simple Beam Timber/Protected	0.55
Arch Timber/Protected	0.55
Truss Timber/Protected	0.60
Tubular Truss Galvanized/ Painted Steel	0.55
Simple Beam Galvanized/ Painted Steel	0.45
Continuous Beam Galvanized/ Painted Steel	0.50
Suspended Galvanized/ Painted Steel	0.60
Arch Galvanized/ Painted Steel	0.50

As stated in equation 11 α value is finally obtained by applying the ERIC framework, based correction factor f_{ERIC} defined through a fully quantitative formulation based on measurable design attributes. Rather than relying on qualitative judgment, the proposed model assigns a numerical score to each of the four ERIC principles, Eliminate, Reduce, Inform, and Control, using proxy variables extracted directly from project, level data. At this stage, only the ERIC

components Eliminate (E) and Reduce (R) are included in the computation of f_{ERIC} . The Inform and Control components are instead treated separately, as they are more closely related to inspection planning and operational accessibility, and their separation helps to preserve analytical clarity.

Accordingly, the simplified correction factor is expressed as:

$$f_{ERIC} = 0.5 \cdot E + 0.5 \cdot R \quad 12$$

where:

- E (Eliminate) quantifies the extent to which maintenance-intensive elements (e.g., joints, bearings) have been avoided through design solutions such as integral bridges or monolithic connections. It is computed as:

$$E = \frac{1}{\eta_{joints} + \eta_{bearings}} \quad 13$$

Where η_{joints} denote the number of joints, and $\eta_{bearings}$ the number of bearings.

- R (Reduce) reflects the adoption of long-life materials (e.g., painted or galvanized steel, FRP) and design features and strategies that simplify or reduce future maintenance requirements.

$$R = \frac{1}{4} (D_{deck} + D_{joint} + D_{bearings} + D_{substructure}) \quad 14$$

The durability coefficients (D) assigned in Table 11 are based on simplified proxy ratings derived from published literature and observed material behaviour under typical service conditions. Instead of explicitly modelling complex deterioration mechanisms, each material was attributed a normalized durability score on a scale from 0 to 1, representing its inherent resistance to ageing, corrosion, and environmental degradation, as well as its long-term performance reliability. This proxy-based approach provides a practical yet evidence-informed quantification of durability across different bridge components, namely, deck/main structural elements, joints, and bearings, and allows for direct comparison between material typologies during the conceptual design stage. The assigned scores were determined through engineering judgment consistent with published studies mentioned in Table 11, considering parameters such as corrosion resistance, chemical stability, expected service life, and maintenance frequency. Within the Reduce component, durability scores are aggregated into a component-level index by combining the scores of the relevant structural subsystems (deck/main load-bearing elements, joints, bearings) through a weighted linear

formulation, where weights reflect their relative contribution to long-term maintenance demand.

Table 11: Durability scores

Component	Durability Score (D)	Condition of validity	Primary Reference
Main structure FRP composite	0.9	typical bridge exposure; corrosion-free material	(Casas & Frangopol, 2017; Saraf, 2020)
Main structure Prestressed concrete	0.75	standard durability design & adequate cover	(fib Bulletin 34 — Model Code for Service Life Design, 2006)
Main structure Reinforced concrete	0.65	conventional RC bridges with standard protection	(Bridge Maintenance Manual, 2019; <i>Eurocode 2: Design of Concrete Structures — Part 2: Concrete Bridges — Design and Detailing Rules</i> , 2019; <i>ISO 15686-7:2017 — Service Life Planning — Part 7: Performance Evaluation for Feedback of Service Life Data from Practice</i> , 2017)
Main structure Galvanized / painted steel	0.85	coating system compliant with ISO 12944	(<i>ISO 12944 — Corrosion Protection of Steel Structures by Protective Paint Systems</i> , 2018; Kim & Nejad, 2018)
Main structure Stainless steel	0.85	non-aggressive atmospheric exposure	(Bridge Maintenance Manual, 2019; <i>Eurocode 3: Design of Steel Structures — Part 1-4: Stainless Steel</i> , 2015)
Main structure Weathering (corten) steel — favourable conditions	0.8	well-drained, ventilated, non-marine exposure; stable patina formation	(Assessment and Maintenance of Existing Structures, 2019; Steel Bridge Maintenance: A Guide for Owners and Practitioners, 2013)
Main structure Weathering (corten) steel — aggressive environment	0.5	marine / de-icing salts / moisture retention / poor drainage	(Assessment and Maintenance of Existing Structures, 2019; Steel Bridge Maintenance: A Guide for Owners and Practitioners, 2013)
Main structure Structural timber (glulam / LVL) — protected design	0.7	structural timber elements with protective detailing, roof/overhangs, controlled moisture exposure	(<i>ISO 15686-7:2017 — Service Life Planning — Part 7: Performance Evaluation for Feedback of Service Life Data from Practice</i> , 2017; Simon et al., 2023)
Structural timber — exposed / high-moisture risk	0.4	outdoor exposure without continuous protection; higher moisture cycling and biological degradation risk	(<i>ISO 15686-7:2017 — Service Life Planning — Part 7: Performance Evaluation for Feedback of Service Life Data from Practice</i> , 2017; Simon et al., 2023)
Bearings Neoprene	0.7	typical service conditions and periodic inspection	(<i>AASHTO LRFD Bridge Design Specifications (9th ed.)</i> , 2020; Bridge Preservation Guide: Maintaining a State of Good Repair Using Cost-

			Effective Investment Strategies, 2011)
Bearings Galvanized / painted steel plates	0.85	compliant coating + routine maintenance	(Bridge Maintenance Manual, 2019; Kim & Nejad, 2018)
Bearings Bituminous / asphaltic	0.6	aging- and temperature-sensitive behaviour	(Bridge Maintenance Manual, 2019; <i>ISO 15686-7:2017 — Service Life Planning — Part 7: Performance Evaluation for Feedback of Service Life Data from Practice</i> , 2017)
Bearings Stainless steel	0.95	corrosion-resistant material in standard exposure	(Assessment and Maintenance of Existing Structures, 2019; <i>Eurocode 3: Design of Steel Structures — Part 1-4: Stainless Steel</i> , 2015)
Bolted joints	0.8	proper detailing, sealing and corrosion protection	(Assessment and Maintenance of Existing Structures, 2019; Hobbacher, 2016)
Welded joints	0.6	higher fatigue & corrosion sensitivity	(Assessment and Maintenance of Existing Structures, 2019; Hobbacher, 2016)

The values reported in the column Condition of validity, specify the environmental and design assumptions under which the assigned durability score is considered representative. Outside these conditions, the expected durability performance may differ significantly, and the score should therefore be interpreted with caution or adapted accordingly.

2.3.2.3 Inspectability Indicator II

Following the assessment of maintainability, which primarily focuses on the reduction and simplification of future maintenance needs, the concept of inspectability emerges as a complementary yet distinct dimension of long-term structural performance. While both dimensions contribute to lifecycle efficiency and structural resilience, inspectability specifically addresses the feasibility and operational burden of conducting technical inspections over time, with a focus on access, monitoring, and procedural complexity.

Over the past years, various methods have been developed to evaluate the inspectability of infrastructures, particularly bridges. Some of these originate from other engineering disciplines, such as mechanical and industrial design (Stolt, 2017; Weisheng, 2021), and have inspired inspection, focused assessment tools. Notable examples include the quality control checklist in the NYSDOT Bridge Inspection Manual (Agrawal et al., 2021; NYSDOT, 2017), and the discussions presented at the Designing Bridges for Inspectability conference (Alampalli & Yannotti, 2023) and in the ASCE Technical Note by Mahamid et al. (2019). However, most of these frameworks assume the presence of an established inspection plan or as, built documentation, which is typically unavailable in early design phases. Furthermore,

they are often qualitative and intended for use in the operational or post, construction phases.

To address this limitation, this study introduces a numerical Inspectability Indicator (II) tailored to the conceptual design stage, where design choices can significantly shape long-term inspection feasibility even before formal protocols are defined. The indicator is formulated as:

$$II = IE \cdot D \quad 15$$

where:

- IE is the percentage of inspectable components or instrumented, monitored elements on the total number of components defined as:

$$IE = \frac{N_{\text{insp}}}{N_{\text{tot}}} \quad 16$$

N_{tot} = total number of components considered relevant for inspection at conceptual design stage as primary structural elements, joints, and bearings.

N_{insp} = number of those components for which the design ensures inspectability, i.e. clear physical access (walkways, galleries, inspection points) or integration of monitoring systems (sensors, embedded instrumentation). Thus, IE ranges from 0 (no components inspectable) to 1 (all components fully inspectable).

- D is the Inspection Difficulty Factor, which quantifies the complexity of performing structural inspections, based on structural layout, access conditions, and technical requirements.

Importantly, while the Maintainability Indicator (MI) already integrates the Eliminate and Reduce components of the ERIC framework, the Inspectability Indicator builds upon the remaining two: Inform and Control. These refer respectively to the clarity and availability of inspection, related documentation, and to the integration of permanent access systems, monitoring sensors, or other features facilitating future inspections. Although not explicitly modelled in the base formula, these ERIC, derived principles are indirectly reflected in both the IE and D components. Higher IE values typically result from design provisions aligned with Control, such as embedded sensors or dedicated access routes.

The sub- components of D (described below) incorporate aspects of Inform, such as the need for specialized tools or undocumented procedures. Unlike traditional qualitative scales, the proposed method allows the Inspection Difficulty Factor (D) to be computed parametrically, based on project, specific values for time disruption and technical complexity. This enables case, by, case customization and ensures consistency across design alternatives, without relying on predefined ordinal tables. The D factor is computed as the arithmetic mean of two sub-scores:

$$D = \frac{D_1 + D_2}{2} \quad 17$$

- D_1 : Functional Disruption. It quantifies the extent to which inspection activities interfere with the normal operation of the bridge, calculated as:

$$D_1 = 1 - \frac{T_{\text{impact}}}{T_{\text{inspection}}} \quad 18$$

Where:

T_{impact} = time during which traffic or bridge operations are negatively affected,

$T_{\text{inspection}}$ = total duration of the inspection campaign.

This ratio captures the operational sensitivity of the bridge to inspection interventions. A lower T_{impact} results in higher D_1 values, reflecting better integration of inspection activities into routine functionality.

The inspection time is modelled at component level, focusing exclusively on the primary load-bearing structure. The footbridge is decomposed into a limited set of structural element classes (deck, main load-bearing members, supports, bearings and structural terminations), and the total in-field inspection time is expressed as:

$$T_{\text{inspection}} = \sum_e T_e \quad 19$$

where T_e denotes the inspection time associated with structural element class e . For each class, T_e is defined as the sum of the durations of the inspection tasks carried out on that element, i.e. $T_e = \sum_{j \in e} \Delta t_j$. Non-structural components such as parapets, railings and ancillary elements are excluded from this definition, as the focus is on the main load-bearing system. For the application to this study, the inspection time of each structural element class e is expressed as:

$$T_e = r_e Q_e, \quad 20$$

where Q_e is the relevant physical quantity (e.g. deck area, member length, number of supports, bearings or joints) and r_e is a reference unit inspection time (expressed in inspector-hours per unit). This formulation is consistent with the component-based logic adopted in bridge-inspection and bridge-management practice, where inspection activities are organised and recorded at the level of structural elements rather than whole structures (FHWA, 2012; Highways England CS 450; AASHTO, 2022). The use of unit inspection times r_e follows the same rationale as productivity-based estimation models widely employed in maintenance and asset management, where operational effort is expressed through unit rates linked to measurable asset quantities (ISO 55000:2014; ISO 13306:2017; Amekudzi-Kennedy & Meyer, 2011). Although specific unit times are not prescribed by codes, they are introduced here as indicative reference values that can be refined or calibrated against recorded inspection data, as commonly done in bridge management systems and inspection planning studies (Frangopol et al., 2004; Neves & Frangopol, 2005; Agrawal et al., 2010). The adopted values (Table 12) have been selected such that the resulting total inspection times for small- to medium-span footbridges fall within the typical range reported for routine visual inspections carried out by two-person teams, which in practice corresponds to approximately 2–3 hours of field time depending on accessibility and structural complexity (FHWA BIRM; EN 13406-series guidance on inspection planning; PIARC, 2019).

Table 12 Reference unit inspection times for primary structural elements, with interpretation

Element	Reference unit inspection time T_e	Comments
Deck slabs [h/m ²]	0.008	About 0.5 min per m ² per inspector. Includes continuous visual scanning of the structural deck/soffit, short stops for observation and documentation. One inspector can typically cover ~120 m ² /h.
Main load-bearing members (girders, arches, trusses, cables, etc.) [h/m]	0.02	About 1.2 min per metre per inspector. Represents systematic observation of main members along their length, focusing on connections, stress-concentration areas and defects visible from accessible viewpoints.
Supports (piers and abutments, including visible parts of foundations) [h/n]	0.25	About 15 min per support per inspector. Includes walking around the support, inspecting faces and interfaces, checking drainage, photographing and recording observations.
Bearings and structural connections [h/n]	0.08	About 5 min per bearing per inspector. Assumes bearings are visually accessible; includes short positioning time, visual check for corrosion/misalignment/debris, and documentation.
Expansion joints / structural terminations (where present) [h/n]	0.12	About 7 min per joint per inspector. Covers observation of sealing continuity, debris accumulation, surface deterioration at the joint interface, and photographic recording.

Two distinct impact measures are considered: (i) the impact on the bridge $T_{\text{impact},B}$, corresponding to the loss of service for pedestrians and cyclists on the deck, and (ii) the impact below the bridge $T_{\text{impact},S}$, corresponding to the loss of service for the underlying systems (such as a road, railway or public space). The concept of impact time does not appear as an explicit quantity in existing inspection standards; however, it is directly consistent with the way availability, downtime and operational interference are treated in asset-management and maintenance standards (ISO 55000:2014; ISO 13306:2017). Bridge-inspection guidelines (FHWA BIRM; Highways England CS 450; AASHTO MBE) explicitly require the assessment and management of traffic or service restrictions during inspections, even if they do not provide a quantitative metric. In this work, $T_{\text{impact},B}$ and $T_{\text{impact},S}$ are introduced as a quantitative formalisation of this concept, expressing the portion of the inspection time during which the bridge or the underlying infrastructure is partially or fully unavailable to users.

$$T_{\text{impact},B} = I_{\text{bridge}} \cdot T_{\text{inspection}} \quad 21$$

$$T_{\text{impact},S} = I_{\text{below}} \cdot T_{\text{inspection}} \quad 22$$

where I_{bridge} and I_{below} are dimensionless impact factors in the range 0–1, representing the proportion of the inspection time during which the service is partially or fully unavailable on the bridge or on the underlying system, respectively. The qualitative interpretation is straightforward:

- $I = 0$ corresponds to no interference.
- $I = 0.5$ to partial interference for approximately half of the inspection time
- $I = 1$ to full closure for almost the entire inspection

Since the two impact times are proportional to $T_{\text{inspection}}$, the corresponding dimensionless indicators coincide with the impact factors themselves, i.e. $\rho_{\text{bridge}} = I_{\text{bridge}}$ and $\rho_{\text{below}} = I_{\text{below}}$, which provide a concise and comparable measure of inspection intrusiveness in conceptual-design evaluations.

- D₂: Technical Complexity

The sub, factor D₂ measures the technical complexity associated with conducting structural inspections, reflecting the level of effort, specialization, and procedural burden required during routine monitoring operations. While D₁ captures the

external functional impact, D_2 is an internal complexity index that anticipates inspection, related challenges arising from design, specific conditions.

To enable structured and replicable evaluation already during conceptual design, D_2 is defined as the arithmetic mean of three normalised sub-indicators:

$$D_2 = \frac{1}{3}(D_{eq} + D_{ex} + D_{pr}) \quad 23$$

Where:

- D_{eq} – Equipment Intensity: Measures the extent to which non, standard equipment is required for inspection (e.g., special platforms, drones, or lifting devices).
- D_{ex} – Specialized Skill Requirement: Evaluates whether standard inspection teams can operate, or whether specialized operators (e.g., rope access technicians, confined space personnel) are needed.
- D_{pr} – Process Complexity: evaluates the complexity of inspection sequences, including the need for multi, phase operations, risk containment, or safety isolations.

Each component is rated on a structured scale from 0.25 (high complexity) to 1.0 (optimal simplicity), depending on specific project attributes. These values are not arbitrarily chosen, but grounded in established methodological principles as described in the following- Normative consistency: The discrete values (1.0, 0.75, 0.5, 0.25) are aligned with rating systems used in international standards such as ISO 13822:2010 Annex B, CEEQUAL, Envision, and BREEAM, which employ ordinal scales converted into normalized numerical values to support design, phase performance evaluation.

Fuzzy logic and engineering judgment: The approach is inspired by rule-based reasoning and fuzzy logic principles, commonly applied in early, stage engineering evaluations to handle uncertainty and partial knowledge. This allows expert, based qualitative assessments to be translated into quantitative scores usable in multi criteria decision tools like MCDA or AHP. Academic precedent: Several frameworks in the fields of structural resilience and maintainability (e.g., [Zio & Pedroni, 2013], [Norouzi & Ghasemi, 2025]) explicitly adopt normalized discrete scales in their robustness, risk, or inspection metrics. These studies validate the applicability of such scoring methods where data scarcity and conceptual abstraction are present. By grounding the D_2 sub, score system in recognized standards and academic methods, the model ensures that even early, stage design

decisions are supported by replicable, comparative, and technically justifiable indicators, bridging qualitative design reasoning with structured numerical modelling. Table 13 summarizes mentioned scores.

Table 13: Inspection Technical Complexity Sub-Indicators

Sub, Factor	Score = 1.0 (Optimal)	0.75 (Acceptable)	0.5 (Complex)	0.25 (Critical)
Deq	Standard tools only (visual, manual)	Minor additional tools (e.g., ladders, handheld sensors)	Requires powered access (e.g., lifting platform, drone)	Specialized equipment (e.g., underbridge unit, barge, confined, space tools)
Dex	General inspection staff	Technicians with basic structural knowledge	Certified personnel (e.g., rope, access, welding inspector)	Special licenses or multi, disciplinary team (e.g., diver + NDT + rope access)
Dpr	Single, step inspection, easily repeatable	Two, step, minimal setup or coordination	Multi, phase or dependent on timing/coordination (e.g., night access)	High, risk, complex sequencing (e.g., requires temporary removal of barriers)

2.3.3 Environment performance

In recent years, various methodologies have been developed to evaluate the sustainability of buildings, focusing on identifying critical and specific indicators for these structures. These methodologies typically consider indicators such as energy efficiency, material sustainability, and lifecycle impact assessment. Several methods are currently being developed for infrastructure assessment, with potential extensions to specific cases involving cycle footbridges.

For instance, Milani et al. (2020a) provide a comprehensive framework for assessing the sustainability of urban footbridges, focusing on energy and material efficiency. Tres Junior et al. (2023) evaluate the sustainable performance of cycle footbridges in urban areas, highlighting the importance of integrating environmental and social criteria. Hendrawan et al. (2022) discuss methods and indicators for sustainable infrastructure design, emphasizing the need for adaptable and resilient structures.

In this study, the proposed indicators were identified by drawing on the aforementioned methods and frameworks, selecting three aspects that can be objectively and quantitatively defined during the preliminary phase (Figure 20). These indicators are intended to be manageable by a design team without requiring specialized expertise or disproportionate design effort for their definition.

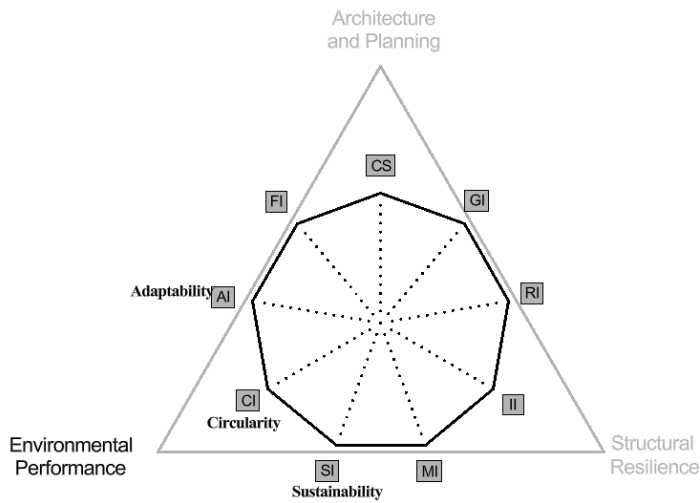


Figure 20 Tripartite structure for environmental performance macro theme.

2.3.3.1 Sustainability Indicator (SI)

The analysed systems in chapter 1 and resumed in Table 14 provide a comprehensive overview of approaches for assessing infrastructure sustainability. While these methods are effective for certifying projects in advanced stages or post, completion, infrastructure sustainability is primarily shaped by decisions made during the planning and early design phases. Bragança et al. (2019) highlighted that early design choices significantly influence life cycle impacts and costs, a concept later extended to infrastructure projects by Gupta et al. (2016)

This finding aligns with research by Shahtaheri et al. (2018), which emphasizes that environmental, economic, and social aspects of infrastructure are often overlooked in early design phases, potentially compromising overall sustainability performance. To achieve sustainability goals, it is crucial to develop methods that support informed decision making during conceptual design.

Among the various indicators considered in the reviewed SIRSs, only those meeting the following essential criteria were selected: (i) quantifiable in the conceptual design phase, (ii) directly comparable across projects, (iii) repeatable to ensure consistency, (iv) relevant to sustainability objectives, (v) easily integrable into decision-making processes, and (vi) intuitively understandable by stakeholders. As projects progress, sustainability indicators become more reliable due to their link to quantifiable metrics. However, in the preliminary phase, many SIRS indicators remain qualitative and subjective, despite their significant

influence on overall sustainability. Ugwu et al. (2006) demonstrate how key performance indicators (KPIs) tailored to infrastructure projects, including bridges, enhance sustainability assessment at early design stages. Similarly, Ashraf et al. (2012) propose a framework for infrastructure sustainability assessment that integrates environmental, economic, and social aspects, reinforcing the importance of well-defined quantitative indicators in decision making. The study addresses the existing gap by identifying indicators that can be quantified and objectively assessed in the conceptual design phase.

These indicators are based on mathematical calculations, validated databases, and sector benchmarks included in certification systems. While specific project details may influence indicator selection, prioritizing numerical evaluation enhances reliability.

Bueno et al. (2015) reviewed existing tools for transport infrastructure sustainability assessment, highlighting the necessity of the early, stage integration of life cycle methodologies such as LCA, LCC, and S, LCA. Additionally, recent studies on sustainability and infrastructure assessment frameworks highlight how decisions taken during the early stages of design can significantly influence long-term infrastructure performance.

Table 14 Sustainable Infrastructure Rating Systems comparison

SIRSs	Greenroads	Infrastructure Sustainability (IS)	Envision	INVEST	SuRe (FAST Infra)	BREEAM Infrastructure	SNBS Infrastructure
Data							
Year of launch	2010	2012	2012	2010	2015 (2024)	2004 (2022)	2020
Version	v.3 2020	v. 2.1 (2021)	v.3 2018	v.1.3 2018	v.2 2021	v.6 2019 (2022)	v.1 2020
Institution	Greenroads International	Institute Sustainability Council of Australia	Institute of Sustainable Infrastructure (ISI)	Federal Highway Administration (FHWA)	Global Infrastructure Basel (GIB)	Building Research Establishment (BRE)	Sustainable Construction Network Switzerland (NNBS)
Geography	U.S.	Australia, N.Z.	U.S.	U.S.	Switzerland	U.K.	Switzerland
Applicable to	Roads and highways Bicycle paths Bridges	Roads and highways Bridges	Roads Ports Bridges and footbridges	Roads and highways Multimodal transportation	Urban infrastructure (footbridges) Water systems	Bridges and footbridges Tunnels Water networks	Roads Railways

	Footbridges Road tunnels	Footbridges Ports Tunnels Water infrastructure Renewable energy (e.g., wind, solar)	Water infrastructure Treatment plants Renewable energy Public buildings Green urban spaces	projects (including bridges, footbridges, tunnels, and railways)	Energy Transport networks (roads, bridges) Sustainable urban and rural projects	Sewer systems Energy grids Urban regeneration projects Green infrastructure	Bridges and footbridges Tunnels Water networks Energy Communication, protection, mobility infrastructure Public buildings and services
Applicable Project phases (UNI 16310)	Preliminary design Detailed design Construction	Planning Preliminary design Detailed design Construction Operation	Planning Preliminary design Detailed design Construction Operation	Planning Preliminary design Detailed design Construction Operation	Planning Preliminary design Detailed design Construction Operation Decommissioning	Planning Preliminary design Detailed design Construction Operation Decommissioning	Planning Preliminary design Detailed design Construction Operation
Total Indicators	62	64	60	64	61	248	75
Categories	Project requirements Environment and water Construction activities Materials and design Utilities and controls Access and livability Creativity and effort *	Governance Economic performance Resource use Environmental impact Workforce and community Innovation	Quality of life Leadership Resource allocation Natural world climate and resilience	System planning Project development Operations and maintenance *	Environment Society Governance	Management Resilience Communities and stakeholders Land use and ecology Landscape and historic environments Pollution Resources Transport	Environment Economy Society
Approach	LCA suggested LCC suggested	LCA mandatory LCC mandatory	LCA mandatory LCC mandatory	LCA suggested LCC suggested	LCA mandatory LCC mandatory	LCA mandatory LCC suggested	LCA mandatory LCC mandatory

	S-LCA not explicitly included	S-LCA suggested	S-LCA suggested	S-LCA not explicitly included	S-LCA mandatory	S-LCA not explicitly included	S-LCA suggested
Principal databases and sector benchmarks	Ecoinvent US LCI Database AASHTO Pavement Design PSILCA SHDB	Australian Material AusLCI Ecoinvent PSILCA	Ecoinvent US LCI Database ELCD SHDB	US EPA LCA Benchmarks FHWA Sustainability Guidelines AASHTO Material Databases	UNEP Environmental Data OECD Benchmarks Ecoinvent IFC Performance Metrics PSILCA SHDB	Ecoinvent DEFRA Biodiversity Net Gain ICE Database ILCD PSILCA SHDB	Swiss KBOB Database Ecoinvent Swiss Federal LCA Database PSILCA SHDB

* INVEST is organized in categories according to project phases. These categories are made of 64 indicators concerning environmental, cost, and social aspects.

Table 15 summarizes the selected quantitative indicators applicable in the conceptual design of footbridges, where “1” indicates inclusion in the rating system and “0” indicates exclusion. Each indicator is classified under one of the three LCSA pillars: environmental, economic, or social.

Table 15 Sustainability quantitative indicators

SIRSs Indicators	LSCA Category	Greenroads	Infrastructure Sustainability (IS)	Envision	INVEST	SuRe (FAST Infra)	BREEAM Infrastructure	SNBS Infrastructure
Global Potential Warming (CO ₂ -eq)	Environment	0	1	1	1	1	1	1
Energy Consumption (kWh)	Environment	0	1	1	1	1	1	1
Recycled Materials % (Percentage of total)	Environment	0	1	1	0	1	1	1
Waste Management	Environment	0	1	1	0	1	1	1

(kg or tons)								
Water Use (m ³)	Environment	0	1	1	0	1	1	1
Construction Costs (USD)	Economic	0	1	1	1	1	1	1
Operational Costs (USD)	Economic	0	1	1	1	1	1	1
Sustainable Transport Use % (Percentage of trips)	Social	0	1	1	1	1	1	1
Land Use Efficiency	Social	0	1	1	0	1	1	1
Biodiversity Impact (m ²)	Social	0	1	1	0	1	1	1
Economics Opportunities (n.jobs)	Social	0	1	1	0	1	1	1

Mentioned analysis shows that key indicators include Global Warming Potential (GWP) and Energy Consumption (EC) from LCA, Construction Costs (CCs) and Operational Costs (OCs) from LCC, and Sustainable Transport Use (STU) from S, LCA. The reliability of these estimates varies, with LCA being the most standardized due to its extensive databases and well, established methodologies. LCC, while valuable, is less suitable for early, stage analysis due to the frequent unavailability of detailed financial data for operational and dismantling stages [66]. Similarly, the evaluation of social sustainability through S, LCA remains underdeveloped, as challenges in defining, interpreting, and quantifying social impacts limit its applicability. Sierra et al. [67] highlighted that S, LCA often overlaps with LCC and LCA, showing, for example, that in assessing Sustainable Transport Use (STU), economic, environmental, and social dimensions are deeply interconnected. Given the current lack of standardization and comprehensive assessment frameworks, the authors note that social indicators remain less relevant in the conceptual design phase compared to environmental and economic indicators and consider STU as part of LCC and LCA. As S, LCA continues to evolve, its integration into early, stage infrastructure evaluation will require further methodological advancements. In the present study, rather than introducing an explicit and separate Social Life Cycle Assessment (S, LCA), social considerations are implicitly addressed through the first three architectural and planning, related

indicators introduced in the framework. These include design choices that influence accessibility, urban integration, and user experience, factors which are known to have substantial social impact yet are more effectively evaluated through qualitative and spatial parameters at early design stages. This integrative approach ensures that the most salient social aspects are still captured without requiring the implementation of a formalized S, LCA model, which remains underdeveloped for conceptual infrastructure design. Therefore, rather than implementing a full Life Cycle Assessment (LCA), which is often impractical at the conceptual design stage due to complexity and data intensity, this study proposes a simplified methodology based on two measurable indicators:

1. Global Warming Potential (GWP) – covering environmental performance.
2. Total Cost (TC) – reflecting economic sustainability over the entire service life.

These two indicators are computed over four main project phases, planning and design, construction, operation, and decommissioning, and then normalized by the infrastructure's area and expected service life, as shown in equations below.

$$GI = \frac{\sum GWP_i}{A \cdot L} \left[\frac{\text{kgCO}_2\text{-eq}}{\text{m}^2\text{y}} \right] \quad 24$$

$$TC = \frac{\sum C_i}{A \cdot L} \left[\frac{\$}{\text{m}^2\text{y}} \right] \quad 25$$

Where:

- GWP_i denotes the estimated CO₂-equivalent emissions for each life cycle phase (A1–C4) associated with the structural elements. The results are case-specific and reflect the adopted LCA datasets, as well as regional production conditions and applicable regulatory frameworks.
- C_i denotes the life cycle costs associated with the structural elements. The results are case-specific and reflect the adopted cost data and regional market conditions.
- A is the total deck area.
- L is the structure's service life in years.

To synthesize environmental and economic aspects into a unified metric without relying on external benchmarks, this study proposes a weighted combination of the Global Warming Indicator (GI) and Total Cost (TC), both

expressed on per-square-meter and per-year basis. The Sustainability Indicator (SI) is calculated using a weighted geometric mean of specific environmental impact and specific cost, allowing criteria with different units to be combined meaningfully without prior conversion, while preserving proportional influence according to the chosen weights.

$$SI = 1 / [\left(\frac{\sum GWP_i}{A \cdot L} \right)^{w_{en}} \cdot \left(\frac{\sum C_i}{A \cdot L} \right)^{w_{ec}}] \quad 26$$

Where w_{en} and w_{ec} are weighing factors such as $w_{en} + w_{ec} = 1$, reflecting the relative importance assigned to environmental and economic performance and calibrated based on project priorities or stakeholder preferences. In this work three weighting scenarios were defined based on international guidelines such as ISO 14040:2006: Scenario A (70% Costs / 30% Environment) reflects traditional procurement practices; Scenario B (60% / 40%) is consistent with the European Union Green Public Procurement recommendations (Directive 2014/24/EU, 2014) which suggest that environmental criteria should account for at least 30–40% of the evaluation; Scenario C (50% / 50%) aligns with ISO 14044:2006 principles on value choices and with current international strategies towards climate neutrality, where economic and environmental performance are considered equally relevant.

Unlike benchmark-based indicators, this formulation is initially expressed in physical units and normalized with respect to area and service life, preserving transparency and enabling direct comparison across project alternatives of different scale and lifespan. It also allows the designer to transparently explore trade-offs between emissions and cost at the conceptual stage. It is important to note that, in the proposed formulation, no external benchmark values are deliberately introduced. This choice stems from the intent to maintain the method as broadly applicable and adaptable, especially in early design phases where predefined reference values may not be contextually relevant or available. The Sustainability Indicator (SI) is thus conceived as a relative decision-making tool, where its utility lies in the consistent comparison between design alternatives developed under the same assumptions and units. Although SI is subsequently transformed onto the common 1–6 evaluation scale adopted for aggregation within the Global Quality Indicator (GQI), its formulation remains grounded in physically meaningful quantities, thereby preserving the transparency and interpretability of the underlying environmental assessment. However, the structure of the model readily allows for the future integration of benchmark or target values, should the project context or stakeholder requirements demand so. In such cases, SI can be normalized or scaled against reference thresholds (e.g., from national standards, sustainability

rating systems, or historical data), thereby extending its interpretive power for certification or policy alignment.

2.3.3.2 Circularity Indicator CI

While frameworks such as Level(s) , EU Sustainable Buildings Framework (2017) 2.2 Construction and demolition waste and SIRS promote circular economy principles, including durability, adaptability, and material recovery, they do not provide a direct, numerical indicator of circularity potential that can be applied at the conceptual design stage. To address this gap, a Circularity Indicator (CI) is proposed in this study. It allows for a preliminary, yet meaningful quantification of circular design strategies based on material choices and end, of, life potential. The equation is the following:

$$CI = RM + RU + RC \quad 27$$

Where:

- RM (Recycled Materials) is the percentage of recycled materials used during construction, defined as:

$$RM = \frac{\sum m_i \cdot RM_i}{\sum m_i} \quad 28$$

- RU (Reusability) is the percentage of structural components that can be reused at the end of the structure's service life:

$$RU = \frac{\sum m_i \cdot RU_i}{\sum m_i} \quad 29$$

- RC (Recyclability) is the percentage of materials that can be recycled after deconstruction.

$$RC = \frac{\sum m_i \cdot RC_i}{\sum m_i} \quad 30$$

Each component is expressed as mass-based percentage, consistently with EN 15804+A2, KBOB 2022 and Ecoinvent databases. Although different materials exhibit different densities, the mass-based formulation ensures that the indicator reflects actual material flows and end-of-life potentials, avoiding distortions related to component count or geometric volume. This approach is conceptually based on the Material Circularity Indicator (MCI) developed by the Ellen MacArthur Foundation, while simplifying its application for early, phase infrastructure design. Similarly, the Circularity Calculator developed at Delft University of Technology

(Saidani et al., 2024) provides early, stage tools to estimate circularity potential based on recycled content, reusability, and recyclability, validating the methodological basis of the CI proposed here. In addition, recent academic works highlights the need for harmonized practical circularity indicators that can be applied in early design to guide strategic choices. Similarly, structured tools such as the National Circularity Assessment Framework for Buildings, developed under the European Circular Economy Platform, show how mass, based metrics and modular material scoring systems can support circularity benchmarking in early, stage design. To be noted that if RM can be easily estimated by the design team, RU and RC are more articulated and context dependant, for this reason those values are based on internationally recognized life cycle assessment databases and standards, namely Ecoinvent 3.8, the Swiss KBOB 2022 recommendations, and the European standard EN 15804+A2. Reusability and Recyclability percentage according to material type are resumed in Table 16.

Table 16: Reusability and Recyclability percentage according to materials

Material	RU – Reusability (% mass)	RC – Recyclability (% mass)	Main Sources
Structural steel (rolled sections, S355J0)	10% (welded) – 30% (bolted/modular)	90–95%	EN 15804+A2; KBOB 2022; Ecoinvent 3.8
Reinforced concrete (in situ, with formwork)	~0%	20–30%	EN 15804+A2; KBOB 2022; Ecoinvent 3.8
Precast concrete (standard elements)	5–10% (if demountable panels)	30–40% (better quality aggregates)	EN 15804+A2; KBOB 2022; Ecoinvent 3.8
Prestressed concrete (prefabricated)	5–10% (limited reuse)	30–40%	EN 15804+A2; KBOB 2022; Ecoinvent 3.8
Fiber, reinforced concrete (FRC)	0%	25–35% (as granular material)	Ecoinvent 3.8; recent FRC studies
Cross Laminated Timber (CLT)	30–50%	60–70%	EN 15804+A2; KBOB 2022; Ecoinvent 3.8
Glue, laminated timber (Glulam)	40–60% (beams/arches can be reused)	60–75%	EN 15804+A2; KBOB 2022; Ecoinvent 3.8
Suspension cables (high, strength steel)	20–30% (if accessible and removable)	95–98% (steel wires recycling)	Ecoinvent 3.8; EN 15804+A2 (steel cables)
Bearings / composite parts	0–10%	50–70%	Ecoinvent 3.8; secondary literature

2.3.3.3 Adaptability Indicator AI

The Adaptability Indicator (AI) is designed to evaluate the renovation potential and future flexibility of construction systems, with relevance to long-term functionality and resilience in changing contexts. The AI builds upon the

framework proposed in Level(s) Indicator 2.3 for adaptability and renovation (Dodd et al., 2017), offering a dimensionless score that reflects how well a structure can accommodate future transformations in use, capacity, or technology. Notably, the AI is formulated to avoid redundancy with other indicators included in this evaluation framework, specifically those addressing architectural and planning quality, and structural robustness. While those indicators already incorporate economic, spatial, and resilience, related considerations, the AI focuses exclusively on adaptive capacity over time, providing a complementary perspective that supports integrated and future, oriented design decisions.

The methodology integrates principles and criteria from several established SIRS, and relevant standards such ISO 20887(2020). In this study, the AI is computed using a binary checklist approach, where each adaptability dimension is evaluated as either present (1) or absent (0). The indicator is then expressed as the ratio of fulfilled criteria over the total number of criteria considered. The checklist includes the six key dimensions:

- Functional Flexibility (FF) – The ability of the structure to support different or evolving functions, such as converting a pedestrian bridge into a light, vehicle crossing.
- Expandability & Modularity (EM) – The potential for extending, enlarging, or reconfiguring the structure without major interventions, often through modular or prefabricated components.
- Reconfigurability (RC) – The capacity to adapt spatial configurations or components non, invasively, such as implementing temporary or removable elements.
- Integration Potential (IP) – The ability to seamlessly connect future systems or installations (e.g., mobility infrastructure, energy systems)
- Technology Readiness (TR) – The potential to integrate advanced technologies such as smart sensors, IoT systems, or adaptive lighting.
- Climate Responsiveness (CC) – The inherent adaptability of the system to evolving climate conditions, including temperature variations, flooding, or heat resilience. The final Adaptability Indicator is calculated as:

$$AI = N_s/N_t \quad 31$$

Where N_s is the number of satisfied criteria and N_t is the total number of criteria considered (typically 6). The resulting score ranges from 0 (no adaptability) to 1

(yes adaptability), providing a clear, non, redundant metric for comparing structural solutions based on their long-term adaptability and functional resilience.

The adoption of a binary checklist structure for the Adaptability Indicator represents a deliberate methodological choice. Unlike structural performance parameters, adaptability is difficult to quantify objectively during conceptual design because it depends on future scenarios, functional changes, technological developments, and user requirements that are often uncertain or unknown at the time of assessment. Furthermore, many adaptability-related criteria are commonly evaluated through qualitative judgement or expert interpretation, potentially reducing transparency and repeatability. For this reason, the proposed approach transforms the principal dimensions of adaptability into explicit and verifiable design checkpoints. The objective is not to quantify the degree of adaptability with high precision, but rather to ensure that the fundamental conditions enabling future transformation are systematically considered during the conceptual phase. In this sense, the indicator should be interpreted both as an assessment tool and as a design-oriented checklist supporting awareness and decision-making during early-stage design.

2.4 Step 3: comparative assessment

In Figure 21 the common criteria and indicators exposed in previous sections are summarised.

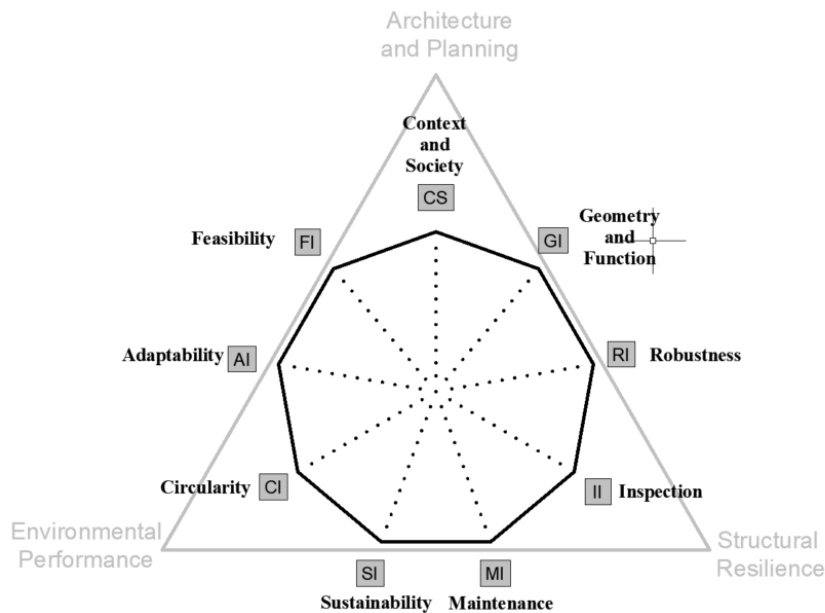


Figure 21: Proposed framework indicators.

To allow comparability, all indicators are normalised on a common 1–6 scale, with 1 representing the least desirable and 6 the most desirable value. This is achieved via a linear min–max transformation applied to each indicator. The choice of a discrete 1–6 range balances resolution and usability: it enables more nuanced distinctions than simpler ordinal scales (e.g., 1–3), while avoiding the false precision of continuous or overly wide scales (e.g., 0–10). This approach supports early-stage evaluations, where input data are often qualitative or estimated. Importantly, since the Weighted Sum Model (WSM) is invariant under linear transformations, the selected numerical range does not influence the final ranking outcome but improves clarity and consistency in the scoring process. In this way, the min–max scaling method is applied, and, for each indicator x , the minimum ($x_{\min}$) and maximum ($x_{\max}$) values observed in the comparison are identified, and then each value is transformed as:

$$\begin{cases} N(x) = 1 + 5 \cdot \frac{(x-x_{\min})}{(x_{\max}-x_{\min})} & x_{\min} \neq x_{\max} \end{cases} \quad 32$$

Where $N(x)$ is the normalized value on the 1–6 scale.

In the case where all alternatives achieve the same value for a given indicator ($x_{\min} = x_{\max}$), the indicator does not contribute to the discrimination process. For analytically derived indicators (e.g., RI, II, MI), the numerical values do not possess an intrinsic absolute meaning and are only interpretable in relative terms across the set of alternatives. For this reason, min–max normalisation is applied whenever variability exists; conversely, when all values coincide ($x_{\min} = x_{\max}$), a neutral score of 3.5 is assigned to all alternatives, reflecting the fact that no performance difference can be established. By contrast, for checklist-based indicators (e.g., FI, CS, GI), the raw score expresses a proportion of fulfilled requirements and thus carries an intrinsic absolute meaning. In this case, when all alternatives reach the same score, a proportional mapping is applied through:

$$N(x) = 1 + 5x \quad 33$$

preserving the level of fulfilment without introducing artificial relative differences.

To follow, the Global Quality Indicator GQI is defined as the sum of each indicator's normalized value:

$$GQI = FI + CS + GI + RI + II + MI + SI + CI + AI \quad 34$$

Yielding a range from 9 to 54, with each component defined earlier. The initial assessment uses equal weights for all indicators; project alternatives can then be compared visually using radar charts. It is important to note that, in the proposed formulations, no external benchmarks are introduced deliberately. This choice stems from the intent to keep the method broadly applicable and adaptable, particularly in early design phases where predefined reference values may not be relevant or available. The indicators are thus conceived as components of a relative decision-making tool, whose utility lies in the consistent comparison of alternatives developed under the same assumptions and units. However, the model's structure readily allows for the integration of benchmark or target values in the future, should project conditions or stakeholder requirements demand it. In such cases, values could be normalised or scaled against reference thresholds (e.g., national standards, sustainability rating systems, or historical datasets), thereby extending their interpretive power for certification or policy alignment.

2.5 Step 4: multicriteria assessment

This phase integrates potential design improvements and refines project options ahead of the final decision stage. As an initial step, assigning equal weights to all indicators (Gozzi & Guante Henriquez, 2025) offers a neutral baseline, enabling unbiased observation of relationships between criteria and revealing possible correlations or redundancies. This exploratory stage helps refine the framework's structure before developing more targeted weighting strategies. In practice, priorities vary: some contests demand high resilience (e.g., above railways or motorways), while others prioritise robustness, sustainability, or cost-effectiveness. Fixed weights are therefore unsuitable for all scenarios. Weight allocation should reflect both contextual conditions and project objectives, allowing for nuanced evaluations. To address this, the method introduces the Weighted Global Quality Indicator (WGQI):

$$WGQI = \sum w_i \cdot I \quad 35$$

Where w_i is the weight assigned to indicator I .

Table 17 presents predefined weight sets for typical bridge design contexts, such as “Above railways and motorways” or “Sustainable infrastructure”, intended to support transparent early-stage evaluation. The values were obtained through structured expert elicitation involving five professionals with experience in bridge engineering, infrastructure design, and sustainable construction (see Appendix A). Each expert assigned weights to the indicators for each scenario, and the final sets

reflect the average of their responses. While indicative rather than prescriptive, these weights provide a realistic and context-sensitive basis for preliminary multi-criteria assessments. Thresholds or exclusion criteria may also be applied if required, although they are not included in this study.

Table 17: Example weights for different design scenarios

Design scenarios	Weights	wFI	wCS	wGI	wRI	wII	wMI	wSI	wCI	wAI
1_Above railways and motorways		10%	5%	20%	20%	15%	10%	5%	5%	10%
2_Urban context		10%	20%	20%	5%	5%	5%	10%	10%	15%
3_Sustainable infrastructure		10%	5%	10%	5%	5%	5%	20%	20%	20%
4_Above water		10%	5%	20%	25%	10%	10%	5%	5%	10%

The method also allows for the use of thresholds or exclusion criteria, depending on the specific context and project constraints although the authors have not included them in this work because they are considered not relevant to the method that proposes a direct comparison between design solutions. At present, the lack of a sufficiently large dataset of case studies or consistent literature makes it difficult to define precise, universally applicable weight sets. The predefined weights adopted in this study are based on the authors' professional and academic experience with similar infrastructure projects. While they serve as illustrative scenarios to support early, stage comparisons, their selection remains indicative. In future developments, the rationale behind these weights will be made more explicit, potentially through the inclusion of an appendix to ensure transparency and reproducibility. Applying this framework to a wider range of case studies will help to develop a more robust reference base for defining appropriate weight distributions. To further refine the weight assignment process, future work will explore the use of Monte Carlo simulations to test the sensitivity of different weighting schemes. These techniques will support the development of adaptive and data, informed weight configurations tailored to specific project conditions. Moreover, integrating machine learning (ML) with multi, criteria decision-making (MCDM) techniques is expected to enhance scenario evaluation and automate weight optimization based on project typologies, stakeholder priorities, and contextual parameters.

2.6 Step 5: decision making.

As illustrated in Figure 9 the method concludes in a decision-making phase where stakeholders are provided with the tools to make an informed and transparent choice, grounded in the Weighted Global Quality Indicator (WGQI). This indicator consolidates the multidimensional performance of each design alternative into a single, interpretable value, offering a clear basis for comparison. However, the WGQI does not merely support final selection, it also enables the initiation of an iterative refinement process. Thanks to its numerical definition, the WGQI can be systematically analysed, allowing the design team to revisit earlier stages of the workflow and fine, tune the project based on performance outcomes. Although not explored in depth within this paper, this phase also opens the possibility of investigating interrelationships between indicators.

To be noted that, line with its diagnostic and design-support purpose, the proposed framework is conceived as context-dependent and therefore applied site-specifically.

Each infrastructure project operates within a unique constellation of physical, social, regulatory, and environmental conditions; consequently, indicators are interpreted in relative rather than absolute terms. Their value depends not only on measurable performance but also on qualitative aspects such as spatial integration, accessibility, and constructability. This approach follows the logic of situated multi-criteria evaluation (Gervásio & da Silva, 2014; Favi et al., 2018; Gkoumas & Bontempi, 2020), which recognises that sustainability, resilience, and design quality cannot be assessed independently of territorial and conceptual constraints.

Therefore, the validation phase presented through the case studies (Chapter 3) does not aim at cross-case statistical generalisation, but rather at testing the internal coherence, responsiveness, and contextual adaptability of the framework within distinct design environments. This methodological stance ensures that the tool remains flexible, interpretable, and applicable across a variety of project typologies and scales, supporting evidence-based reasoning in early design stages.

By examining how different performance domains influence one another, stakeholders can gain insight into potential trade, offs or synergies. This, in turn, can inform targeted modifications to design strategies, shifting the project in one direction or another in response to evolving priorities or constraints. In this sense, the WGQI not only acts as a decision, support tool but also as a diagnostic instrument, capable of guiding design optimization through quantitative feedback.

For demonstration purposes, this decision-making framework is applied to three real, world case studies, illustrating how different weighting strategies influence final evaluations and support evidence, based comparisons.

Chapter 3

Case Studies

3.1 Rationale for Case Study Selection

3.1.1 Case-Based Research as the Framework's Epistemological Basis

The adoption of case studies as a validation strategy for methodological research in engineering design is epistemologically grounded rather than illustrative. In the field of structural and infrastructure design, and particularly in the conceptual design of bridges, decision making processes are shaped by the simultaneous interaction of structural reasoning, material strategy, geometric constraints, contextual conditions, regulatory requirements, and sustainability objectives. These interactions cannot be meaningfully isolated or exhaustively explored through abstract or purely parametric models. Case based research therefore provides an appropriate epistemological framework for testing decision support methods intended to operate in early design stages (Flyvbjerg, 2006; Yin, 2018).

Within this dissertation, the proposed multi criteria framework for the conceptual design of pedestrian and cycling bridges is validated through three case studies derived from the author's direct professional practice as a structural engineer. The selected cases correspond to real design processes developed within author's professional engineering office (Zanini Gozzi Sagl based in Lugano CH⁴) and include design competitions as well as feasibility and preliminary design studies. Their origin in professional practice ensures a high level of technical realism, data reliability, and contextual complexity, which are essential for evaluating a framework aimed at supporting real world design decisions. The case studies are not retrospective reconstructions, but projects developed under actual constraints related to site conditions, regulatory frameworks, stakeholder requirements, and design timelines.

The use of professionally developed projects as case studies does not aim to assess the quality of the final design outcomes, nor to promote specific solutions. Instead, these projects are employed as epistemic devices through which alternative conceptual options generated for the same design problem can be systematically compared. Their value lies in the possibility of observing how different structural concepts, material choices, and design strategies can be evaluated within a consistent and transparent decision support framework, in line with the concept of

⁴ www.zaninigozzi.ch

analytical generalisation rather than statistical representativeness (Eisenhardt, 1989).

From a design research perspective, case studies are widely recognised as a suitable approach for investigating processes in which qualitative judgement and quantitative assessment coexist. As highlighted in the methodological literature, including Yin (2018), Cross (2021), and Blessing and Chakrabarti (2009), case based research supports context dependent investigation and analytical depth, allowing theoretical constructs to be examined under realistic conditions rather than idealised assumptions. This is particularly relevant for research focused on decision support frameworks, where the objective is to structure and make explicit design reasoning rather than to predict outcomes.

In this sense, the case studies adopted in this research function as a bridge between theoretical development and professional practice. They provide the necessary epistemological grounding for testing the proposed framework under conditions that reflect the complexity, uncertainty, and contextual specificity of conceptual bridge design, thereby establishing a robust foundation for the validation process described in the following sections.

3.1.2 Criteria for case selection

The three case studies presented in this research were selected according to explicit methodological criteria aimed at ensuring that the proposed framework could be tested across the full range of design dimensions embedded in its structure. In particular, the selection process was guided by the need to explore the three macro areas defined in Chapter 2, namely Architecture and Planning, Structural Resilience, and Environmental Performance, as well as the different design scenarios represented through alternative weighting schemes. The case studies were therefore chosen not to maximise numerical representativeness, but to provide complementary and contrasting conditions under which these dimensions and scenarios could be meaningfully examined. As anticipated, the selected cases are drawn from the author's professional practice and correspond to real design processes developed in competition and feasibility contexts, which makes them particularly suitable for testing the framework under realistic design conditions. At the same time, they are not intended to constitute an exhaustive or systematic sample of structural typologies, nor to provide a comprehensive classification of

static schemes, but rather to function as case studies through which the behaviour of the proposed macro areas and design scenarios can be observed and assessed.

A first selection criterion thus, concerned contextual diversity, which is directly related to the Architecture and Planning macro area. The selected cases span different spatial, regulatory, and governance settings, including a constrained urban design competition in Delémont, a metropolitan feasibility study in Turin, and a peri urban open competition in Niederwangen. This diversity allows the framework to be tested under varying degrees of urban density, spatial integration requirements, and planning constraints, thereby enabling the assessment of how architectural and contextual indicators behave across distinct design environments.

A second criterion addressed design variability and structural configuration, which are central to the Structural Resilience macro area. Each case study includes multiple design alternatives developed for the same problem statement, differing in structural scheme, material strategy, and support configuration. This characteristic makes it possible to evaluate how changes in structural concept and construction logic influence robustness, inspectability, maintainability, and overall resilience related indicators, while keeping contextual conditions comparable within each case.

Environmental Performance constituted a third guiding criterion in the selection of cases. All projects explicitly address sustainability related objectives, such as, and in some cases these aspects were formally required by the competition briefs and feasibility mandates under which the projects were developed. The growing inclusion of environmental criteria in such documents reflects their central role in contemporary infrastructure design and provides an appropriate context for testing the proposed framework. In this respect, the inclusion of a case based on the reuse of structural elements extends the validation to boundary conditions of circular design, allowing the framework's environmental and circularity indicators to be tested under both conventional and innovative material strategies.

In addition to covering the three macro areas, the selected cases were chosen to support the application of different design scenarios through alternative weighting schemes. The diversity of stakeholders, decision contexts, and project objectives embedded in the three cases enables the exploration of policy oriented, designer oriented, and balanced weighting scenarios, thereby testing the sensitivity and transparency of the framework when stakeholder priorities change.

Finally, data completeness and traceability were essential selection requirements. All case studies provide sufficient technical documentation to support the full application of the framework, from indicator calculation to aggregation and synthesis. This ensures that the evaluation remains grounded in verifiable design data and that the influence of the macro areas and weighting scenarios can be interpreted consistently across cases.

Through this selection strategy, the case study corpus was constructed to ensure systematic coverage of the framework's core dimensions while maintaining methodological coherence. The chosen cases therefore constitute a structured testing ground for examining how architectural, structural, and environmental considerations interact within different design scenarios during the conceptual design of pedestrian and cycling bridges.

3.1.3 Case studies as instruments for framework validation

In this research, the case studies are used as structured instruments for validating the proposed multi criteria decision support framework. Their function is operational and methodological, as they are intended to test the internal coherence, applicability, and consistency of the framework when applied to real conceptual design problems, rather than to justify the epistemological use of case-based research, which has been addressed in Section 3.1.1.

Each case study constitutes an independent application of the framework, developed under specific contextual, procedural, and design conditions. This allows the framework to be examined across different project settings while maintaining a consistent evaluation structure based on the same indicators, macro areas, and aggregation logic. The case studies are therefore treated as distinct validation instances rather than as elements of a statistically comparable sample, and their role is to reveal how the framework behaves when confronted with heterogeneous design constraints.

Within this research, Steps 1 and 2 of the proposed frameworks, which concern problem framing and indicator definition, are fixed a priori as intrinsic components of the methodology and therefore remain constant across all case studies. The role of the case studies is instead to support the application and validation of Steps 3 to 5, corresponding to comparative assessment, multi-criteria aggregation, and decision synthesis. This distinction reflects the intended use of the framework as a decision-support tool for evaluating alternative design options under predefined

evaluation criteria, rather than for redefining the criteria themselves in each application.

A key aspect of the validation concerns the structural dimension of conceptual design, particularly the role of static schemes, load bearing configurations, and structural typologies. The selected cases include variations in structural logic, spanning systems, material structural behaviour, and support arrangements. These variations are not intended to provide a systematic or exhaustive classification of static systems, but to verify that the framework is capable of consistently evaluating conceptually different structural strategies and capturing their implications for structural resilience, constructability, inspectability, maintainability, and long-term performance at an early design stage.

The case studies support validation at three complementary levels. First, they provide operational validation by confirming that all steps of the framework, from indicator calculation to aggregation and ranking, can be implemented using data typically available during conceptual design, without relying on idealised assumptions. Second, they enable sensitivity testing through the application of different weighting scenarios, which represent alternative design perspectives and stakeholder priorities, allowing the transparency and robustness of the decision-making process to be assessed. Third, they allow qualitative comparison across cases through the observation of recurring behaviours in indicator performance, without requiring direct numerical equivalence between different projects.

All case studies are developed through the complete application of the framework up to Step 5, corresponding to the decision-making stage. Differences between cases are not related to the level of methodological completion, but to the nature of the underlying design processes, such as design competitions and feasibility studies, which influence the decision context and stakeholder priorities rather than the structure of the evaluation itself.

Through this validation strategy, the case studies function as a controlled and realistic testing environment for the proposed framework. They demonstrate its ability to operate consistently across different structural configurations, contextual conditions, and weighting scenarios, reinforcing its relevance for both methodological research and professional conceptual design practice.

3.2 Case Studies Structure and Methodological Implementation

3.2.1 Data sources and decision-matrix structure

The case studies analysed in this research are based on data derived from real design processes developed within multidisciplinary project teams, including design competitions and feasibility or preliminary studies. Primary data sources consist of original project documentation produced by the design teams, such as competition briefs, feasibility reports, drawings, technical specifications, material take offs, and structural calculations. These sources provide the quantitative and qualitative information required to populate the indicators defined in Chapter 2.

The design processes involved collaboration between different professional roles, including structural engineers, architects, and, where applicable, specialists in construction, sustainability, and infrastructure planning. This team-based setting reflects typical professional practice and ensures that the data used for the case studies incorporate multiple disciplinary perspectives, which is particularly relevant for testing a decision support framework intended to operate in interdisciplinary conceptual design contexts.

Secondary data sources include applicable regulatory frameworks and guidance documents, which inform the definition of boundary conditions and support the interpretation of indicator values. The framework is intentionally applied in a site specific and team specific manner, as it is designed to compare alternative conceptual solutions developed for the same project and evaluated by the same design team. This condition ensures internal consistency in assumptions, design intent, and interpretation criteria, allowing differences in results to be attributed to the design options themselves rather than to variations in context or evaluators. The framework is therefore not intended to compare solutions across different projects or teams directly, but to support structured and transparent decision making within a given project setting, while remaining transferable as a methodological protocol to other contexts and design teams.

For each case study, the available information was structured into a decision matrix. In this matrix, rows correspond to the set of indicators defined within the three macro areas Architecture and Planning, Structural Resilience, and Environmental Performance, while columns represent the alternative design options developed for the same project. This structure provides a transparent and

reproducible basis for comparing alternatives within each case and ensures methodological consistency across different case studies.

3.2.2 Framework application protocol and decision steps

The methodological framework defined in Chapter 2 is applied to all case studies through a common and standardised application protocol. The protocol does not redefine the framework steps but specifies the conditions under which they are implemented consistently across different projects, ensuring methodological coherence and comparability of results.

For each case study, the framework is applied in its entirety, following the five-step structure defined in Chapter 2 without modification at the case level. The decision problem, indicators, aggregation logic, and weighting scenarios are therefore fixed a priori, and are not adapted or recalibrated for individual projects. This ensures that differences in outcomes reflect variations in design alternatives, contextual conditions, and decision scenarios, rather than changes in the evaluation procedure.

All design alternatives developed for the same project are evaluated using the same indicator set and aggregation rules, and the framework is systematically applied up to the decision-making stage. The decision outcome is thus always explicitly defined for each case study, providing a clear and consistent basis for subsequent interpretation in the case specific analyses.

3.2.3 Normalisation, weighting, and aggregation criteria

Normalisation, weighting, and aggregation of indicator values are performed in accordance with the principles and procedures defined in Chapter 2, while their application is tailored to the specific context of each case study. Normalisation criteria are defined at the case study level and applied consistently to all design alternatives developed for the same project. This approach reflects the site-specific nature of the framework and ensures that indicator values support meaningful internal comparison between options evaluated under identical contextual and decision conditions, without implying direct comparability across different projects or design teams.

As the framework is conceived as a decision support tool for comparative evaluation in conceptual design, no absolute threshold values are defined for the indicators. The assessment does not aim to verify compliance with predefined minimum or target values, but to support structured comparison between alternative design solutions within the same project. Indicator values are therefore interpreted in relative terms, allowing designers to reason about trade-offs, balance between macro areas, and the implications of different design strategies at an early design stage.

Weighting is applied through predefined weighting scenarios resumed in Table 17 that reflect different design perspectives and stakeholder priorities. These scenarios are defined independently of the individual case studies and are applied without modification within each project. This approach allows the influence of alternative priority settings to be explored systematically, while avoiding case specific calibration of weights that could compromise comparability.

Aggregation follows the hierarchical structure of the framework, with indicators combined within their respective macro areas and subsequently synthesised into an overall performance score. The aggregation logic is identical for all case studies, ensuring that variations in results are attributable to differences in design alternatives and decision scenarios rather than to changes in evaluation criteria or computational procedures.

3.2.4 Tools and visualisation standards

The implementation of the proposed framework was supported by a set of computational and visualisation tools developed progressively during the research. The initial implementation was carried out using spreadsheet-based calculation sheets, which allowed systematic testing of the framework logic, indicator formulation, and aggregation structure in a transparent and accessible environment. This phase was essential for verifying the internal consistency of the method and for structuring the decision matrices used in the case studies.

Subsequently, the framework was formalised through a set of dedicated scripts developed in Python. This step enabled the automation of indicator calculation, normalisation, weighting, and aggregation procedures, reducing the risk of manual errors and improving reproducibility. The use of scripted workflows also facilitated iterative testing across multiple design alternatives and weighting scenarios, supporting sensitivity analysis and methodological refinement.

In a later stage, the computational core implemented through Python scripts was integrated into a dedicated application designed to support interactive exploration of results and comparative evaluation of design alternatives. The application was conceived as a decision support interface rather than as an optimisation or black box tool, maintaining full transparency of input data, intermediate calculations, and aggregated outputs. A detailed description of the computational implementation, including the structure of the Python scripts, data processing workflow, and application interface, is provided in Appendix B.

Across all implementations, results are structured and presented through a combination of numerical decision matrices and graphical representations. Numerical matrices ensure full traceability of indicator values and aggregation steps, allowing results to be verified analytically. Graphical visualisation is systematically employed to support interpretation at the conceptual design stage, with particular emphasis on radar charts as a standard representation across all case studies.

Radar charts are adopted because they are particularly suited to representing multi-dimensional performance profiles structured around a limited number of indicators and macro areas. Within the proposed framework, radar charts enable the simultaneous visualisation of indicator values on a common normalised scale, facilitating the identification of balance, trade-offs, and dominant strengths or weaknesses within a single design alternative. This form of representation supports comparative reasoning between alternatives developed for the same project, which is central to the decision support objective of the framework.

Consistent visualisation standards, including axis definition, scaling, and graphical layout, are applied across all case studies to ensure that visual differences between alternatives reflect actual variations in indicator performance rather than artefacts of representation. Radar charts therefore constitute an integral component of the methodological protocol, supporting both internal discussion within design teams and communication of comparative results to non-specialist stakeholders.

3.2.5 Protocol summary

This section has defined the common methodological structure through which the proposed framework is applied to all case studies presented in this chapter. By specifying data sources, decision matrix organisation, application protocol, normalisation and aggregation criteria, and visualisation standards, the section

establishes a consistent and reproducible basis for the empirical validation of the framework.

The protocol is applied identically across all case studies and is not modified at the project level. Differences in results are therefore attributable to variations in design alternatives, contextual constraints, and decision scenarios rather than to methodological adjustments. This ensures that each case study functions as a controlled application of the same evaluation logic, allowing the behaviour of the framework to be examined under different design conditions. On this basis, the following sections present the individual case studies. For each project, the protocol defined in this section is applied to a set of alternative conceptual design solutions developed for the same site and decision context. The case studies are structured to illustrate how the framework supports comparative reasoning and explicit decision making at the conceptual design stage, without redefining the methodological premises established in Chapters 2 and 3.2. Together, the protocol and the case studies form the empirical foundation for the cross-case interpretation developed in Chapter 4, where qualitative trends, recurring patterns, and methodological insights emerging from the applications are discussed.

3.3 Case Study 1

Competition for pedestrian and bicycle bridge in Delémont (CH)

3.3.1 Context and design objectives

This case study refers to a design competition promoted in 2022 by the Municipality of Delémont for the construction of a new pedestrian and bicycle bridge within a dense urban environment. The competition is formally defined in the Cahier des charges du concours pour la Passerelle CFF à Delémont⁵ issued by the Municipality, which specifies the project objectives, boundary conditions, and evaluation criteria. The project forms part of the third generation Agglomeration Programme and is embedded within broader objectives related to sustainable mobility, urban continuity, and long-term infrastructure integration, as stated in the competition brief.

⁵ Available on <https://competitions.espazium.ch/fr/concours/decides/passerelle-secteur-gare-sud-delemont>.

The primary objective of the project is to strengthen the local slow mobility network by providing a continuous and accessible north–south connection between urban districts currently separated by major transport infrastructures. As illustrated in Figure 22, the intervention plays a strategic role within the city scale mobility framework, contributing to the continuity of pedestrian and cycling routes and supporting modal shift by improving the attractiveness and legibility of non-motorised connections. In this perspective, the bridge is conceived as a component of sustainable urban infrastructure rather than as an isolated engineering object.

The project site is characterised by a high degree of spatial and functional constraint, resulting from the coexistence of railway infrastructure, urban road traffic, and adjacent built fabric. The competition area, shown in Figure 23, includes the Swiss Federal Railways tracks and the Route de Desserte Urbaine, both of which must remain fully operational during construction, as explicitly required by the competition documentation. In addition, the competition brief requires the preservation of a reserved corridor for potential future adaptations of the railway infrastructure, introducing further spatial constraints that limit admissible bridge positioning and structural depth. The bridge is therefore required to comply with stringent clearance, safety, and operational requirements, while integrating barrier free pedestrian access and dedicated cycling ramps with limited gradients, in accordance with accessibility regulations defined in the brief. These conditions generate a highly controlled design environment in which geometric configuration, structural depth, construction sequencing, and material choice are tightly interrelated. As specified in the competition brief and supported by the preliminary feasibility studies accompanying the tender documentation, the need for lightweight solutions, prefabrication, and efficient erection above active transport corridors significantly restricts the range of feasible structural systems and effectively leads to steel as the primary load bearing material. Within this framework, sustainability is addressed not through the selection of an unconstrained or idealised site, but through the optimisation of structural concepts, material efficiency, durability, and adaptability under real urban and infrastructural constraints explicitly defined by the competition requirements. All design alternatives are developed for the same site and respond to identical functional, regulatory, and spatial conditions, allowing contextual and planning related parameters to remain constant.

This condition makes the Delémont project particularly suitable for the validation of the proposed decision support framework as a tool for sustainable infrastructure design. By isolating the influence of structural schemes, material quantities, and design strategies within a fixed urban context defined by the

competition brief, the case study allows the framework to be tested as a means of supporting informed and transparent decision making oriented toward sustainability objectives under realistic boundary conditions.

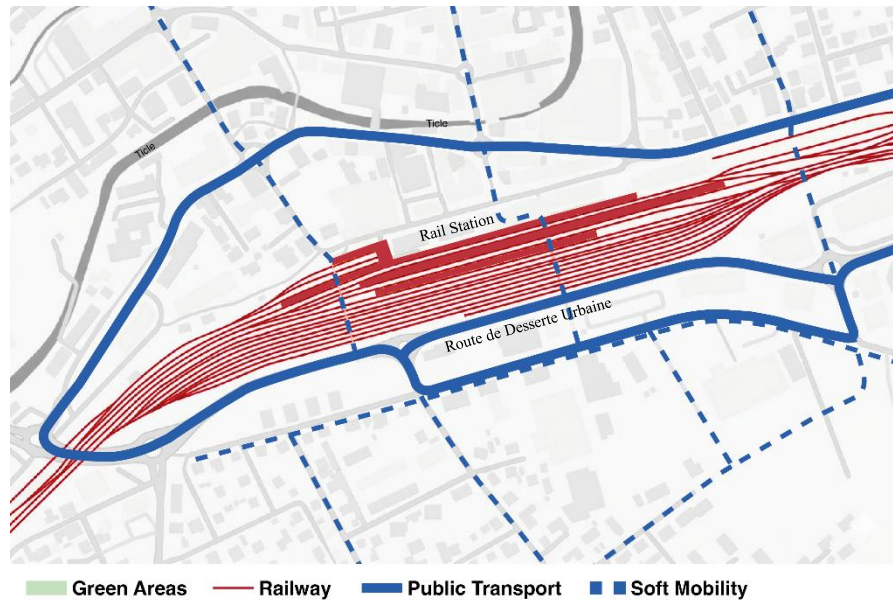


Figure 22 Case study 1: North-South connection diagram.

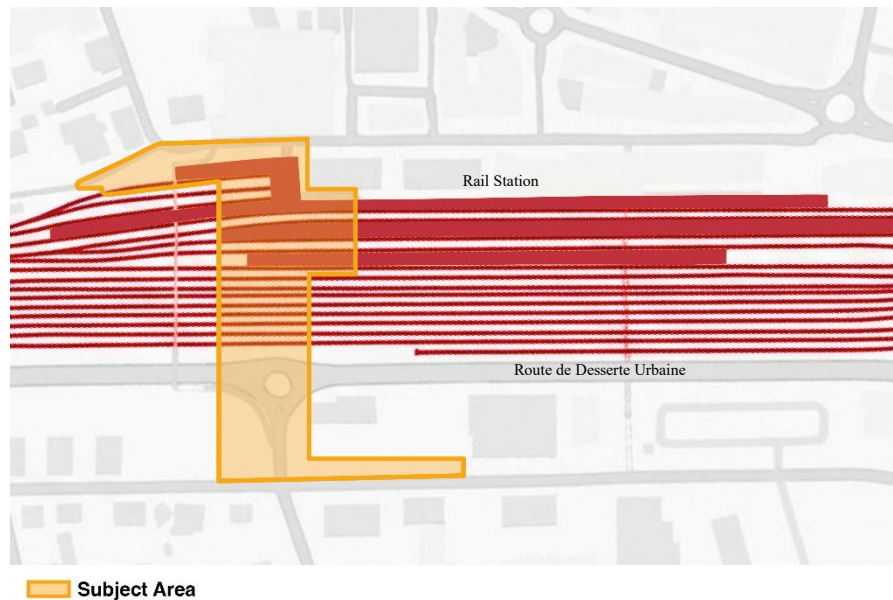


Figure 23 Case study 1, competition area.

3.3.2 Design alternatives and input data

Within the competition framework, four design alternatives were developed for the same project site, all located within the limited competition area and subject to identical spatial, functional, and regulatory constraints imposed by the dense urban context and the presence of active railway infrastructure. The reduced size of the site and the strict clearance and alignment requirements effectively fix the position of the bridge, ensuring that all alternatives are directly comparable. While the location and boundary conditions remain constant, the alternatives differ in terms of structural scheme, load bearing configuration, and material strategy, reflecting distinct conceptual responses to the same constrained design problem. This set of alternatives provides a controlled basis for analysing how different structural concepts perform under fixed infrastructural and contextual conditions. Figure 24 illustrates the main input information related to site insertion, geometric configuration, and material strategies for each alternative, while Table 18 summarises the additional quantitative input data required for the application of the decision support framework.

- Case 1A: consists of a composite timber system with a collaborating CLT deck and main timber twin beam, arranged in simply supported spans over four supports, with V-shaped steel pillars providing vertical support.
- Case 1B: is based on a continuous steel box-girder system with composite floor slabs, supported on three piers, with the central span fully crossing the railway and rectangular box-section supports.
- Case 1C: adopts a continuous steel truss system integrated with the handrails, combined with secondary steel beams and a CLT deck, and is supported on four V-shaped supports per truss.
- Case 1D: consists of continuous twin steel beams with secondary beams and a CLT deck, supported on three piers, with the central span fully crossing the railway corridor and V-shaped steel pillars providing vertical support.

For all design alternatives, the foundations are realised in RC, with deep foundation systems adopted for the supports located in proximity to the railway infrastructure to resist accidental actions associated with potential train derailment and structural steel is modelled as low-carbon electric arc furnace (EAF) steel with high recycled content.

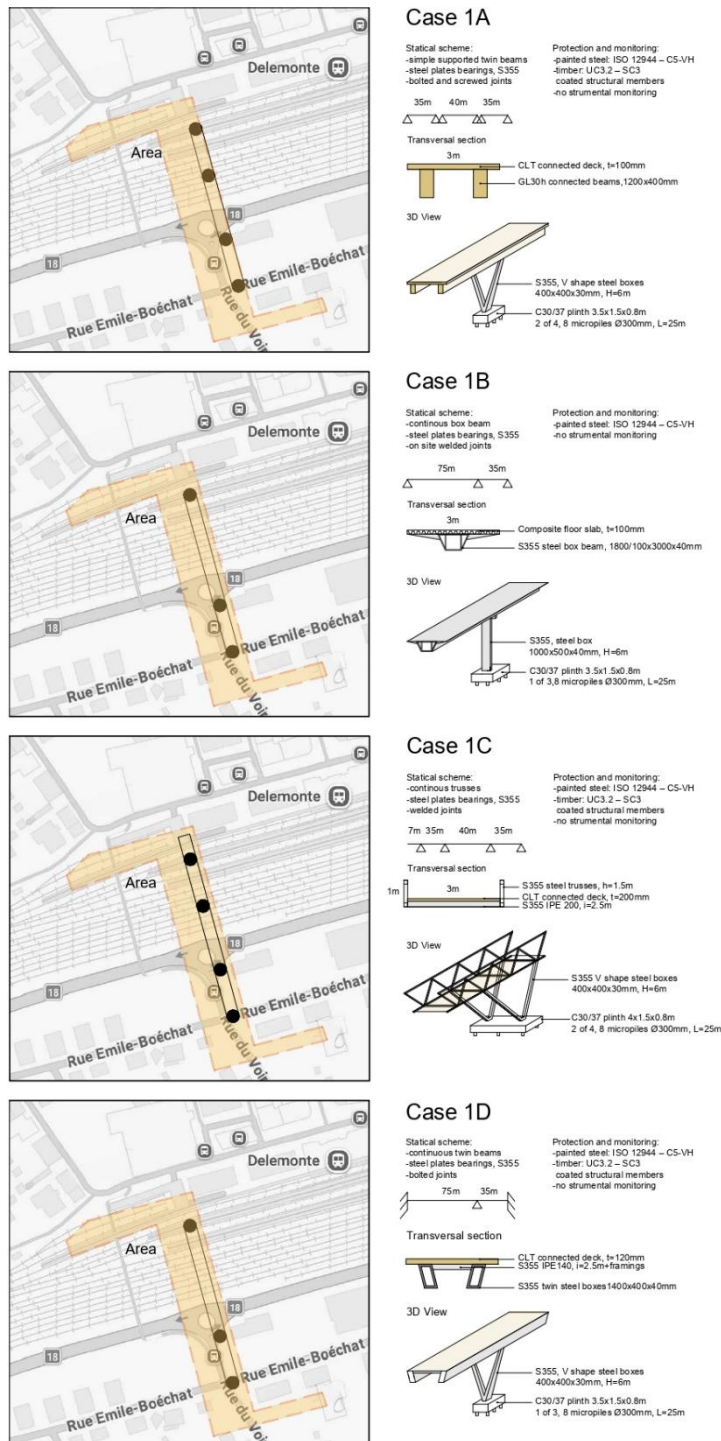


Figure 24 Overview of the four design alternatives developed for case study 1. The figure illustrates the input information related to site insertion, geometric configuration, and material strategy for each alternative, while maintaining identical boundary conditions and alignment constraints.

Table 18: Complete set of input data for the four design alternatives, structured according to the indicators defined in the proposed multi-criteria framework and used for the calculation of all indicator values.

Indicator	Case	U.M	1A	1B	1C	1D
RI	ULS_capacity	%	0.95	0.8	0.7	0.92
	GSA_percent_LL	%	0	0.27	0.1	0.05
	N_crit	n.	5	1	2	1
	N_tot	n.	10	5	11	8
	Hazard_label	-	2b2	2b2	2b2	2b2
MI	Life	Years	100	100	100	100
	Initial cost IC	chf	2200000	3690000	2700000	3300000
	alfa id	-	Simple beam timber/protected	Continuous beam galvanized/ painted steel	Truss galvanized/ painted steel	Simple beam galvanized/ painted steel
	eta_joints	n.	2	2	4	6
	Joint types	-	Bolted joints	Welded joints	Welded joints	Bolted joints
	eta_bearings	n.	6	3	16	10
	Bearing types	-	Bearings Galvanized / painted steel plates	Bearings Galvanized / painted steel plates	Bearings Galvanized / painted steel plates	Bearings Galvanized / painted steel plates
	Substructure materials	-	Bearings Galvanized / painted steel plates	Bearings Galvanized / painted steel plates	Bearings Galvanized / painted steel plates	Bearings Galvanized / painted steel plates
	Deck materials	-	Main structure Structural timber (glulam / LVL) — protected design	Main structure Galvanized / painted steel	Main structure Galvanized / painted steel	Main structure Galvanized / painted steel
II	Deck area	m2	330	330	351	330
	Length Main load- bearing members (girders, arches, trusses, cables, etc.)	m	220	110	234	220
	N°Main load-bearing members (girders, arches, trusses, cables, etc.)	n.		2	50	3
	N° Supports (piers and abutments, including visible parts of foundations)	n.	4	3	16	5
	N°Bearings and structural connections	n.	12	6	4	16
	N°Expansion joints / structural terminations	n.	3	2	4	4
	Ibridge Bearings and structural connections	-	0.5	0.5	0.5	0.5
	Ibridge Main load- bearing members (girders, arches, trusses, cables, etc.)	-	0	0.5	0.5	0

	Ibridge Supports (piers and abutments, including visible parts of foundations)	-	0	0	0	0
	Ibridge Bearings and structural connections	-	0.5	0.5	0.5	0.5
	Ibridge Expansion joints / structural terminations	-	0.5	0.5	0.5	0.5
	Ibelow Deck area	-	1	1	1	1
	Ibelow Main load-bearing members (girders, arches, trusses, cables, etc.)	-	1	1	0.5	1
	Ibelow Supports (piers and abutments, including visible parts of foundations)	-	0	0	0	0
	Ibelow Bearings and structural connections	-	0	0	0	0
	Ibelow Expansion joints / structural terminations	-	0	0	0	0
	Eq. Level	-	1	2	1	1
	Skills level	-	4	4	4	4
	Process level	-	4	4	4	4
SI	GWP_plan	kgCO ₂ eq	0	0	0	0
	GWP_A1-A5	kgCO ₂ eq	51922	236678	141874	192197
	GWP_B1-B7	kgCO ₂ eq	11859	9729	8094	5340
	GWP_C1-C4	kgCO ₂ eq	4619	5540	3561	3095
	C_plan	chf	308000	516600	378000	462000
	C_ A1-A5	chf	2200000	3690000	2700000	3300000
	C_ B1-B7	chf	440000	738000	540000	660000
	C_ C1-C4	chf	320000	553500	405000	495000
	Scenario	-	B	B	B	B
CI	material_code	-	glulam	steel_bolted_S355	steel_welded_S355	steel_welded_S356
	mass_kg	kg	270799	551700	309125	381170
	RM	kg	14195	216000	117000	188400
	RU	kg	10562365	108000	19500	94200
	RC	kg	94587	360000	206550	300023

For the Delémont case study, the Global Warming Potential (GWP) is assessed over life cycle stages A1–C4 based on material-specific datasets from

ÖKOBAUDAT⁶ and IBU.data⁷, in accordance with EN 15804+A2. In the absence of consistent Swiss datasets for all materials, these are adopted as representative European proxies. As the objective of the study is to compare alternative design solutions, this approach is considered appropriate and ensures consistency across all scenarios.

3.3.3 Framework application

The proposed multi-criteria decision-support framework is applied to the four design alternatives developed for the Delémont competition, focusing on Steps 3 to 5, namely comparative assessment, multi-criteria aggregation, and decision synthesis. As defined by the methodology, Steps 1 and 2, which concern problem framing and indicator definition, are intrinsic to the framework and remain fixed, ensuring consistency across all applications.

For this case study, the evaluation is conducted adopting Weighting Scenario 3 (Sustainable Infrastructure) defined in Table 17. This scenario is selected because the competition brief explicitly emphasises sustainability and long-term adaptability as primary design objectives. Consequently, the evaluation prioritises environmental performance and long-term infrastructural quality, while still ensuring structural adequacy and architectural coherence. This weighting therefore reflects the priorities expressed in the competition programme rather than an arbitrary methodological choice.

Using the decision input data summarised in Table 18, each indicator is calculated and normalised according to the procedures described in Chapter 2 and Section 3.2. The resulting indicator-level outputs constitute the analytical basis for the multi-criteria aggregation and the subsequent decision synthesis.

Table 19 to Table 25 report the indicator results grouped by macro-area, including Architecture and Planning, Structural Resilience, and Environmental Performance. These tables present the intermediate evaluation outputs prior to aggregation and ensure full transparency and traceability of the assessment process.

⁶ ÖKOBAUDAT (2024). *ÖKOBAUDAT – Sustainable Construction Information Portal*. Federal Ministry for Housing, Urban Development and Building. Available at: <https://www.oekobaudat.de>.

⁷ IBU – Institut Bauen und Umwelt e.V. (2024). *IBU.data – Environmental Product Declarations database*. Available at: <https://ibu-epd.com>.

Table 26 summarises the global quality factors while Table 27 summarises the weighted indicators and weighted global quality factors.

Visual results as radars chart are reported in Figure 25.

Architectural and Planning

Table 19 Case study 1. Architecture and Planning indicator values, raw and normalized (1–6), for the four design alternatives.

alt_id	FI	CS	GI	FI_1_6	CS_1_6	GI_1_6
1A	0.83	0.67	0.92	6.00	4.30	6.00
1B	0.67	0.67	0.92	1.00	4.30	6.00
1C	0.75	0.67	0.67	3.50	4.30	1.00
1D	0.75	0.67	0.92	3.50	4.30	6.00

Structural Resilience

Table 20 Case study 1. Resistance to collapse indicator values, raw and normalized (1–6), for the four design alternatives.

alt_id	R	SL	H	RI	RI_1_6
1A	0.00	0.50	1.00	0.00	1.00
1B	0.27	0.80	1.00	0.22	6.00
1C	0.10	0.82	1.00	0.08	2.90
1D	0.05	0.88	1.00	0.04	2.00

Table 21 Case study 1. Maintenance indicator values, raw, aggregated, and normalized (1–6), for the design alternatives.

alt_id	alpha0	alpha	E	R	f_ERIC	MI	MI_1_6
1A	0.55	0.00254	0.13	0.80	0.46	0.017869109	6.00
1B	0.50	0.00247	0.20	0.79	0.49	0.010977325	1.00
1C	0.55	0.00230	0.05	0.79	0.42	0.01608121	4.70
1D	0.45	0.00203	0.06	0.84	0.45	0.014964459	3.89

Table 22 Case study 1. Inspection indicator values, raw, aggregated, and normalized (1–6), for the design alternatives.

alt_id	IE	Timpact	Tinsp	D1	Deq	Dex	Dpr	D	II	II_1_6
1A	1	9.02	9.36	0.04	1.00	0.25	0.25	0.27	0.27	2.50
1B	1	6.10	6.31	0.03	0.75	0.25	0.25	0.23	0.23	1.00

1C	1	9.29	12.29	0.24	1.00	0.25	0.25	0.37	0.37	6.00
1D	1	9.24	10.05	0.08	1.00	0.25	0.25	0.29	0.29	3.20

Environmental performance

Table 23 Case study 1. Sustainability indicator values, raw, aggregated, and normalized (1–6), for the design alternatives.

alt_id	GWP_sum	C_sum	GI	TC	SI_raw	SI_1_6
1A	68400	3178000	6.051	99.333	0.10	6
1B	251947	5498100	32.432	166.609	0.04	1
1C	153530	4023000	19.565	114.615	0.06	2.6
1D	200632	4917000	28.428	149	0.05	1.4

Table 24 Case study 1. Circularity indicator values, raw, aggregated, and normalized (1–6), for the design alternatives.

alt_id	CI	CI_1_6
1A	0.062	6
1B	0.005	1.2
1C	0.002	1
1D	0.011	1.7

Table 25 Case study 1. Adaptability indicator values, raw, aggregated, and normalized (1–6), for the design alternatives.

alt_id	AI	AI_1_6
1A	0.5	1
1B	0.8	4.3
1C	0.8	4.3
1D	1	6

Indicators Aggregation

Table 26 Case study 1. Aggregated indicator values and global quality factor (GQF)

alt_id	FI	CS	GI	RI	MI	II	SI	CI	AI	GQF
1A	6.00	4.30	6.00	1.00	6.00	2.50	6.00	6	1.00	32.8
1B	1.00	4.30	6.00	6.00	1.00	1.00	1.00	1.2	4.30	25.8
1C	3.50	4.30	1.00	2.90	4.70	6.00	2.60	1	4.30	30.3
1D	3.50	4.30	6.00	2.00	3.89	3.20	1.40	1.7	6.00	32.0

Indicators weighting

Table 27 Case study 1. Indicator weighted values and weighted global quality factor (GQF) under Weighting Scenario 3.

alt_id	wFI	wCS	wGI	wRI	wMI	wII	wSI	wCI	wAI	wGQF
1A	0.60	0.22	0.60	0.05	0.30	0.13	1.20	1.20	0.20	4.49
1B	0.35	0.22	0.60	0.10	0.19	0.16	0.28	0.34	1.20	3.44
1C	0.35	0.22	0.10	0.15	0.24	0.30	0.52	0.20	0.86	2.93
1D	0.10	0.22	0.60	0.30	0.05	0.05	0.20	0.24	0.86	2.62

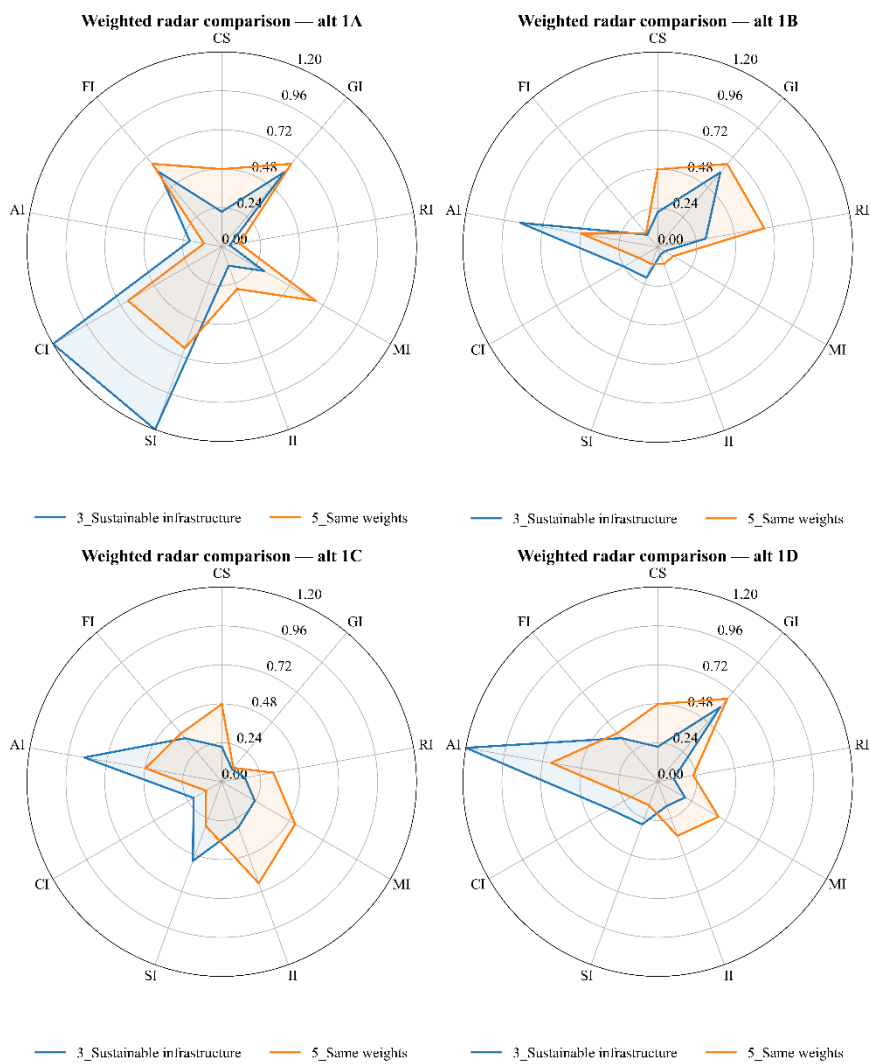


Figure 25 Case study 1. Radar chart comparing the performance of the four design alternatives under Weighting Scenario 3 (Sustainable Infrastructure), highlighting the influence of sustainability-oriented priorities on the indicator profile.

3.3.4 Case-specific results

When considering the unweighted indicator scores, Alternatives 1A and 1D exhibit comparable overall profiles, albeit characterised by different performance distributions. Alternative 1A is marked by high environmental and material-related scores, while Alternative 1D displays a more balanced behaviour across structural, functional, and adaptability-related indicators. This comparison highlights two competing conceptual strategies that perform similarly when no explicit prioritisation is applied.

Under Weighting Scenario 3 (Sustainable Infrastructure), the two alternatives diverge significantly. The application of sustainability-oriented weights amplifies the contribution of environmental and lifecycle-related indicators, resulting in Alternative 1A becoming the clear top-ranked option. This shift is primarily driven by its maximum scores in Sustainability (SI) and Circularity (CI), which receive substantial weight within the selected scenario. Therefore, the strong environmental performance of Alternative 1A outweighs its lower scores in Resistance to collapse (RI) and Inspectability (II).

By contrast, Alternative 1D, despite its balanced and robust overall profile, is penalised under the same weighting scheme due to comparatively low values in Sustainability and Circularity. This outcome illustrates how weighting scenarios do not merely rank alternatives but actively shape the interpretation of what constitutes “best performance” at the conceptual design stage.

In the subsequent design development phase, Alternative 1D was not retained due to construction-related constraints associated with the competition requirements. In particular, construction strategies requiring temporary works above the active railway tracks were not permitted, which limited the feasibility of the proposed deck construction solution. The alternative was therefore excluded at a later project stage on the basis of operational constraints external to the conceptual multi-criteria evaluation.

3.4 Case study 2

Feasibility study for a pedestrian and bicycle bridge in Turin (Italy)

3.4.1 Context and design objectives

This case study refers to a feasibility study commissioned in 2023 by the Municipality of Turin (IT) for the development of a new pedestrian and bicycle bridge aimed at strengthening the city-wide cycling and slow mobility network. Unlike Case Study 1, the intervention does not originate from a design competition but from a direct design mandate, with the objective of assessing the technical and strategic feasibility of alternative bridge solutions within a highly constrained infrastructural context.

The primary functional objective of the intervention is to provide a direct and continuous pedestrian and bicycle connection between the Via Nizza area, characterised by the presence of a major urban park and the Architecture Faculty of the Politecnico di Torino, and the Crocetta district and the Piazza d'Armi area. At present, this connection is largely forced to rely on the Corso Dante Road overpass, which represents a significant barrier for slow mobility due to traffic intensity, limited comfort, and reduced safety for pedestrians and cyclists. The proposed bridge is therefore conceived as an alternative, grade-separated crossing that improves accessibility, legibility, and user safety while avoiding interaction with heavy vehicular traffic.

The study is framed within the broader urban mobility policies promoted by the Municipality of Turin, which identify the expansion and continuity of the cycling network as a key lever for reducing private car use and improving accessibility between urban districts.

As illustrated in Figure 26, the project is embedded within the city's official cycling mobility plan (in dashed blue), and the proposed footbridge is conceived as a strategic link intended to overcome a major infrastructural barrier represented by an intensively used railway corridor. The project area is characterised by the presence of a multi-track railway line with high traffic frequency, representing one of the most critical railway infrastructures within the urban fabric of Turin. Train circulation must always remain fully operational, and any intervention in proximity to the railway is subject to stringent safety, clearance, and operational requirements.

As a consequence, railway-related safety considerations constitute the primary driver of the design process, strongly influencing admissible bridge alignment, structural configuration, construction sequencing, and material choices.

Within this framework, two alternative areas for the bridge crossing were identified by the Municipality as potentially suitable for the intervention as shown in Figure 27. Both areas are located along the same railway corridor and respond to identical functional objectives in terms of pedestrian and bicycle connectivity, but differ in spatial configuration, proximity to existing urban fabric, and interaction with railway infrastructure. The feasibility study therefore addresses a dual decision problem: the selection of the most appropriate crossing location and the evaluation of alternative structural solutions compatible with the dominant safety constraints.

In contrast to Case Study 1, sustainability is not the primary decision criterion guiding the assessment. While environmental and life-cycle considerations are explicitly included in the analysis, the dominant objective of the study is to ensure the highest possible level of safety with respect to railway operations, including robustness against accidental actions, minimisation of interference with train circulation, and reduction of construction and maintenance risks.

For this reason, the application of the decision-support framework adopts Weighting Scenario 1 (Safety-Oriented Infrastructure), which prioritises indicators related to structural resilience, robustness, inspection, and operational reliability. All design alternatives considered in this case study are developed under the same regulatory framework, railway safety prescriptions, and functional requirements for pedestrian and bicycle use.

By keeping these boundary conditions constant, the study isolates the influence of site selection and structural concept on overall performance, allowing the proposed framework to be tested as a tool for supporting transparent and safety-driven decision making in the early stages of infrastructure planning under highly constrained railway conditions.

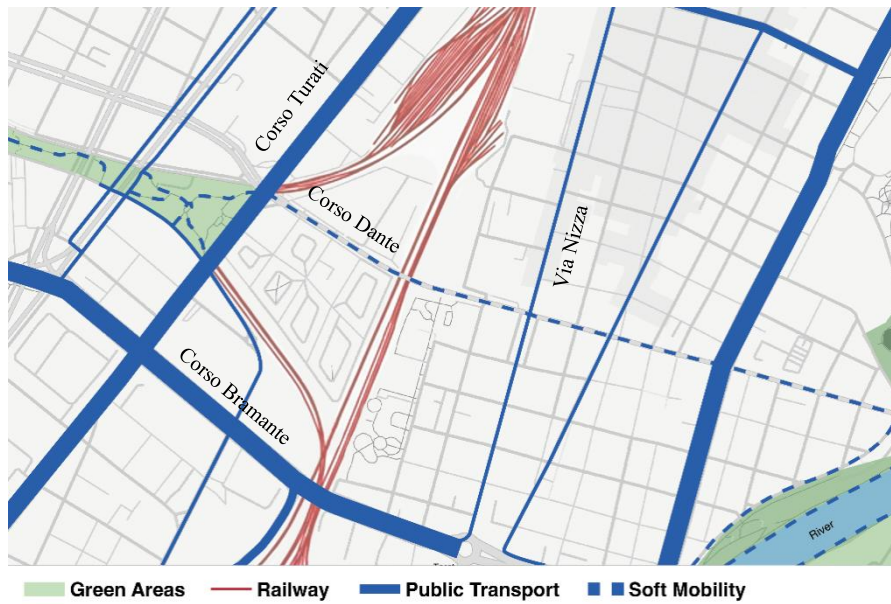


Figure 26 Case study 2 (Turin): location and territorial context of the pedestrian and bicycle bridge, highlighting the urban constraints and infrastructural interfaces.



Figure 27 Case study 2 (Turin): overview of the project area and alignment of the proposed bridge within the existing urban fabric.

3.4.2 Design alternatives and input data

Within the feasibility study framework, four design alternatives were developed to address the pedestrian and bicycle crossing of the railway corridor. All alternatives respond to identical functional requirements in terms of accessibility, geometric standards for slow mobility, and regulatory constraints defined by the Municipality of Turin and the applicable RFI (Rete Ferroviaria Italiana) standards, which impose particularly stringent prescriptions regarding clearances, construction methods, and safety in proximity to active railway infrastructure.

The alternatives are distributed across two distinct crossing areas identified during the preliminary phase of the study. Area 1 is characterised by a relatively open spatial configuration, allowing greater geometric flexibility but requiring a longer bridge span and an extended crossing over the railway tracks.

Area 2 is located in close proximity to the existing Corso Bramante Road overpass and allows for a shorter crossing length, at the expense of a more constrained spatial context and stronger interaction with existing infrastructure. This dual-area setup enables a comparative assessment not only between structural concepts but also between alternative site selections under identical safety-driven constraints.

Two alternatives (Case 2A and Case 2B) are developed in Area 1, where the increased span length and exposure above the railway corridor led to design solutions that actively engage three-dimensional structural behaviour in order to enhance robustness and redundancy.

The remaining two alternatives (Case 2C and Case 2D) are developed in Area 2, where the shorter crossing length allows more conventional structural typologies, albeit within a tighter geometric and infrastructural envelope.

The four design alternatives are defined as follows:

- Case 2A (Area 1): curved alignment with a continuous composite steel deck composed of twin longitudinal steel girders and secondary transverse beams. The deck is supported by four V-shaped steel pylons, from which inclined stay cables are anchored, activating a three-dimensional structural behaviour through deck–pylon–cable interaction.

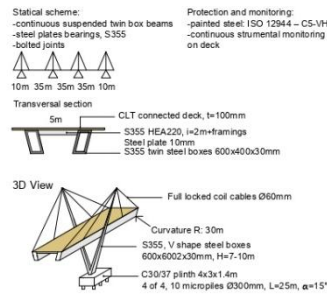
- Case 2B (Area 1): curved alignment with a continuous asymmetric steel box-girder deck. The structure is suspended by three steel pylons through inclined hangers, providing reduced structural depth over the railway corridor and adequate torsional stiffness in compliance with RFI safety requirements.
- Case 2C (Area 2): straight alignment with a prefabricated prestressed concrete box-girder deck. The bridge consists of simply supported spans resting on reinforced concrete piers cast in situ, favouring prefabrication and minimising on-site operations above the railway.
- Case 2D (Area 2): straight alignment with twin timber girders and a collaborating CLT deck. The structural scheme is based on simply supported spans supported by reinforced concrete piers cast in situ, combining a lightweight deck solution with a conventional substructure.

For all alternatives and the structural steel is modelled as low-carbon EAF steel with high recycled content, furthermore substructure elements located in proximity to the railway are designed in reinforced concrete and comply with RFI requirements related to accidental actions, construction safety, and railway operability.

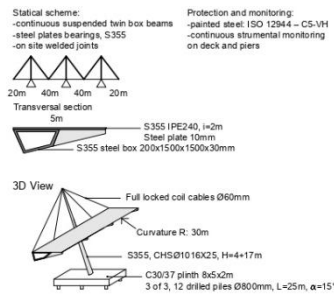
Figure 28 provides an overview of the four design alternatives, while Table 28 summarises the complete set of quantitative input data used for the application of the multi-criteria decision-support framework.



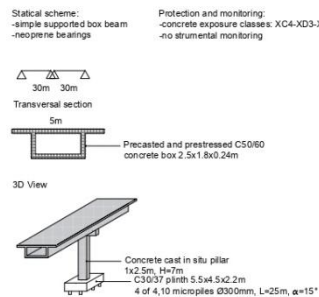
Case 2A



Case 2B



Case 2C



Case 2D

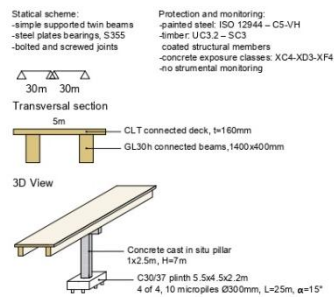


Figure 28 Case study 2: overview of the design alternatives developed for the feasibility study, illustrating differences in structural typology, geometry, and material strategy under identical boundary conditions.

Table 28 Complete set of input data for the four design alternatives, structured according to the indicators defined in the proposed multi-criteria framework and used for the calculation of all indicator values.

Indicator	Case	U.M	2A	2B	2C	2D
RI	ULS_capacity	%	0.244	0.3	0.3	0.4
	GSA_percent_LL	%	0.1	1	0	0
	N_crit	n.	3	0	1	2
	N_tot	n.	7	7	3	4
	Hazard_label	-	2b2	none	2a2	2a2
MI	Life	Years	100	100	100	100
	Initial cost IC	chf	2172150	2313800	1185000	1106200
	alfa id	-	suspended galvanized/ painted steel	suspended galvanized/ painted steel	simple beam reinforced concrete	simple beam timber/protected
	eta_joints	n.	6	2	0	0
	Joint types	-	Bolted joints	Welded joints	Welded joints	Bolted joints
	eta_bearings	n.	8	3	4	8
	Bearing types	-	Bearings Galvanized / painted steel plates	Bearings Galvanized / painted steel plates	Bearings Neoprene	Bearings Galvanized / painted steel plates
	Substructure materials	-	Main structure Stainless steel	Main structure Galvanized / painted steel	Main structure Reinforced concrete	Main structure Reinforced concrete
	Deck materials	-	Main structure Galvanized / painted steel	Main structure Galvanized / painted steel	Main structure Prestressed concrete	Main structure Structural timber (glulam / LVL) — protected design
II	Deck area	m2	625	500	300	300
	Length Main load-bearing members (girders, arches, trusses, cables, etc.)	m	562.5	225	60	120
	N°Main load-bearing members (girders, arches, trusses, cables, etc.)	n.	64.5	51	2	6
	N° Supports (piers and abutments, including visible parts of foundations)	n.	4	3	4	4
	N°Bearings and structural connections	n.	6	2	4	8
	N°Expansion joints / structural terminations	n.	2	2	4	8
	Ibridge Bearings and structural connections	-	0.5	0.5	0.5	0.5
	Ibridge Main load-bearing members (girders, arches, trusses, cables, etc.)	-	0	0	0.5	0.5
	Ibridge Supports (piers and	-	0.5	0	0.5	0.5

	abutments, including visible parts of foundations)					
	Ibridge Bearings and structural connections	-	0	0	0.5	0.5
	Ibridge Expansion joints / structural terminations	-	0	0	0.5	0.5
	Ibelow Deck area	-	0	0	1	1
	Ibelow Main load-bearing members (girders, arches, trusses, cables, etc.)	-	0	0	1	1
	Ibelow Supports (piers and abutments, including visible parts of foundations)	-	1	0	1	1
	Ibelow Bearings and structural connections	-	0	0	1	1
	Ibelow Expansion joints / structural terminations	-	0	0	1	1
	Eq. Level	-	1	1	3	3
	Skills level	-	2	2	2	2
	Process level	-	1	1	2	2
SI	GWP_plan		0	0	0	0
		kgCO ₂ eq				
	GWP_A1-A5		222806	353022	273741	251400
		kgCO ₂ eq				
	GWP_B1-B7		146701	122120	21517	29218
		kgCO ₂ eq				
	GWP_C1-C4		2479	5347	5098	8154
		kgCO ₂ eq				
	C_plan	chf	3041101	327600	168000	154000
CI	C_A1-A5	chf	21722150	2340000	1200000	1100000
	C_B1-B7	chf	4344430	468000	240000	220000
	C_C1-C4	chf	3258322	351000	180000	165000
	Scenario	-	A	A	A	A
	material_code	-	glulam	steel_bolted_S355	steel_welded_S355	steel_welded_S356
	mass_kg	kg	700357	2041492	1301625	977825
	RM	kg	198000	96000	0	0
	RU	kg	102433	0	90000	2048000
	RC	kg	445039	0	437906	264936

For the case study in Turin (Italy), the Global Warming Potential (GWP) is assessed over life cycle stages A1–C4 based on material-specific datasets from ÖKOBAUDAT and IBU.data, in accordance with EN 15804+A2. Although Italian datasets (e.g. EPD Italy) are available for specific products, consistent and comparable data were not available for all materials; therefore, European datasets are adopted as representative proxies. As the objective of the study is to compare

alternative design solutions, this approach is considered appropriate and ensures consistency across all scenarios.

3.4.3 Framework application

Also in this case, the proposed multi-criteria decision-support framework is applied to the set of four design alternatives developed within the feasibility study, following the methodological structure defined in Chapter 2. The application focuses on the comparative assessment and aggregation phases, while problem framing and indicator definition remain fixed, ensuring full consistency with the previous case study.

The evaluation is conducted adopting Weighting Scenario 1 (Safety-Oriented Infrastructure), reflecting the dominant role of railway-related safety constraints and operational reliability in the Turin context. In this scenario, greater relevance is assigned to indicators associated with structural resilience (robustness, inspection, and maintenance), while architectural-planning aspects and environmental performance are retained as complementary criteria.

Using the decision input data summarised in Table 28, each indicator is calculated and normalised according to the procedures described in Chapter 2 and Section 3.2. The resulting indicator-level outputs constitute the analytical basis for the multi-criteria aggregation and the subsequent decision synthesis. The resulting indicator-level outputs are reported in Table 29 to Table 35, grouped by macro-area (Architecture and Planning, Structural Resilience, and Environmental Performance), providing full transparency and traceability of the assessment process. Aggregated indicator values and Global Quality Factors are summarised in Table 35, while Table 36 reports the weighted results under the selected weighting scenario. A visual synthesis of the comparative performance of the four alternatives is provided by the radar chart in Figure 29.

Architectural and Planning

Table 29 Case study 2. Architecture and Planning indicator values, raw and normalized (1–6), for the four design alternatives.

alt_id	FI	CS	GI	FI_1_6	CS_1_6	GI_1_6
2A	0.92	0.75	0.75	6.00	6.00	6.00
2B	0.83	0.67	0.58	1.00	5.20	1.00
2C	0.92	0.25	0.75	6.00	1.00	6.00

2D	0.83	0.25	0.75	1.00	1.00	6.00
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Structural Resilience

Table 30 Case study 2. Resistance to collapse indicator values, raw and normalized (1–6), for the four design alternatives.

alt_id	R	SL	H	RI	RI_1_6
2A	0.10	0.57	1.00	0.06	1.30
2B	1.00	1.00	1.00	1.00	6.00
2C	0.00	0.67	1.00	0.00	1.00
2D	0.00	0.50	1.00	0.00	1.00

Table 31 Case study 2. Maintenance indicator values, raw, aggregated, and normalized (1–6), for the design alternatives.

alt_id	alpha0	alpha	E	R	f_ERIC	MI	MI_1_6
2A	0.60	0.00273	0.07	0.84	0.45	0.02	1.44
2B	0.60	0.00296	0.20	0.79	0.49	0.01	1.00
2C	0.45	0.00208	0.25	0.68	0.46	0.04	6.00
2D	0.55	0.00241	0.13	0.75	0.44	0.04	5.43

Table 32 Case study 2. Inspection indicator values, raw, aggregated, and normalized (1–6), for the design alternatives.

alt_id	IE	Timpact	Tinsp	D1	Deq	Dex	Dpr	D	II	II_1_6
2A	1	1.5	35.94	0.96	1.00	0.75	1.00	0.94	0.94	5.80
2B	1	0	19.3	1.00	1.00	0.75	1.00	0.96	0.96	6.00
2C	1	8.1	10.8	0.25	0.50	0.75	0.75	0.46	0.46	1.00
2D	1	11.1	14.8	0.25	0.50	0.75	0.75	0.46	0.46	1.00

Environmental performance

Table 33 Case study 2. Sustainability indicator values, raw, aggregated, and normalized (1–6), for the design alternatives.

alt_id	GWP_sum	C_sum	GI	TC	SI_raw	SI_1_6
2A	371987	32366004	6.47	57.01	0.03	6.00
2B	480489	3486600	9.61	69.73	0.03	1.00
2C	300356	1788000	10.01	59.60	0.03	2.70
2D	288772	1639000	9.53	54.09	0.03	4.30

Table 34 Case study 2. Circularity indicator values, raw, aggregated, and normalized (1–6), for the design alternatives.

alt_id	CI	CI_1_6
2A	1.06	3.20
2B	0.05	1.00
2C	0.41	1.80
2D	2.37	6.00

Table 35 Case study 2. Adaptability indicator values, raw, aggregated, and normalized (1–6), for the design alternatives.

alt_id	AI	AI_1_6
2A	0.5	6
2B	0.5	6
2C	0	1
2D	0	1

Indicators Aggregation

Table 36 Case study 2. Aggregated indicator values and global quality factor (GQF)

alt_id	FI	CS	GI	RI	MI	II	SI	CI	AI	GQF
2A	6.00	6.00	6.00	1.30	1.44	5.80	6.00	3.20	6.00	41.74
2B	1.00	5.20	1.00	6.00	1.00	6.00	1.00	1.00	6.00	28.20
2C	1.00	1.00	6.00	1.00	5.43	1.00	4.30	6.00	1.00	26.73
2D	6.00	1.00	6.00	1.00	6.00	1.00	2.70	1.80	1.00	26.50

Indicators weighting

Table 37 Case study 2. Indicator weighted values and weighted global quality factor (GQF) under Weighting Scenario 1.

alt_id	wFI	wCS	wGI	wRI	wMI	wII	wSI	wCI	wAI	wGQF
2A	0.60	0.30	1.20	0.26	0.14	0.87	0.30	0.16	0.60	4.43
2B	0.10	0.26	0.20	1.20	0.10	0.90	0.05	0.05	0.60	3.46
2C	0.60	0.05	1.20	0.20	0.60	0.15	0.14	0.09	0.10	3.13
2D	0.10	0.05	1.20	0.20	0.54	0.15	0.22	0.30	0.10	2.86

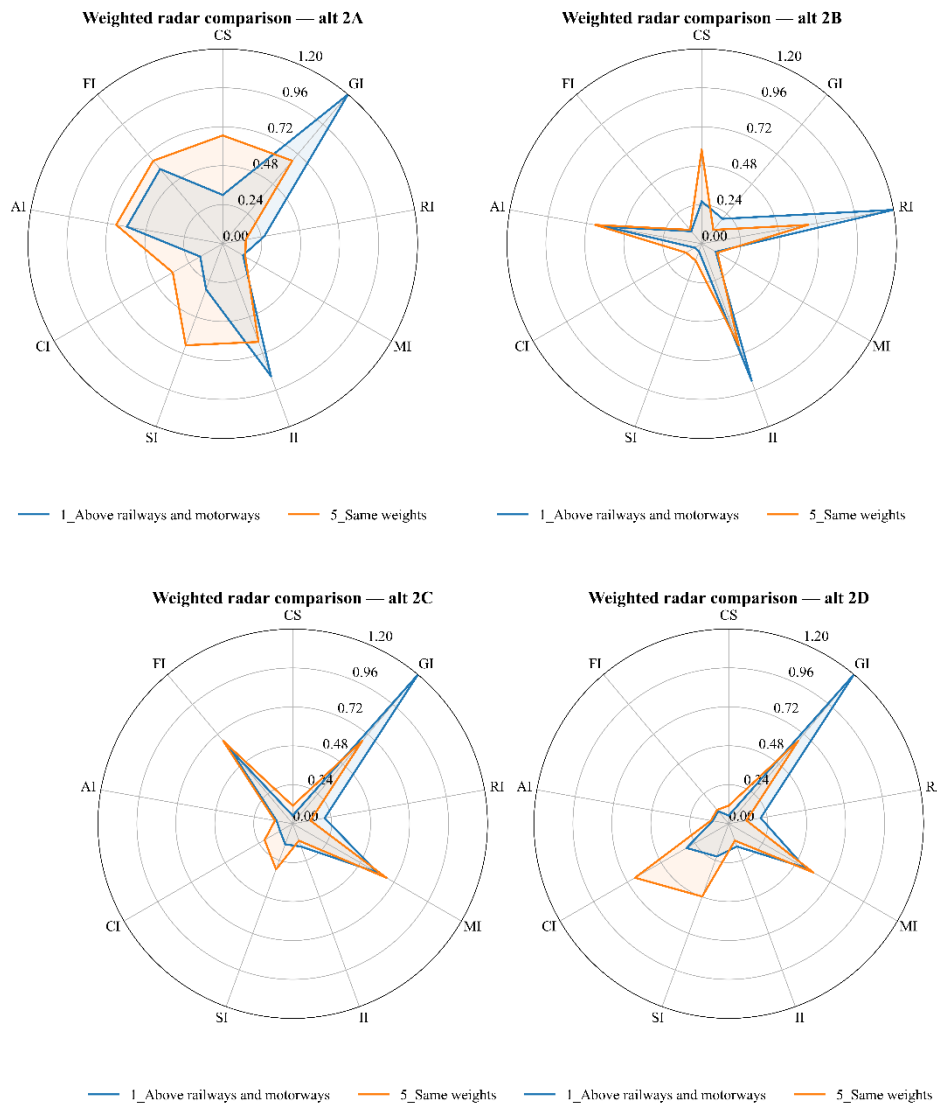


Figure 29 Case study 2. Radar chart comparing the performance of the four design alternatives under Weighting Scenario 1

3.4.4 Case-specific results

The interpretation of the results for Case Study 2 is first carried out prior to the application of any weighting scenario, in order to examine how the performance of the design alternatives is influenced by the initial analytical focus and by the selection of specific indicator groups. This preliminary reading is particularly relevant in the context of a feasibility study, where early design decisions are often guided by a limited set of dominant concerns.

When attention is restricted to the indicators associated with structural resilience, namely Resistance to collapse (RI), Maintenance (MI), and Inspectability (II), Alternative 2B emerges as the most favourable solution. This alternative achieves the maximum normalised score in RI, reflecting a high level of redundancy and favourable behaviour under abnormal or accidental scenarios. In addition, it performs very strongly in Inspectability (II), indicating reduced exposure to railway interference during inspection activities and a limited number of critical components requiring frequent access. Its performance in Maintenance (MI) is also competitive when compared with the other alternatives, suggesting a structurally efficient solution from an operational standpoint.

Within this restricted analytical perspective, the structurally articulated scheme adopted in Alternative 2B appears particularly well aligned with the dominant safety-driven assumptions underpinning the feasibility study. By contrast, Alternative 2A, despite its spatial and architectural articulation, exhibits lower unweighted values in RI, while Alternatives 2C and 2D, based on more conventional static schemes, show limited performance across all three resilience-related indicators. If the evaluation were to be based exclusively on this subset of criteria, the conclusion would naturally favour Alternative 2B as the most robust and operationally reliable option.

However, this reading also highlights a fundamental limitation of partial indicator-based interpretation. By focusing exclusively on resilience-related performance, other relevant dimensions of design quality, such as functional integration, spatial continuity, environmental performance, and adaptability, remain outside the scope of the analysis, despite being explicitly addressed by the framework. As a result, the apparent superiority of a given alternative reflects not an absolute assessment of quality, but rather the implicit assumptions embedded in the initial analytical focus.

In this sense, the unweighted results of Case Study 2 should be interpreted as a diagnostic phase rather than as a decision outcome. They illustrate how early design hypotheses and the prioritisation of specific performance dimensions can strongly influence the perceived ranking of alternatives, particularly in highly constrained infrastructural contexts such as railway crossings. This observation underlines the necessity of a holistic and structured multi-criteria evaluation, in which structural resilience is assessed alongside architectural, environmental, and long-term infrastructural considerations before any explicit prioritisation is introduced through weighting scenarios.

3.5 Case study 3

Competition for pedestrian and bicycle bridge in Niederwangen, (Switzerland)

3.5.1 Context and design objectives

This case study refers to an open, single-stage design competition promoted in 2024 by the Municipality of Köniz (Canton of Bern, Switzerland) for the construction of a new pedestrian overpass (“Passerelle Niederwangen”) in the area of the Niederwangen railway station. The competition was conducted in accordance with SIA Regulation 142 and formally defined through the official competition programme and accompanying documentation issued by the Municipality.

The procedure involved the disciplines of civil engineering, architecture, and landscape architecture, with civil engineering explicitly identified as a mandatory discipline for the planning teams. The intervention is positioned within a broader transformation process of the station district and the adjacent development area “Juch-Hallmatt”, including major public facilities such as the new Bern Police Centre. In this context, the primary objective is to provide a direct, high-quality pedestrian connection between the railway station and the development focus on the opposite side of the transport infrastructures.

Existing pedestrian routes are described in the competition documentation as unattractive and characterised by long detours, and they are not dimensioned for the expected increase in pedestrian demand linked to the planned urban developments. As illustrated by the pedestrian flow scheme (Figure 30) the footbridge is conceived as a strategic element within the local pedestrian network, intended to absorb and reorganise future movement patterns between the station and “Juch-Hallmatt” while improving legibility, comfort, and perceived safety of the connection.

The project therefore addresses not only a point-to-point crossing, but a network-level discontinuity generated by the coexistence of rail and major road infrastructures. The competition area and admissible construction perimeter (Figure 31) define a strongly constrained design environment, in which alignment, structural depth, and construction sequencing must be compatible with the operational requirements of the railway and the national road infrastructure.

The competition brief explicitly emphasises the need to control impacts on these infrastructures during construction and to account for additional constraints such as groundwater protection measures.

Within this framework, the competition seeks project proposals that combine functional efficiency, structural robustness, and long-term durability with a high degree of architectural and landscape integration.

Sustainability and everyday usability are explicitly addressed as evaluation dimensions, with reference to the SNBS Infrastructure standard (phase 2) and to criteria of *alltagsgerechte Planung*⁸ defined in the competition brief.

All design alternatives are therefore developed within the same contextual, regulatory, and functional conditions, allowing the subsequent assessment to focus on differences arising from conceptual and structural design choices rather than from site-dependent parameters.

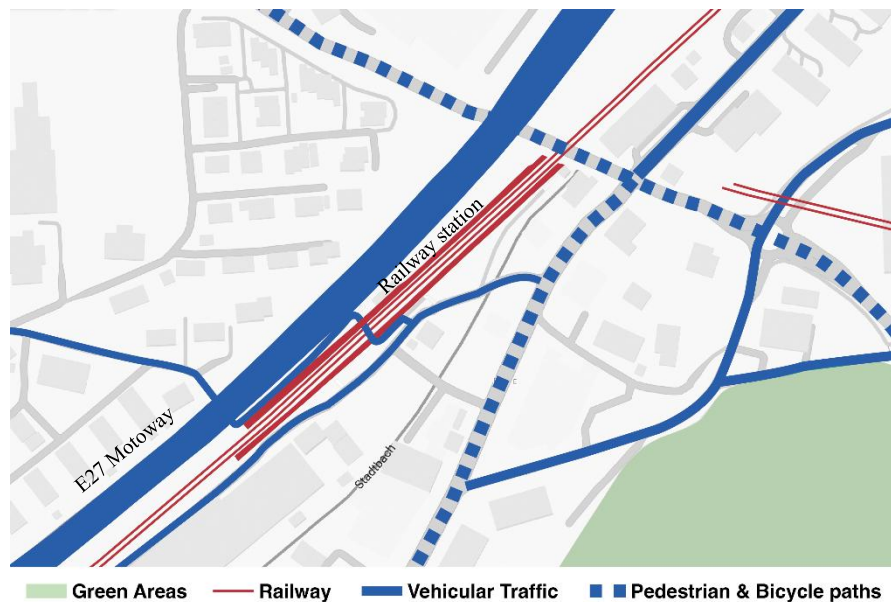


Figure 30 Case study 3 (Niederwangen): territorial and landscape context of the competition area, showing the relationship between the bridge site and surrounding infrastructure.

⁸ Available at <https://competitions.espazium.ch/de/wettbewerbe/aperti/passerelle-niederwangen>

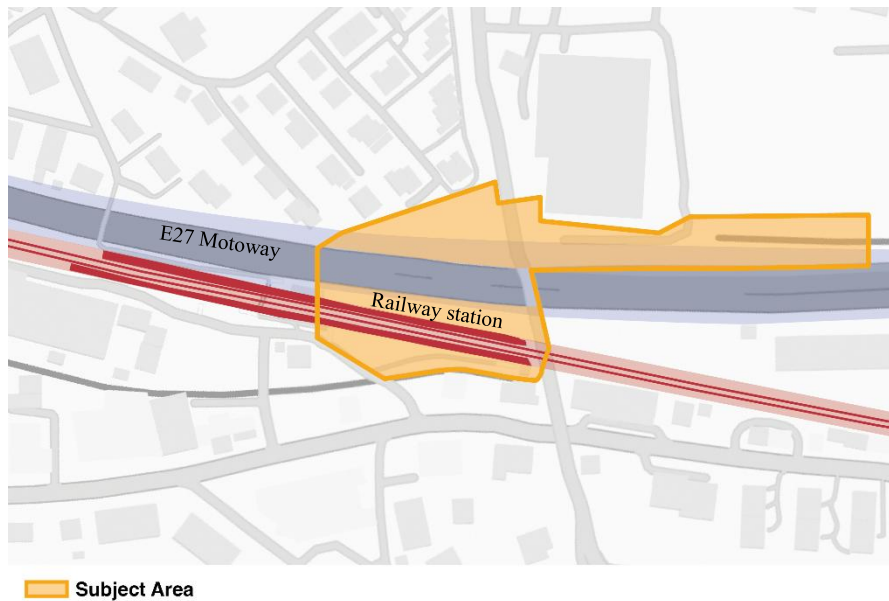


Figure 31 Case study 3 (Niederwangen): competition perimeter and spatial constraints defining the design problem and boundary conditions.

3.5.2 Design alternatives and input data

Within the competition framework, four design alternatives were developed for the same project area, all located within the competition perimeter and subject to identical functional, regulatory, and infrastructural constraints.

The competition area allows for different geometric layouts of the pedestrian crossing, leading to alternative alignments that respond to the same connectivity objectives under fixed boundary conditions.

Two alternatives adopt an alignment substantially perpendicular to the main road infrastructure, with the aim of minimising the overall bridge length, while the other two alternatives follow a diagonal alignment in order to establish a more direct connection towards the designated pedestrian access points. These differences in plan layout reflect distinct spatial strategies for addressing pedestrian connectivity within an extra-urban context characterised by major transport infrastructures. Despite the variation in alignment, all four alternatives share the same general static scheme.

The structural configuration is governed by the need to cross the railway and road corridors while respecting predefined and limited areas for structural supports. In all cases, the admissible locations for supports are restricted to the two outer

abutments and to an intermediate zone situated between the railway and the road infrastructure.

As a consequence, the alternatives are developed under identical structural boundary conditions, ensuring a consistent basis for comparison. While alignment and spatial configuration vary, the design alternatives differ primarily in terms of structural typology and material strategy, reflecting distinct conceptual approaches within a common static framework. This combination of variable geometric layout and fixed structural constraints provides a controlled setting for analysing the influence of spatial and structural choices on overall performance.

The extra-urban character of the site and the strong presence of transport infrastructures significantly influence the spatial organisation of the alternatives and play a relevant role in the evaluation of indicators within the Architecture and Planning macro-area.

Differences in alignment directly affect parameters related to functional integration, spatial continuity, and legibility of the pedestrian connection, which are explicitly captured by the corresponding indicators of the proposed decision-support framework.

Figure 32 illustrates the main input information related to site insertion and geometric configuration for the four alternatives, while Table 38 summarises the quantitative input data used for the subsequent multi-criteria assessment.

The four design alternatives are briefly described below, focusing on alignment strategy, structural typology, and material choice, while all other contextual and regulatory conditions are kept constant.

- Case 3A: straight alignment perpendicular to the motorway, adopting a spatial Vierendeel-type structural system composed of reused steel elements. The deck is supported by a continuous girder system resting on three supports, located at the two outer abutments and within the intermediate support zone between the transport infrastructures.
- Case 3B: diagonal alignment with longer spans compared to Case 3A, based on a twin steel truss system. The two parallel trusses are connected by transverse beams at deck level and at roof level, forming a three-dimensional structural configuration. The structure is supported by three reinforced concrete supports cast in situ, located at the two outer abutments and within the intermediate support zone.

- Case 3C: straight alignment perpendicular to the motorway, consistent with Case 3A, based on a central steel box-girder system. The deck is stiffened by transverse ribs and a continuous orthotropic deck plate acting as an in-plane stiffening element. The bridge is conceived as an uncovered structure and is supported by a continuous girder scheme resting on three supports located at the two outer abutments and within the intermediate support zone.
- Case 3D: straight alignment perpendicular to the motorway, based on a design-for-demountability approach. The structural system consists of two central steel HEB girders combined with secondary H-shaped steel beams, supporting a screwed CLT deck panel. All primary connections are realised using bolted joints and standardised steel profiles, allowing for disassembly and potential reuse of structural components. The bridge follows a continuous girder scheme resting on three supports located at the two outer abutments and within the intermediate support zone.

As the other cases the structural steel is modelled as low-carbon EAF steel with high recycled content. For the Niederwangen case study, the Global Warming Potential (GWP) is assessed over life cycle stages A1–C4 based on material-specific datasets from ÖKOBAUDAT and IBU.data, in accordance with EN 15804+A2. In the absence of consistent Swiss datasets for all materials, these are adopted as representative European proxies. Reused structural steel is modelled without allocation of primary production impacts (A1–A3), assuming these are attributed to the original life cycle, while only impacts related to transport and reconditioning processes (A4–A5) are considered. As the objective of the study is to compare alternative design solutions, this approach is considered appropriate and ensures methodological consistency across all scenarios.

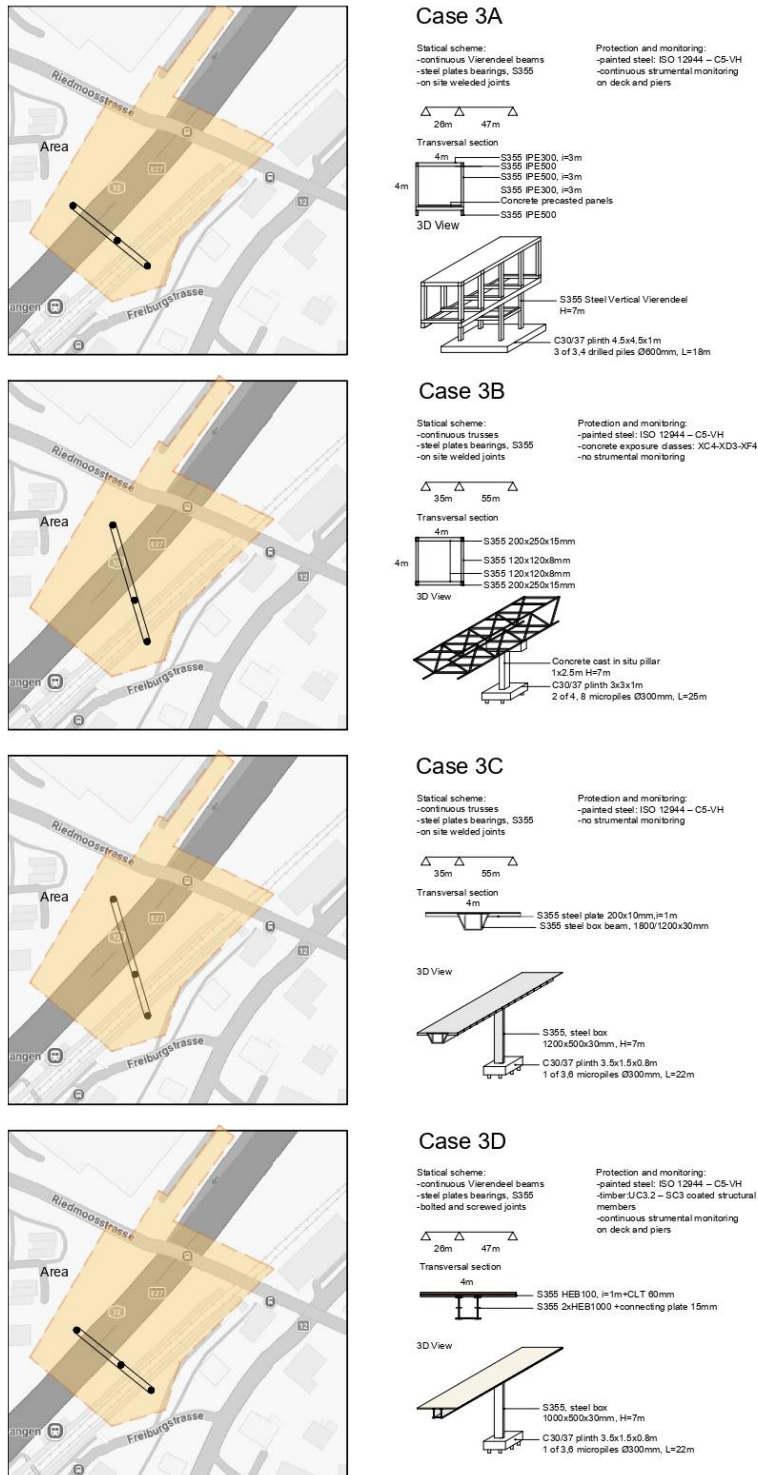


Figure 32 Case study 3: overview of the design alternatives proposed for the competition, highlighting structural configuration, span arrangement, and material strategy.

Table 38 Complete set of input data for the four design alternatives, structured according to the indicators defined in the proposed multi-criteria framework and used for the calculation of all indicator values.

Indicator	Case	U.M	3A	3B	3C	3D
RI	ULS_capacity	%	0.68	0.84	0.53	0.85
	GSA_percent_LL	%	0.36	0.07	0.60	0.50
	N_crit	n.	1	1	1	1
	N_tot	n.	7	7	5	6
	Hazard_label	-	2a3	2a3	2c3	2c3
MI	Life	Years	100	100	100	100
	Initial cost IC	chf	660000	750000	1565000	500000
	alfa id	-	tubular truss galvanized/ painted steel	tubular truss galvanized/ painted steel	continuous beam galvanized/ painted steel	continuous beam galvanized/ painted steel
	eta_joints	n.	3	3	3	3
	Joint types	-	Welded joints	Welded joints	Welded joints	Bolted joints
	eta_bearings	n.	3	3	3	3
	Bearing types	-	Bearings Galvanized / painted steel plates	Bearings Galvanized / painted steel plates	Bearings Galvanized / painted steel plates	Bearings Galvanized / painted steel plates
	Substructure materials	-	Main structure Galvanized / painted steel	Main structure Reinforced concrete	Main structure Galvanized / painted steel	Main structure Galvanized / painted steel
	Deck materials	-	Main structure Galvanized / painted steel	Main structure Galvanized / painted steel	Main structure Galvanized / painted steel	Main structure Galvanized / painted steel
II	Deck area	m2	292	360	360	292
	Lenght Main load-bearing members (girders, arches, trusses, cables, etc.)	m	341	660	450	438
	N°Main load-bearing members (girders, arches, trusses, cables, etc.)	n.	51	122	91	75
	N° Supports (piers and abutments, including visible parts of foundations)	n.	3	3	3	3
	N°Bearings and structural connections	n.	6	6	6	6
	N°Expansion joints / structural terminations	n.	2	2	2	2
	Ibridge Bearings and structural connections	-	0.5	0.5	0.5	0.5
	Ibridge Main load-bearing members (girders, arches, trusses, cables, etc.)	-	0.5	0.5	0.5	0.5
	Ibridge Supports (piers and abutments, including visible parts of foundations)	-	0.5	0.5	0.5	0.5
	Ibridge Bearings and structural connections	-	0.5	0.5	0.5	0.5

	Ibridge Expansion joints / structural terminations	-	0.5	0.5	0.5	0.5
	Ibelow Deck area	-	0.5	0.5	0.5	0.5
	Ibelow Main load-bearing members (girders, arches, trusses, cables, etc.)	-	0.5	0.5	0.5	0.5
	Ibelow Supports (piers and abutments, including visible parts of foundations)	-	0.5	0.5	0.5	0.5
	Ibelow Bearings and structural connections	-	0.5	0.5	0.5	0.5
	Ibelow Expansion joints / structural terminations	-	0.5	0.5	0.5	0.5
	Eq. Level	-	1	2	3	1
	Skills level	-	1	3	2	1
	Process level	-	1	2	2	1
SI	GWP_plan	kgCO ₂ eq	0	0	0	0
	GWP_A1-A5	kgCO ₂ eq	24153	68411	109966	115728
	GWP_B1-B7	kgCO ₂ eq	478	229	665	1981
	GWP_C1-C4	kgCO ₂ eq	1121	993	1191	2553
	C_plan	chf	92400	105000	219100	70000
	C_ A1-A5	chf	660000	750000	1565000	500000
	C_ B1-B7	chf	132000	150000	313000	100000
	C_ C1-C4	chf	99000	112500	234750	75000
	Scenario	-	B	B	B	B
CI	material_code	-	steel_bolted_S355	steel_bolted_S355	concrete_prestressed_precast	Glulam
	mass_kg	kg	429104	210975	277150	153850
	RM	kg	124000	0	0	0
	RU	kg	37200	18000	20000	18380
	RC	kg	222106.4	93543.75	190857.5	54672.5

3.5.3 Framework application

The proposed multi-criteria decision-support framework is applied to the four design alternatives developed for the Niederwangen competition in order to compare different spatial layouts and structural typologies within a shared and highly constrained infrastructural context. As in the previous applications, the problem framing and the indicator structure remain unchanged, ensuring methodological consistency across case studies, while the analysis focuses on the comparative and aggregative phases of the framework.

Given the specific characteristics of the site, the evaluation is carried out under two distinct weighting assumptions. Weighting Scenario 1 (Above railways and motorways) is adopted to reflect the dominant role of major transport infrastructures in defining the design problem. This scenario prioritises indicators related to structural resilience, robustness, inspection, and operational reliability, which are particularly critical in situations involving crossings above high-risk railway and motorway corridors.

In parallel, Weighting Scenario 2 (Urban context) is applied to explore the influence of spatial configuration and alignment strategies on overall performance. This scenario places greater emphasis on indicators belonging to the Architecture and Planning macro-area, allowing the effects of different layout choices, namely perpendicular versus diagonal alignments to be explicitly assessed in terms of functional integration, spatial continuity, and legibility of the pedestrian connection within an infrastructure-dominated environment.

For both scenarios, indicator values are calculated and normalised following the procedures described in Chapter 2, based on the decision input data summarised in Table 17. The resulting indicator profiles are subsequently aggregated under each weighting scenario, enabling a comparative interpretation of the four alternatives and an assessment of the sensitivity of the results to different priority structures.

The detailed indicator results grouped by macro-area are reported from Table 39 to

Table 45, while the aggregated and weighted global quality factors obtained under the two weighting scenarios are summarised in Table 47 and

Table 48. These results provide the analytical basis for the case-specific discussion presented in the following section.

Architectural and Planning

Table 39 Case study 3. Architecture and Planning indicator values, raw and normalized (1–6), for the four design alternatives.

alt_id	FI	CS	GI	FI_1_6	CS_1_6	GI_1_6
3A	0.83	0.75	0.83	4.30	6.00	6.00
3B	0.67	0.58	0.75	1.00	1.00	1.00
3C	0.67	0.58	0.75	1.00	1.00	1.00
3D	0.92	0.58	0.83	6.00	1.00	6.00

Structural Resilience

Table 40 Case study 3. Resistance to collapse indicator values, raw and normalized (1–6), for the four design alternatives.

alt_id	R	SL	H	RI	RI_1_6
3A	0.36	0.86	1.00	0.31	6.00
3B	0.07	0.86	1.00	0.06	1.00
3C	0.60	0.80	0.61	0.29	5.70
3D	0.50	0.83	0.61	0.25	4.90

Table 41 Case study 3. Maintenance indicator values, raw, aggregated, and normalized (1–6), for the design alternatives.

alt_id	alpha0	alpha	E	R	f_ERIC	MI	MI_1_6
3A	0.55	0.00	0.17	0.79	0.48	0.06	3.93
3B	0.55	0.00	0.17	0.74	0.45	0.05	3.54
3C	0.50	0.00	0.17	0.79	0.48	0.03	1.00
3D	0.50	0.00	0.17	0.84	0.50	0.08	6.00

Table 42 Case study 3. Inspection indicator values, raw, aggregated, and normalized (1–6), for the design alternatives.

alt_id	IE	Timpact	Tinsp	D1	Deq	Dex	Dpr	D	II	II_1_6
3A	1.00	10.62	21.24	0.50	1.00	1.00	1.00	0.75	0.75	6.00
3B	1.00	17.55	35.10	0.50	1.00	0.50	0.75	0.63	0.63	1.00
3C	1.00	13.35	26.70	0.50	1.00	0.75	0.75	0.67	0.67	2.70
3D	1.00	12.57	25.13	0.50	1.00	1.00	1.00	0.75	0.75	6.00

Environmental performance

Table 43 Case study 3. Sustainability indicator values, raw, aggregated, and normalized (1–6), for the design alternatives.

alt_id	GWP_sum	C_sum	GI	TC	SI_raw	SI_1_6
3A	25752	983400	0.732	33.678	0.137	6
3B	69633	1117500	2.701	31.042	0.086	3.3
3C	111822	2331850	5.138	64.774	0.043	1
3D	120262	745000	4.765	25.261	0.077	2.8

Table 44 Case study 3. Circularity indicator values, raw, aggregated, and normalized (1–6), for the design alternatives.

alt_id	CI	CI_1_6
3A	0.89	6.00
3B	0.53	1.60
3C	0.76	4.40
3D	0.48	1.00

Table 45 Case study 3. Adaptability indicator values, raw, aggregated, and normalized (1–6), for the design alternatives.

alt_id	AI	AI_1_6
3A	0.50	1.00
3B	0.50	1.00
3C	0.67	2.70
3D	1.00	6.00

Indicators Aggregation

Table 46 Case study 3. Aggregated indicator values and global quality factor (GQF)

alt_id	FI	CS	GI	RI	MI	II	SI	CI	AI	GQF
3A	4.30	6.00	6.00	6.00	3.93	6.00	6.00	6.00	1.00	45.23
3B	6.00	1.00	6.00	4.90	6.00	6.00	2.80	1.00	6.00	39.70
3C	1.00	1.00	1.00	5.70	1.00	2.70	1.00	4.40	2.70	20.50
3D	1.00	1.00	1.00	1.00	3.54	1.00	3.30	1.60	1.00	14.44

Indicators weighting

Table 47 Case study 3. Indicator weighted values and weighted global quality factor (GQF) under Weighting Scenario 1.

alt_id	wFI	wCS	wGI	wRI	wMI	wII	wSI	wCI	wAI	wGQF
3A	0.43	0.30	1.20	1.20	0.39	0.90	0.30	0.30	0.10	5.12
3B	0.60	0.05	1.20	0.98	0.60	0.90	0.14	0.05	0.60	5.12
3C	0.10	0.05	0.20	1.14	0.10	0.41	0.05	0.22	0.27	2.54
3D	0.10	0.05	0.20	0.20	0.35	0.15	0.17	0.08	0.10	1.40

Table 48 Case study 3. Indicator weighted values and weighted global quality factor (GQF) under Weighting Scenario 2.

alt_id	wFI	wCS	wGI	wRI	wMI	wII	wSI	wCI	wAI	wGQF
3A	0.43	1.20	1.20	0.30	0.20	0.30	0.60	0.60	0.15	4.98
3B	0.60	0.20	1.20	0.25	0.30	0.30	0.28	0.10	0.90	4.13
3C	0.10	0.20	0.20	0.29	0.05	0.14	0.10	0.44	0.41	1.92
3D	0.10	0.20	0.20	0.05	0.18	0.05	0.33	0.16	0.15	1.42

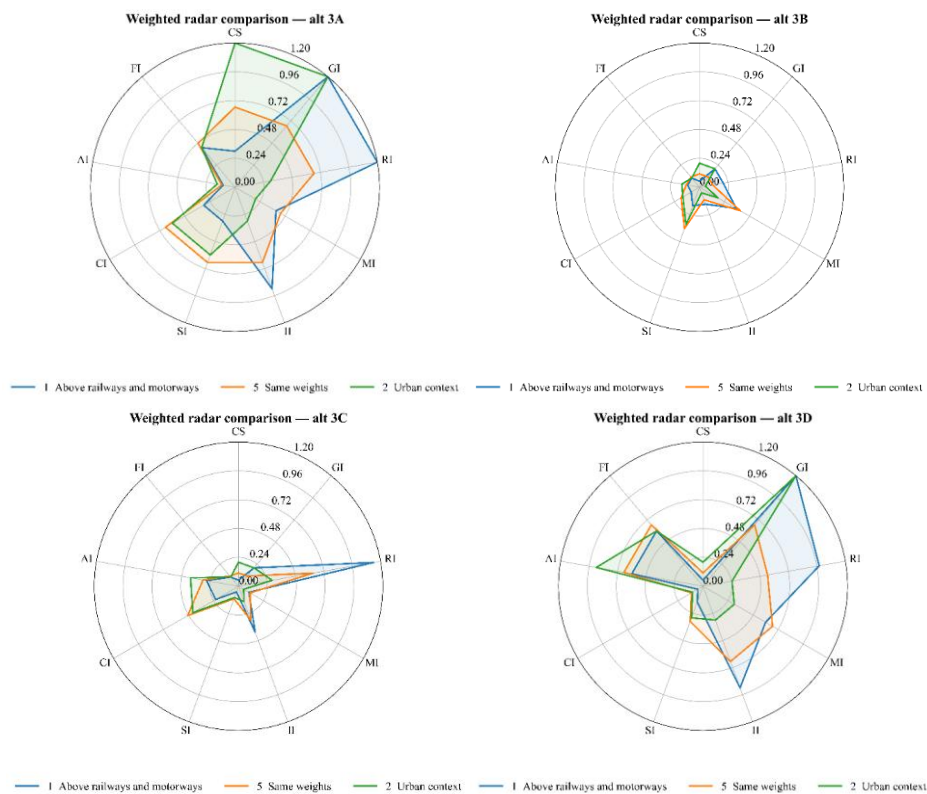


Figure 33 Case study 3. Radar chart comparing the performance of the four design alternatives under Weighting Scenarios 1 and 2

3.5.4 Case-specific results

The results of Case Study 3 are interpreted by progressively examining the outcomes obtained under different analytical assumptions, starting from the unweighted indicator aggregation and subsequently considering the effects introduced by the application of the weighting scenarios defined for this competition context.

When the aggregated results are analysed without the application of weighting scenarios (Table 45), Alternative 3A clearly emerges as the highest-performing solution. This outcome is the result of a consistently strong performance across all macro-areas, with particularly high values in Structural Resilience, Environmental Performance, and Circularity. The straight and compact alignment adopted in Alternative 3A, combined with a continuous structural scheme and the use of reused steel elements, leads to a favourable balance between robustness, operational simplicity, and life-cycle efficiency. As a consequence, Alternative 3A achieves a high Global Quality Factor even in the absence of any explicit prioritisation among indicators.

From a structural perspective, the unweighted superiority of Alternative 3A is largely driven by its excellent performance in Resistance to collapse (RI) and Inspectability (II). The limited number of critical components, the clarity of the load-bearing system, and the reduced exposure of structural elements above transport infrastructures contribute to a robust and easily inspectable configuration. At the same time, the reuse-oriented material strategy results in very low environmental impacts and high circularity scores, reinforcing the overall performance of the alternative when all indicators are treated with equal relevance.

When Weighting Scenario 1 (Above railways and motorways) is applied (Table 46), the ranking of the alternatives changes significantly. Under this scenario, Alternatives 3A and 3B achieve equivalent weighted Global Quality Factors, indicating comparable overall performance when priority is assigned to indicators related to structural resilience, robustness, inspection, and operational reliability. While Alternative 3A continues to benefit from its compact configuration and strong inspection-related performance, Alternative 3B gains relevance due to the intrinsic redundancy of its twin-truss structural system. The three-dimensional load transfer mechanisms and the distributed structural behaviour of the truss solution provide favourable characteristics under abnormal and accidental loading scenarios, which are explicitly emphasised in this weighting scheme. The

convergence of performance between Alternatives 3A and 3B under Weighting Scenario 1 highlights how structurally articulated systems, although more complex and materially intensive, can become competitive when safety-oriented priorities dominate the evaluation. In this context, the increased length and structural complexity of Alternative 3B, which are penalised in unweighted or environmentally oriented assessments, are counterbalanced by its robustness-related advantages. By contrast, Alternatives 3C and 3D remain clearly separated from the leading options under Weighting Scenario 1. In particular, Alternative 3D exhibits a comparatively low weighted performance despite its explicit design-for-demountability strategy. Although the extensive use of bolted connections and standardised steel profiles provides advantages in terms of adaptability and potential reuse, the resulting structural system shows limited redundancy and lower performance in Resistance to collapse (RI). In addition, the exposure of multiple primary components increases inspection demands above critical infrastructures, negatively affecting Inspectability (II). These aspects significantly reduce the suitability of Alternative 3D in a scenario dominated by safety and operational reliability requirements. Under Weighting Scenario 2 (Urban context) (Table 47), which assigns greater importance to indicators belonging to the Architecture and Planning macro-area, Alternative 3A once again emerges as the top-ranked solution. Its straight alignment perpendicular to the motorway ensures a clear and legible pedestrian connection, minimises detours, and supports efficient integration within the local pedestrian network. These characteristics are directly reflected in high values for Functional Integration (FI) and Geometric Integration (GI). Alternative 3B, despite offering a more expressive diagonal alignment, is penalised under this scenario by its increased length and structural complexity, which reduce its functional efficiency and spatial clarity within the given extra-urban context. Overall, the results of Case Study 3 demonstrate that Alternative 3A represents a robust and consistently high-performing solution across all analytical assumptions, confirming the effectiveness of its underlying conceptual strategy. Alternative 3B emerges as a competitive option only when safety-driven priorities dominate the evaluation, while Alternatives 3C and 3D remain systematically disadvantaged due to structural and operational limitations that outweigh their potential benefits within the specific competition framework. The case study therefore illustrates how the relative performance of design alternatives is strongly influenced by the adopted weighting assumptions, while also highlighting the value of solutions capable of maintaining high performance across multiple evaluative perspectives.

Chapter 4

Results and Discussion

4.1 Cross-case synthesis and patterns

The application of the proposed multi-criteria framework to the three case studies, Delémont, Turin, and Niederwangen, enabled an evaluation of its behavior under heterogeneous design conditions and weighting scenarios. Each case study represents a site-specific validation of the method, corresponding respectively to a constrained design competition, an urban feasibility study, and an open-context competition.

Since the datasets are not statistically comparable in absolute terms, the analysis was conducted on an intra-case basis. Although the final rankings rely on normalized dimensionless indicators, the use of physically meaningful quantities during indicator formulation remains important.

These quantities preserve transparency and traceability between the evaluation results and the underlying structural, environmental, and operational characteristics of the alternatives. Their role is therefore not to support direct statistical comparison between different case studies, but rather to maintain a direct connection between the assessment and measurable project attributes, while preserving the possibility of future benchmark- or target-based applications.

Accordingly, the interpretation of results is primarily based on the relative performance of alternatives within each case study, while the cross-case discussion focuses on the identification of recurring patterns and context-dependent dynamics rather than on direct numerical comparison.

Across all cases, three consistent observations can be identified.

- First, the Structural Resilience indicators, namely Resistance to collapse (RI), Maintainability (MI), and Inspectability (II), exhibit a stable and coherent behaviour within each case study. Although their relative influence on the global score varies according to the applied weighting scenario, these indicators consistently play a decisive role in differentiating alternatives. This confirms the capacity of the framework to capture essential structural qualities that are largely independent of contextual variability.
- Second, Environmental and lifecycle-related indicators, including Sustainability (SI), Circularity (CI), and Adaptability (AI), show higher variability across alternatives and case studies. Their behaviour is

strongly influenced by material strategy, construction logic, and reuse potential, making them particularly sensitive to design choices rather than to contextual constraints. This variability highlights their role as design-driven indicators and confirms their relevance in supporting early-stage exploration of alternative strategies.

- Third, Architecture and Planning indicators, namely Feasibility (FI), Contextual Sensitivity (CS), and Geometric Integration (GI), remain relatively invariant within each case study. This behaviour reflects the fact that these indicators are primarily determined by site-specific spatial, regulatory, and urban constraints that are common to all alternatives within a given project. Their limited variability confirms their function as boundary conditions rather than as performance differentiators.

Taken together, these observations demonstrate that the framework effectively distinguishes between context-determined and design-driven dimensions of quality. This ability to preserve internal coherence while remaining sensitive to design variability supports the framework's applicability across heterogeneous conditions without loss of interpretability.

4.2 Indicators trade-offs and interdependencies

To investigate how the indicators interact within each case study, correlation matrices were computed using the unweighted indicator scores on a 1 to 6 scale. Each indicator was treated as a quantitative variable, while each design alternative was considered an observation. Correlation analysis is employed to explore whether variations in one indicator are systematically associated with variations in another across the set of conceptual alternatives.

Pearson's correlation coefficient was adopted as a descriptive and diagnostic measure. The indicators are expressed on a normalised numerical scale with consistent intervals and are intended to represent relative performance differences rather than ordinal rankings. Under these conditions, Pearson correlation is appropriate for identifying linear co-variation patterns while preserving information on the relative magnitude of variations (Montgomery, 2012; Norman, 2010). The objective of the analysis is not statistical inference, but the assessment of the internal coherence and logical consistency of the indicator system when applied to real design situations.

The use of correlation analysis in this context is consistent with established practices in multi-criteria decision analysis, where correlations are applied to explore interdependencies among criteria and to support the interpretation of trade-offs rather than to derive predictive models (Figueira et al., 2005).

In bridge design and sustainability-oriented decision frameworks, Pearson correlation has been explicitly used to analyse relationships among structural, environmental, and lifecycle indicators as part of exploratory and comparative assessments (Milani & Kripka, 2020b).

Given the site-specific nature of the case studies, correlation values are interpreted in relation to the design context and to the underlying structure of the indicator system, rather than through predefined thresholds or tests of statistical significance. Indicators exhibiting zero variance across alternatives result in mathematically undefined correlation values and are therefore reported as zero, indicating the absence of observable co-variation within the analysed design space.

Within the proposed framework, correlation analysis serves as an interpretative tool that supports the identification of synergies and trade-offs emerging from different structural, material, and spatial design strategies at the conceptual stage. This approach is consistent with recent multi-criteria frameworks for resilient and sustainable infrastructure design, where correlations are used to enhance transparency and understanding of indicator interactions rather than to optimise a single objective (Choobdarian & Biondini, 2025).

4.2.1 Case study 1

The correlation analysis for the Delémont case study, reported in Figure 34, was conducted using the unweighted aggregated indicator values, in order to examine interaction patterns among indicators independently of weighting assumptions.

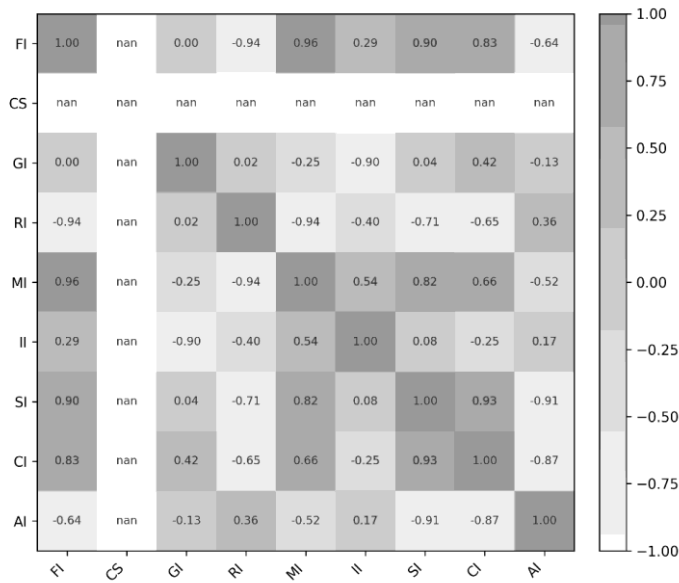


Figure 34 Correlation heat matrix of aggregated indicator values (unweighted, normalised scale 1–6) for Case Study 1.

Here, the key observations emerging from the correlation heat matrix are summarised and briefly discussed.

- MI–SI (+) and MI–CI (+): strong synergy between maintainability, sustainability, and circularity, indicating that material-efficient and reuse-oriented solutions also tend to perform favourably in terms of long-term operation and maintenance.
- SI–CI (+): sustainability and circularity are closely aligned, confirming the consistency between life-cycle environmental performance and reuse strategies.
- RI–SI (–) and RI–CI (–): resistance to collapse exhibits an inverse relationship with sustainability and circularity, revealing a trade-off between robustness-oriented structural strategies and material-efficient solutions.
- CI–AI (–): circularity shows an inverse relationship with adaptability, highlighting a tension between highly optimised reuse strategies and flexibility-oriented structural configurations.
- Architecture and Planning indicators show no variance across alternatives and therefore do not contribute to correlation patterns.

The correlation structure observed in Figure 34 provides insight into how different dimensions of performance interact within the constrained design space of the Delémont competition. Because all alternatives are developed for the same site and under identical regulatory and geometric conditions, Architecture and Planning indicators act as fixed boundary conditions rather than active drivers of differentiation. As a result, the observed interaction patterns primarily reflect relationships among structural performance, lifecycle behaviour, and material strategy. The strong co-variation between Maintainability, Sustainability, and Circularity indicates that, in this context, solutions characterised by reduced material intensity and reuse-oriented design approaches tend to perform consistently well across multiple lifecycle-related dimensions. This confirms that environmental performance is not an isolated outcome but is closely linked to construction logic and long-term operational considerations at the conceptual design stage. At the same time, the inverse relationship between Resistance to collapse and both Sustainability and Circularity highlights an inherent tension between robustness-oriented structural strategies and material-efficient solutions. Structural configurations that maximise redundancy and robustness tend to rely on increased material quantities or more complex assemblies, which negatively affects environmental and circularity-related indicators under the given constraints. This trade-off is not absolute but emerges clearly within the limited range of feasible solutions defined by the competition brief.

The negative relationship between Circularity and Adaptability further suggests that reuse-oriented solutions in this case study are highly optimised for the specific context and therefore less flexible with respect to future modification or functional change. This reflects a design logic in which performance optimisation under tight constraints may limit the potential for adaptability, even when reuse and sustainability objectives are explicitly addressed.

Overall, the Delémont case study demonstrates how correlation analysis can reveal latent performance tensions that are not immediately apparent from aggregated scores alone. These interaction patterns help explain why certain alternatives exhibit comparable overall performance when unweighted indicators are considered yet diverge significantly once specific weighting scenarios are applied. In this sense, the correlation analysis supports a more informed interpretation of the multi-criteria results, clarifying the structural and environmental implications of different conceptual strategies before preference-driven aggregation is introduced.

4.2.2 Case study 2

As in Case Study 1, the correlation matrix shown in Figure 35 is constructed using the unweighted aggregated indicator values, allowing interaction patterns among indicators to be examined independently of any weighting assumptions. This approach makes it possible to interpret the internal structure of the indicator system prior to the introduction of preference-driven priorities.

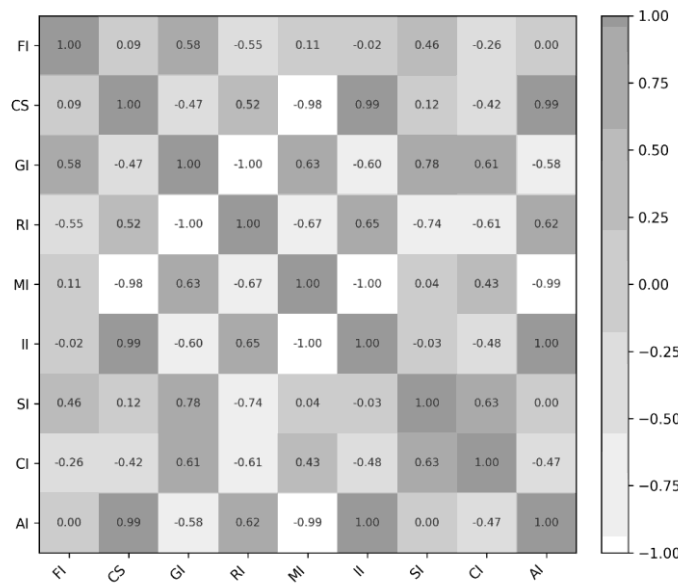


Figure 35 Correlation heat matrix of aggregated indicator values (unweighted, normalised scale 1–6) for Case Study 2.

Here, the key observations emerging from the correlation heat matrix are summarised and briefly discussed.

- RI–SI (+) and RI–CI (+): positive co-variation between resistance to collapse, sustainability, and circularity, indicating that structurally robust solutions can simultaneously support low environmental impact and reuse-oriented strategies.
- II–CI (+): strong relationship between inspectability and circularity, reflecting the role of accessible and demountable structural systems in enhancing both operational reliability and reuse potential.
- MI shows weaker correlations with other indicators, suggesting a reduced influence of maintenance constraints in this extra-urban context.

- Architecture and Planning indicators primarily reflect alignment strategies and spatial configuration, without generating systematic antagonisms with structural or environmental performance.

As in Case Study 1, the correlation matrix reported is constructed using the unweighted aggregated indicator values, allowing the interaction patterns among indicators to be analysed independently of any weighting assumptions. This approach enables the internal structure of the indicator system to be examined before preference-driven priorities are introduced and is particularly relevant in a feasibility-study context characterised by strong external constraints.

The correlation structure observed in Figure 35 reflects the highly constrained urban and railway-dominated environment of the Turin case study. In this context, strict safety requirements, limited geometric flexibility, and the need to minimise interference with active railway operations strongly condition the relationships between structural performance, lifecycle behaviour, and circular design objectives.

The pronounced inverse relationship between Resistance to collapse (RI) and Circularity (CI) highlights a fundamental tension between robustness-oriented structural strategies and reuse-oriented solutions. Structurally conservative configurations, designed to ensure safety and operational reliability, typically rely on increased material quantities, redundancy, or irreversible construction techniques. Under the given urban constraints, these characteristics tend to reduce the potential for disassembly and reuse, thereby negatively affecting circularity-related performance.

By contrast, the strong positive co-variation observed between Maintainability (MI), Sustainability (SI), and Adaptability (AI) reveals a consistent lifecycle-oriented synergy. Design solutions characterised by simplified construction logic, reduced material diversity, and standardised components tend to perform favourably across multiple lifecycle-related dimensions. In this feasibility-driven context, adaptability emerges not primarily as geometric flexibility, but as the capacity to accommodate maintenance, inspection, and limited future adjustments within a constrained spatial framework.

The inverse relationship between Architecture and Planning indicators (Feasibility, Contextual Sensitivity, and Geometric Integration) and Adaptability further underscores how improvements in spatial feasibility and contextual fit are often achieved at the expense of long-term flexibility. The need to comply with

strict alignment, clearance, and access constraints leads to highly optimised solutions that leave little margin for future modification.

Overall, the Turin case study demonstrates how correlation analysis based on unweighted indicators can reveal context-induced antagonisms that are not immediately apparent from aggregated scores alone. The observed interaction patterns explain why robustness-oriented alternatives tend to be favoured under safety-driven weighting scenarios, while also clarifying the structural and contextual limitations encountered by circular and adaptability-oriented strategies in dense urban feasibility conditions.

4.2.3 Case study 3

The correlation heat matrix reported in Figure 36 is derived from the unweighted aggregated indicator values and provides a direct representation of the interaction patterns among performance dimensions within the conceptual design space of the Niederwangen competition. By excluding weighting assumptions, the analysis highlights intrinsic relationships among indicators that are primarily driven by structural concept, material strategy, and spatial configuration.

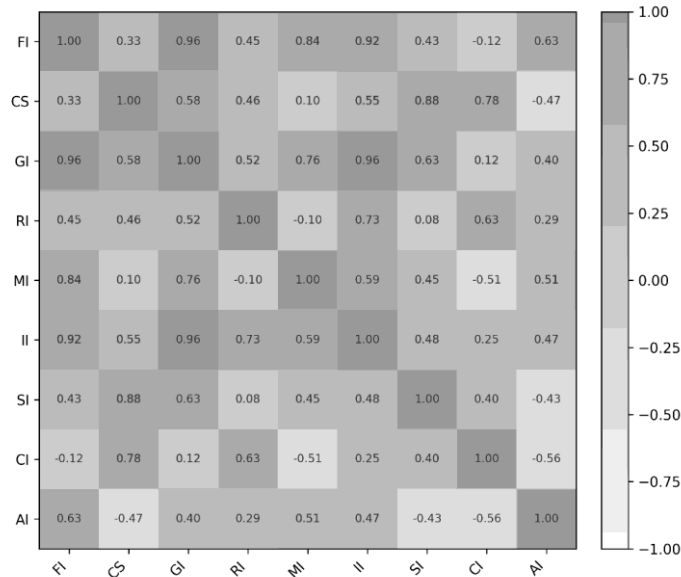


Figure 36 Correlation heat matrix of aggregated indicator values (unweighted, normalised scale 1–6) for Case Study 3.

The main interaction patterns emerging from the correlation heat matrix can be summarized as follows:

- • RI–SI (+) and RI–CI (+): positive co-variation between resistance to collapse, sustainability, and circularity, indicating that structurally robust solutions can be achieved without compromising environmental performance or reuse potential.
- • II–CI (+): strong relationship between inspectability and circularity, highlighting how accessible and demountable structural systems simultaneously support inspection, maintenance, and disassembly.
- • MI (weak correlations): maintainability exhibits relatively weak correlations with other indicators, reflecting the reduced influence of maintenance constraints in the extra-urban context of the Niederwangen site.
- • Architecture and Planning indicators: spatial configuration and alignment strategies remain largely independent from structural and environmental performance, suggesting that contextual integration does not generate significant antagonisms with other design dimensions.
- These interaction patterns reflect the extra-urban context of the Niederwangen competition, where greater geometric freedom and reduced interference with existing infrastructure allow a wider range of structural and material strategies to be explored at the conceptual stage.

Overall, the Niederwangen case study shows how correlation analysis based on unweighted indicators can reveal conditions in which conventional trade-offs between robustness, sustainability, and circularity are mitigated or even reversed. The observed interaction patterns confirm the framework’s sensitivity to contextual variability and its ability to identify design situations in which structural resilience, environmental performance, and circularity can be coherently aligned at the conceptual design stage.

4.2.4 Cross-Case Synthesis

The cross-case comparison confirms that the proposed multi-criteria framework captures stable conceptual relationships while remaining strongly sensitive to contextual and design-specific conditions. Through the analysis of correlation matrices derived from unweighted aggregated indicator values, the framework enables the comparison of interaction patterns across heterogeneous projects independently of weighting assumptions, thereby revealing latent synergies and conflicts embedded within the conceptual design space.

Across the three case studies, several interaction patterns exhibit consistent behaviour. In particular, positive relationships between Maintainability (MI) and Sustainability (SI) are observed in all cases, although with varying intensity. This recurring co-variation confirms the internal coherence of the indicator structure and supports the interpretation of lifecycle-related indicators as mutually reinforcing dimensions at the conceptual stage. A similar tendency is observed in the relationship between Maintainability (MI) and Inspectability (II), reflecting shared dependencies on construction logic, accessibility, and overall system simplicity. The persistence of these relationships across different projects validates the robustness of the framework under diverse regulatory, spatial, and infrastructural conditions.

In contrast, other indicator pairs display pronounced variability in both sign and magnitude, highlighting the framework's sensitivity to contextual constraints and design strategies. The relationships between Resistance to collapse (RI) and Sustainability (SI), as well as between Resistance to collapse (RI) and Circularity (CI), invert across the three case studies. In the constrained urban environments of Delémont and Turin, robustness-oriented strategies tend to conflict with environmental and circularity objectives. In these contexts, resistance to collapse is commonly achieved through increased material quantities, structural complexity, or redundancy constrained within limited geometric envelopes, which negatively affects lifecycle-related indicators.

By contrast, the Niederwangen case study demonstrates that resistance to collapse and sustainability are not inherently conflicting objectives. In this extra-urban context, favourable boundary conditions, including spatial availability, construction accessibility, and reduced interference with existing infrastructures, enable the adoption of structurally redundant and standardised systems without penalising environmental performance. Here, circularity is not primarily driven by extreme material optimisation, but by the availability of reusable components, ease of disassembly, and constructive redundancy, which often involves locally over dimensioned elements. These characteristics simultaneously enhance robustness against disproportionate collapse while supporting reuse potential, durability, and lifecycle efficiency. In this setting, redundancy and over dimensioning do not represent inefficiencies, but function as enabling factors that align robustness and sustainability, resulting in a strong positive correlation between Resistance to collapse and Sustainability.

The Turin feasibility study further highlights the methodological relevance of unweighted multi-indicator analysis. In this highly constrained urban context, strong antagonisms between robustness and circularity coexist with pronounced synergies among maintenance, adaptability, and sustainability. These interaction patterns are not immediately evident when indicators are considered individually or solely through weighted aggregation. Instead, they emerge clearly through correlation analysis, demonstrating that a holistic, multi-indicator interpretation is essential to avoid partial or misleading conclusions in feasibility-driven decision processes. The Turin case therefore illustrates that correlation analysis performed prior to weighting plays a critical interpretative role within the framework, revealing structural tensions that inform, rather than merely follow, preference-driven aggregation.

The relationship between Circularity (CI) and Adaptability (AI) further reinforces this interpretation. The absence of a stable correlation across cases indicates that circularity and adaptability do not inherently coincide but align only when flexibility is explicitly embedded as a design objective. In Niederwangen, circularity is primarily supported by redundancy, accessibility, and component availability rather than by adaptability in the strict sense. Conversely, in constrained urban contexts, adaptability is often limited by geometric and regulatory conditions, even when circularity objectives are actively pursued.

Overall, the cross-case synthesis demonstrates that the proposed framework achieves a balance between conceptual stability and contextual responsiveness. Stable interaction patterns confirm the internal logic of the indicator system, while context-dependent inversions highlight its capacity to reflect real design variability. By combining unweighted correlation analysis with scenario-based weighting, the framework supports a nuanced and transparent interpretation of early-stage design decisions. It thus functions not only as a ranking tool, but as an analytical instrument capable of clarifying the structural, environmental, and lifecycle implications of alternative conceptual strategies before normative priorities are imposed.

These interaction patterns are synthesised visually in Figure 37, which provides a compact cross-case overview of stable synergies and context-dependent inversions among the key indicator pairs identified through unweighted correlation analysis.

	Case 1	Case 2	Case 3
RI-SI	–	–	+
RI-CI	+	–	+
MI-SI	+	+	+
CI-AI	–	+	≈

Figure 37 Grayscale shading and symbols indicate the sign of correlation; the symbol ($\approx$) denotes the absence of systematic co-variation among the analysed alternatives.

4.3 Contextual constraints and the role of weighting scenarios

The application of the proposed multi-criteria framework across the three case studies highlights the decisive role of contextual constraints in shaping the conceptual design space prior to any weighting or aggregation process. Urban density, infrastructural interference, regulatory prescriptions, construction logistics, and operational requirements define the range of admissible structural and material solutions, thereby constraining both the variability of individual indicators and their mutual interactions. As demonstrated in the previous sections, these conditions act upstream of the decision process and cannot be neutralised or compensated through weighting assumptions.

The unweighted correlation analyses presented in Section 4.2 show that many of the most relevant synergies and antagonisms among indicators emerge independently of weighting scenarios. These interaction patterns reflect intrinsic relationships between structural behaviour, construction logic, and lifecycle performance within a given context. In constrained urban environments, such as those represented by the Delémont competition and the Turin feasibility study, the design space is characterised by strong geometric and operational limitations. Under these conditions, robustness-oriented strategies tend to rely on increased material quantities, structural complexity, or tightly constrained redundancy, which amplifies trade-offs with environmental and circularity-related indicators. Conversely, the Niederwangen case study demonstrates that reduced contextual constraints allow alternative design logics based on redundancy, standardisation, and accessibility, leading to synergistic relationships between robustness and sustainability.

Within this framework, weighting scenarios are introduced as an explicitly normative layer of the decision-support process. As discussed in Chapter 2, weighting scenarios are defined as structured representations of alternative priority settings rather than as universally valid coefficients, and their detailed formulation is therefore not reiterated here. Their purpose is not to modify or correct the analytical structure of the problem, but to articulate explicit preferences once the underlying relationships among indicators have been identified.

The case studies confirm that weighting scenarios do not generate new relationships among indicators, nor do they alter the interaction structures revealed through unweighted analysis. Instead, they function as interpretative devices that emphasise specific dimensions of performance in accordance with predefined priorities, such as safety, sustainability, or spatial integration. Consequently, different weighting assumptions may lead to different rankings of design alternatives without undermining the analytical consistency of the framework or the validity of the indicator relationships themselves.

This distinction clarifies the methodological role of weighting within the proposed approach. Weighting is not conceived as a corrective mechanism for contextual constraints, but as a transparent means of translating strategic objectives into decision-oriented outcomes. By clearly separating exploratory analysis from preference-driven aggregation, the framework supports a two-step reasoning process at the conceptual design stage. First, unweighted multi-indicator analysis is used to explore the structure of the design space, identify latent synergies and conflicts, and understand the implications of alternative structural and material strategies. Second, weighting scenarios are applied to support decision-making in line with explicit priorities, without obscuring the analytical insight gained in the exploratory phase.

In this sense, the proposed framework does not reduce conceptual design to a purely numerical optimisation problem. Rather, it provides a structured environment in which contextual constraints, performance interactions, and normative choices are made explicit and traceable. This separation enhances interpretability, reduces the risk of misleading rankings, and strengthens the framework's value as a decision-support tool capable of mediating between engineering reasoning, sustainability objectives, and project-specific decision contexts.

4.4 Validation and limitations

The validation of the proposed multi-criteria framework is grounded in its application to three real and heterogeneous design situations, each characterised by distinct spatial, regulatory, and infrastructural conditions. Rather than aiming at numerical verification or predictive accuracy, the validation strategy adopted in this research focuses on assessing the framework's capacity to structure, clarify, and support conceptual design reasoning in a transparent, traceable, and reproducible manner.

Across all applications, the framework demonstrated a high level of internal coherence. Indicators belonging to the same macro-areas exhibited consistent and interpretable behaviour, while correlation analyses confirmed the presence of logical relationships between structural, environmental, and lifecycle dimensions. These results indicate that the indicator system preserves conceptual consistency when applied to different contexts, supporting the robustness of its hierarchical structure and the validity of the underlying design logic.

Operational validity was confirmed through the practical implementation of the framework using standard design information available at the conceptual stage. All five methodological steps were successfully applied using conventional calculation tools and spreadsheet-based workflows, demonstrating that the framework can be employed without reliance on specialised software or advanced computational infrastructures. This operational simplicity enhances reproducibility and supports the transferability of the method to both academic research and professional design practice.

A defining aspect of the validation concerns the framework's contextual adaptability. Despite substantial differences among the three case studies in terms of scale, material strategy, and regulatory constraints, the evaluation logic remained stable and interpretable. At the same time, the framework proved sensitive to site-specific conditions, allowing context-driven interactions between indicators to emerge clearly. This balance between structural stability and contextual responsiveness confirms that the framework operates as a flexible reasoning system rather than as a rigid evaluation protocol.

From an epistemological perspective, it is important to clarify that the framework does not adopt a statistical inference approach. Each case study is based on four intentionally constructed conceptual design alternatives developed within

real professional design processes and under actual regulatory, spatial, and technical constraints. These alternatives do not constitute a statistical sample but represent deliberate and coherent project propositions formulated to explore a bounded solution space under shared boundary conditions. They are neither random nor independent observations, but mutually related design options generated within the same project context. As such, the assumptions required for inferential statistics, including population representativeness and stochastic variability, are not satisfied. Applying statistical tests in this context would therefore introduce methodological artefacts and risk conveying a false sense of objectivity. Instead, correlation analysis is employed as an exploratory and diagnostic tool, consistent with established practices in multi-criteria decision analysis and design methodology, to reveal interaction patterns and trade-offs without implying statistical causality or generalisation.

Within this validated scope, the framework also exhibits clearly defined boundaries that delimit its intended domain of application. First, the framework presupposes a coherent problem framing and a well-defined set of design alternatives. While it enhances transparency and comparability, it does not compensate for inadequate formulation of the design problem or for poorly articulated conceptual options, which remain a responsibility of the design process itself. In this sense, the framework makes deficiencies in early-stage reasoning explicit rather than concealing them.

Second, the framework is conceived as a decision-support system and does not replace professional or institutional judgment. Final design choices remain inherently normative, context-dependent, and value-driven, particularly in the presence of competing priorities and stakeholder interests. The role of the framework is therefore to structure and inform judgment, not to automate or prescribe decisions.

Third, the framework is intentionally confined to the conceptual stage of design. The use of binary scoring for selected indicators and the level of abstraction adopted in the evaluation prioritise clarity, legibility, and consistency over numerical refinement. While this choice is appropriate for early-stage reasoning under uncertainty, it limits the sensitivity of the method when distinctions between alternatives become incremental or when detailed design development is required. Direct application of the framework to later design phases would therefore require adaptation and refinement.

Finally, the empirical validation is limited to three footbridge projects. Although these cases were deliberately selected to encompass diverse spatial, material, and regulatory conditions, the results should be interpreted as contextually grounded rather than statistically generalisable. The strength of the validation lies in the controlled heterogeneity of the applications, which allows the framework's reasoning structure to be tested across distinct yet comparable design environments.

Taken together, the validation and the explicit delineation of methodological boundaries confirm that the proposed framework functions as a knowledge-based decision-support system rather than as a deterministic optimisation model. It enables the explicit articulation of design reasoning, supports interdisciplinary dialogue, and enhances transparency in early-stage evaluation, while remaining consciously bounded to the domain of conceptual design. Within these boundaries, the framework demonstrates a high degree of scientific credibility, methodological soundness, and applicability to contemporary structural design practice.

Chapter 5

Conclusions and Future Works

5.1 Summary of contributions

This doctoral research has addressed a long-standing gap in structural engineering practice and theory: the lack of structured, transparent, and operational methods to support conceptual design decisions in the early stages of infrastructure projects.

The primary contribution of the thesis lies in the reframing of conceptual structural design as a decision-critical and knowledge-intensive phase, rather than as a purely intuitive or pre-analytical activity. By explicitly positioning conceptual design within a decision-making framework, the research demonstrates how early structural reasoning can be formalised without undermining creativity, architectural intent, or disciplinary dialogue.

More specifically, the main contributions of the research can be summarised as follows:

- Theoretical contribution

The thesis provides a consolidated theoretical interpretation of conceptual design as a cross-disciplinary process in which structural logic, architectural quality, resilience, sustainability, and long-term performance are negotiated simultaneously. By bridging historical perspectives on structural form with contemporary performance-based and lifecycle-oriented approaches, the research clarifies the epistemological role of conceptual design within modern structural engineering.

- Methodological contribution

A structured multi-criteria decision-making (MCDM) framework is developed to support early-stage comparison of alternative structural concepts. The framework translates qualitative design intentions into a coherent system of quantitative and semi-quantitative indicators, enabling transparent, reproducible, and traceable evaluation of conceptual alternatives under uncertainty.

- Indicator system for conceptual design

The research proposes a comprehensive yet modular indicator system addressing:

- architectural and planning quality,

- structural robustness, inspectability, and maintainability,
- environmental sustainability,
- circularity and adaptability.

Unlike conventional evaluation tools applied after design selection, the proposed indicators are explicitly conceived for conceptual-stage applicability, when design freedom is still high and long-term impacts are largely determined.

- Operational contribution through computational implementation

To ensure practical applicability, the framework is implemented in a Python-based computational tool, enabling automated calculation, aggregation, and visualisation of indicator values. This implementation demonstrates that the method is not limited to theoretical discussion but can be integrated into real design workflows in both professional and research contexts.

- Empirical validation through real-world case studies

The framework is tested and validated through three heterogeneous footbridge projects, representing different design contexts, objectives, and constraints. The case studies confirm the framework's ability to:

- make implicit design reasoning explicit,
- clarify trade-offs between competing performance objectives,
- support informed dialogue between designers, clients, and decision-makers at an early stage.

Taken together, these contributions demonstrate that conceptual structural design can be supported by systematic and transparent methods without reducing its integrative and creative nature. The framework does not replace professional judgement; rather, it augments it by making design assumptions, priorities, and consequences explicit.

5.2 Future directions and practical implications

5.2.1 Methodological refinement and uncertainty management

While the framework developed in this thesis has demonstrated conceptual soundness and operational feasibility, its broader potential lies in extending its sensitivity and flexibility. Future research may focus on enhancing the evaluation process by refining the current scoring logic.

The existing binary scoring structure, while effective in promoting clarity, transparency, and consistency during early-stage reasoning, limits the expression of intermediate or uncertain performance levels. The introduction of graded or fuzzy-logic-based scoring systems would enable more nuanced assessments and probabilistic interpretations, particularly in contexts characterised by incomplete information or evolving design constraints.

Future research could investigate the sensitivity of the proposed framework to deterministic assumptions adopted during conceptual design, including hazard-related parameters and proxy coefficients used in the resilience assessment. Scenario-based, probabilistic, or fuzzy approaches could help evaluate the stability of ranking outcomes and quantify the influence of parameter variability on the decision-making process.

In parallel, weighting mechanisms that are currently based on expert judgment could be further developed through entropy-based calibration or data-informed approaches. Such developments would allow adaptive weighting scenarios that reflect contextual priorities while preserving interpretability and transparency.

A further methodological consideration concerns the additive aggregation structure adopted for the Global Quality Indicator (GQI). The weighted-sum formulation was intentionally selected because of its transparency, simplicity, and ease of interpretation, qualities that are particularly valuable during conceptual design. However, as with other additive multi-criteria approaches, the method assumes a compensatory decision logic, whereby strong performance in some criteria may partially offset weaker performance in others. While this assumption is considered acceptable for the exploratory and comparative objectives of the framework, future research could investigate alternative aggregation strategies, including threshold-based, outranking, or hybrid decision models, in order to assess their influence on ranking outcomes and decision robustness.

5.2.2 Integration with digital and parametric design environments

A closely related direction concerns the integration of the framework within digital and parametric design environments. Embedded within parametric modelling or Building Information Modelling workflows, the framework could operate as a real-time feedback system during the conceptual phase.

By linking indicators to geometric, material, and typological parameters, designers would be able to visualise the implications of conceptual decisions as they are made. In this configuration, the framework would evolve from a post-analytical evaluation tool into a **design intelligence support system**, enabling iterative exploration while maintaining traceability and methodological rigour.

5.2.3 Interpretive use of artificial intelligence under uncertainty

Within this digital context, future developments may also explore the selective use of artificial intelligence techniques to support decision-making under uncertainty. Conceptual design is inherently characterised by epistemic uncertainty, qualitative judgments, and partially defined boundary conditions that cannot be fully addressed through deterministic models.

Artificial intelligence approaches could contribute by identifying recurring patterns across alternative design configurations, supporting sensitivity analyses, and exploring families of scenarios rather than by generating automated or optimal solutions. In this sense, AI would function as an **interpretive support** to the framework, enhancing its capacity to structure uncertainty and make assumptions explicit, without replacing the designer's critical judgment.

5.2.4 Application to circular, reusable, and adaptive infrastructures

Another promising field of application concerns circular, reusable, and adaptive infrastructures. The increasing relevance of reuse- and disassembly-oriented design strategies identified in this research suggests that the framework is particularly suited to projects involving adaptive reuse, reversible construction, temporary structures, or the transformation of existing systems.

In such contexts, long-term value is less dependent on static optimisation and more strongly linked to adaptability, reversibility, and life-cycle flexibility. The framework provides a structured means to address these qualities at the conceptual

stage, when typological and system-level decisions remain open and exert the greatest influence on future transformation potential.

5.2.5 Interface with institutional evaluation and procurement systems

Given its transparent and traceable structure, the framework also has the potential to serve as an interface between design research and institutional evaluation systems, such as sustainability assessment schemes and quality-based procurement instruments.

By translating qualitative design reasoning into structured yet context-sensitive indicators, the method could support early-stage sustainability screening, informed decision-making in public procurement, and the evaluation of design quality beyond compliance-based criteria. In this way, the framework may contribute to the development of evidence-informed design governance aligned with European and Swiss sustainability agendas.

5.2.6 Educational and professional dissemination

Finally, the clarity and coherence of the proposed methodology support its dissemination within both academic and professional environments. In educational contexts, the framework can foster interdisciplinary dialogue between architecture and engineering students, encouraging them to articulate and justify design decisions across structural, spatial, and environmental dimensions. In particular, its application within civil engineering education can contribute to increasing awareness of sustainability, resilience, and lifecycle-oriented design, supporting the development of a more integrated understanding of infrastructure performance from the earliest stages of design.

In professional practice, it can operate as a reflective tool for design teams, supporting collaborative reasoning and a shared understanding of project complexity. This pedagogical and professional relevance reflects the broader ambition of the research: to promote an intellectually rigorous and ethically responsible design culture grounded in reasoning, transparency, and contextual awareness.

5.3 Cultural and Professional Dimension of the Framework

Beyond its methodological and operational contributions, this research is rooted in a cultural and ethical understanding of structural design. The proposed framework embodies a conception of design as a civic act that shapes not only the built environment but also collective values, identities, and long-term relationships between society and material resources. In this sense, it aligns with the principles of Baukultur as articulated in the Davos Declaration and in subsequent Swiss policy frameworks.

Within this perspective, the framework promotes a qualitative culture of decision-making in which transparency, interdisciplinarity, and contextual awareness replace formal compliance or stylistic preference. It encourages designers and engineers to engage critically with the ethical implications of construction, recognising each conceptual choice as a negotiation between resource use, cultural continuity, and social responsibility.

The multi-criteria structure itself reflects this ethical stance. By integrating architectural, structural, and environmental dimensions, the framework acknowledges that technical performance cannot be separated from spatial meaning or ecological consequence. The indicators therefore act as mediators between quantitative efficiency and qualitative intent, reinforcing a conception of design in which responsibility and creativity are inseparable.

From this viewpoint, the framework participates in a broader disciplinary shift from a paradigm of optimisation toward a paradigm of care, coherence, and reversibility. The emergent relevance of reuse- and disassembly-oriented design further reinforces this shift, positioning structural systems not as final and irreversible artefacts, but as adaptable material and cultural reservoirs capable of transformation over time.

The cultural ambition of this research thus extends beyond the development of a methodological tool. It contributes to the construction of a shared intellectual framework for contemporary design practice, inviting future generations of professionals to approach structural design not merely as a matter of calculation or compliance, but as an act of meaning-making, understood as a disciplined form of imagination guided by ethics, knowledge, and responsibility toward place and society. In this sense, the framework does not prescribe design solutions, but

supports informed and responsible decision-making, in which structural reasoning becomes an explicit, shared, and culturally grounded component of the design process.

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Appendix A

This appendix describes the procedure adopted to collect and process expert judgments in order to determine the relative importance of the design indicators reported in Table 17. The expert elicitation was developed to obtain informed assessments regarding nine indicators relevant to the conceptual design of pedestrian and cycle bridges. These indicators were grouped into three main thematic areas: Architecture and Planning, Structural Resilience, and Environmental Performance. They were evaluated under four representative project scenarios: Above Railways, Urban Context, Sustainable Infrastructure, and Above Water.

Experts were selected based on their recognised academic and professional experience in bridge design, structural and architectural integration, and infrastructure sustainability. The panel was designed to include a balanced mix of profiles from academia, professional practice, and infrastructure operating authorities, ensuring a comprehensive understanding of both theoretical and practical aspects of bridge design. Each participant received a bilingual questionnaire (English and Italian) explaining the purpose of the study and the evaluation procedure.

For each scenario, experts were asked to assign percentage weights to the nine indicators according to their perceived relative importance within that specific context. The sum of the nine values for each scenario was required to equal one hundred percent. In addition, each expert was asked to indicate a self-assessed confidence level, expressed as a percentage from zero to one hundred, representing the degree of certainty they attributed to their own judgments in that scenario. This additional parameter was used to weight the reliability of each contribution when aggregating the data.

All responses were collected through a digital fillable form and subsequently organised in a spreadsheet for quantitative analysis. Before combining the data, the weights provided by each expert were normalised to ensure comparability and to correct potential rounding differences. For each expert j and indicator i , the normalised weight w'_{ij} was computed as follows:

$$w'_{ij} = \frac{w_{ij}}{\sum_{i=1}^9 w_{ij}} \quad \text{A.1}$$

where w_{ij} represents the weight assigned by expert j to indicator i . This normalisation ensured that the total of all nine indicators per expert equalled one, allowing for a consistent comparison across participants.

To combine the expert judgments, a confidence-weighted arithmetic mean was applied, following the general principles of Cooke's classical model. For each indicator, the final aggregated weight was calculated by multiplying each expert's normalised weight by their self-assessed confidence level, summing these products, and dividing the result by the total sum of all confidence levels. In this way, experts who expressed higher confidence contributed proportionally more to the overall outcome, while the input of all participants was preserved. The computation was performed according to the following formula:

$$W_i = \frac{\sum_{j=1}^N (c_j \cdot w'_{ij})}{\sum_{j=1}^N c_j} \quad \text{A.2}$$

Where W_i is the aggregated weight of indicator i , w'_{ij} is the normalised weight assigned by expert j , c_j is the confidence level reported by expert j , and N is the total number of experts involved.

After aggregation, the resulting weights were normalised again to ensure that the sum of all nine indicators equalled one hundred percent for each scenario. The final normalisation was performed according to the following expression:

$$W_i(\%) = 100 \times \frac{W_i}{\sum_{i=1}^9 W_i} \quad \text{A.3}$$

This procedure produced four sets of results corresponding to the four design scenarios considered. Each set represents the collective distribution of indicator relevance as perceived by the expert panel in that specific context. The results were then summarised in Table 17, which reports the final percentage weight of each indicator per scenario.

A consistency check was conducted to verify the robustness of the results. The confidence-weighted mean was compared to the unweighted arithmetic mean to assess whether the inclusion of confidence levels significantly affected the overall

ranking of indicators. The observed differences were minimal, generally below five percent, confirming the coherence and stability of the elicited data.

The resulting weighted values form the quantitative foundation for the multi-criteria conceptual design framework developed and discussed in Chapter 2. They provide an empirically derived representation of expert consensus regarding the relative importance of the indicators across different bridge design contexts, supporting the proposed decision-making methodology.

Table A1 Consistency checks of the expert-based indicator weighting procedure. The table summarises the comparison between confidence-weighted and unweighted aggregation methods across the four design scenarios considered. The limited deviations observed and the preservation of indicator ranking confirm the internal coherence of the aggregated weights reported in Table 16.

Expert ID	Primary role	Years of experience	Sector	Relevant expertise
E1	Structural engineer (bridges)	>20	Professional practice	Conceptual design, robustness
E2	Architect (infrastructure)	>10	Professional practice	Contextual integration, Baukultur
E3	Asset manager / owner representative	>15	Public authority	Maintenance, inspection, lifecycle
E4	Sustainability / LCA specialist	>10	Consulting / research	LCA, circularity, sustainability
E5	Professor in structural engineering	>20	University	Structural and bridge design
E6	Professor in sustainable construction	>10	University	Constructability, demountability, LCA
E7	Professor in architecture and planning	>20	University	Planning and architectural design

Appendix B

B.1 Purpose of the appendix

This appendix documents the computational implementation developed to operationalise the multi-criteria decision-making (MCDM) framework presented in the main body of the thesis. The purpose of the appendix is not to provide a line-by-line description of the source code, but to explain the logical structure, data flow, and execution logic of the Python-based workflow adopted for indicator calculation, aggregation, and comparative analysis. The appendix ensures the reproducibility of the research and clarifies how theoretical constructs introduced in Chapters 2 and 3 are translated into a consistent computational procedure.

B.2 General structure of the computational workflow

The implementation is organised as a modular pipeline composed of three sequential levels:

1. Indicator calculation
2. Scenario-based aggregation
3. Visualisation and comparison of results

Each level is implemented through independent Python scripts and communicates with the others exclusively through structured input and output files, ensuring loose coupling and traceability of results.

B.3 Indicator calculation modules

At the first level, each performance indicator is computed by a dedicated Python script. Each script operates on a specific Excel input file, which contains the qualitative or semi-quantitative data associated with each design alternative.

For every indicator, the corresponding script:

- reads the input data from a predefined Excel worksheet;
- applies the calculation and normalisation rules defined in the methodological chapters;

- outputs a normalised indicator value on a discrete scale from 1 to 6 for each alternative.

The indicators implemented are:

- FI – Feasibility
- CS – Context and Society
- GI – Geometry and Function
- RI – Robustness
- MI – Maintenance
- II – Inspection
- SI – Sustainability
- CI – Circularity
- AI – Adaptability

At this stage, indicators are computed independently and no weighting or aggregation is applied. The result is a non-weighted performance matrix (Alternative $\times$ Indicator), which can be inspected and validated indicator by indicator.

Scripts are executed via command line, e.g.:

```
python test_ap_indicators.py
```

B.4 Scenario-based aggregation

The second level of the workflow aggregates the normalised indicator values using a weighted sum model. Aggregation is performed by a dedicated Python script that combines the indicator outputs with predefined weighting scenarios.

Each scenario is defined by a specific set of weights assigned to the nine indicators, representing different evaluation contexts. For each scenario, the aggregated score of a design alternative is computed as:

$$S_{a,s} = \sum_{i=1}^n w_{i,s} \cdot I_{a,i} \quad \text{B.1}$$

where:

- $S_{a,s}$ is the aggregated score of alternative a under scenario s ;
- $I_{a,i}$ is the normalised value of indicator i ;

- $w_{i,s}$ is the weight of indicator i in scenario s ;
- n is the number of indicators.

The script produces one aggregated output file per scenario, containing both the weighted indicator values and the final aggregated score for each alternative.

Aggregation is performed using:

```
python aggregate_with_weights.py --scenario "<scenario_name>"
```

Outputs are stored as MCDM_aggregated_[scenario].xlsx files.

B.5 Visualisation and comparative analysis

The final level of the computational workflow is dedicated to the visual interpretation of results. Python scripts are used to generate radar charts and comparative diagrams based on **weighted indicator values**, ensuring consistency between numerical aggregation and graphical representation.

Two main types of comparison are supported:

- comparison of multiple alternatives under a single scenario.
- comparison of multiple scenarios for the same alternative.

This functionality enables sensitivity analysis and highlights how changes in weighting assumptions influence the relative performance of design solutions.

Single radar is produced using:

```
python make_radar_charts.py -I "data/MCDM_aggregated_<scenario>.xlsx"
```

Multi-scenario using:

```
python make_radar_compare_scenarios.py --alts 1A 1B 1C 1D --scenarios  
"3_Sustainable infrastructure" "5_Same weights"
```

B.6 Reproducibility and extensibility

All data exchanges within the workflow are handled through structured Excel files, and all processing steps are explicitly encoded in Python scripts. This ensures full reproducibility of the results presented in the thesis.

The modular architecture allows the framework to be extended by:

- introducing additional indicators.
- defining new weighting scenarios.
- applying the workflow to further case studies without modifying the core logic.

B.7 Concluding remarks

The Python-based implementation described in this appendix provides a transparent and reproducible operationalisation of the proposed MCDM framework. By separating indicator computation, aggregation, and interpretation, the workflow supports a structured evaluation of conceptual design alternatives while preserving interpretability and methodological rigor.

B.8 Availability of computational scripts

The Python scripts implementing the MCDM framework are provided as supplementary material to this thesis.

The scripts are organised in a structured directory and include:

- independent modules for the calculation of each indicator,
- aggregation routines for scenario-based weighting, and
- visualisation tools for comparative analysis.

The source code is intentionally separated from the main manuscript to preserve readability, while ensuring full transparency and reproducibility of the computational procedures. All results presented in Chapters 3 and 4 can be reproduced by executing the scripts using the input files provided.

The scripts implementing the MCDM framework are maintained in a private GitHub repository:

<https://github.com/valeriagozzi-ship-it/phd-data-set>

The repository is not publicly accessible; however, access can be granted upon reasonable request for verification and reproducibility purposes.