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Sustainability and resilience indicators for conceptual design of cycle-pedestrian bridges. Interaction with robustness, inspectability, and maintenance metrics

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1. Introduction and state of the art: sustainability in footbridges

Sustainability plays a pivotal role in the design of pedestrian and cycling bridges, enhancing urban connectivity while minimizing environmental impact. Despite the growing interest and the development of Sustainable Infrastructure Rating Systems (SIRS) [1], integrating sustainability principles into early design stages remains challenging. Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) are well-established and objectively measurable methodologies; however, Social Life Cycle Assessment (S-LCA) remains underdeveloped and largely qualitative, due to the absence of standardized frameworks [2]. Critical gaps persist—particularly in terms of standardization and methodological heterogeneity—which hinder the comparability and applicability of sustainability assessments across different geographic and regulatory contexts. At the same time, recent regulatory trends increasingly emphasize structural parameters such as robustness, maintenance, and inspection. This underscores the need for integrated approaches that combine sustainability and structural performance from the earliest stages of design. While several studies [3] explore these aspects individually, a systematic and quantifiable framework for their integration during conceptual design—where decisions have the greatest long-term impact—is still lacking. This extended abstract originates from a broader research project that addresses this gap [4] proposing a structured, numerical decision-support framework for integrating sustainability and structural indicators into the design of pedestrian and cycling bridges. The focus of this work is placed on the interaction between these indicators, explored through the analysis of two real-world case studies.

2. Methods and 5 indicators framework

The proposed method intends is to identify quantifiable indicators that enable designers to objectively assess a project solution during conceptual design, ensuring informed decision-making. Key sustainability indicators were selected based on their alignment with existing SIRS frameworks and their applicability to conceptual design. The indicators were chosen using the following criteria: i) recognized in current SIRS frameworks, ii) easily numerically quantifiable in the early design phase, iii) comparable across projects, iv) repeatable, v) relevant for decision-making, vi) integrable into engineering workflows, and vii) understandable by stakeholders. Based on these criteria, five primary indicators are shown and defined in table 1

Table 1 Indicators description e numerical definition

Indicator	Definition
Global Warming Potential Indicator (GI)	CO2 equivalent emissions (GPWi) along the life cycle
Total Cost (TC)	Project cost (Ci) in CHF along the life cycle
Robustness (RO)	Demand-Capacity Ratio (DCR, GSA 2013[5]) with sensitivity factor (K)
Inspection (IN)	Percentage of inspectable-monitored components (IE), adjusted by difficulty inspection factor (D)
Maintenance (MA)	Maintenance grade (ME) considering international standards, adjusted by quality factor (Q)

Indicators are aggregated using a Weighted Sum Model (WSM) within a Multi-Criteria Decision-Making (MCDM) framework normalized to a scale 1 to 6 based on each case study design options [6]. A Systems Thinking approach [7] maps interdependencies, identifying feedback loops and trade-offs within the design process.

3. Case studies and results

The method, implemented in Python, was validated through two steel footbridges case studies: a preliminary design in Turin, Italy, and competition in Delémont, Switzerland. Four alternative designs per case were assessed, and Pearson correlation matrices were used to analyze indicator relationships (Fig. 1 and 2).

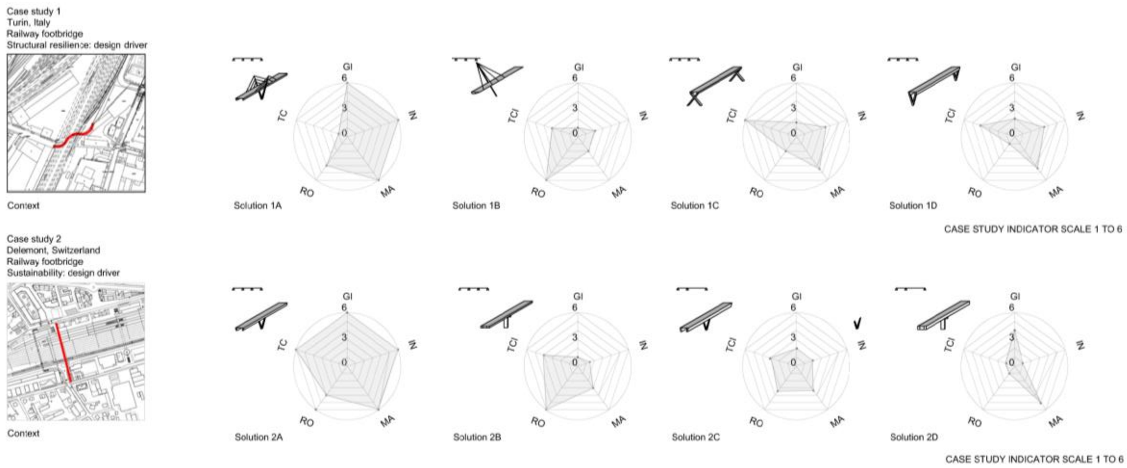

Figure 1. Case studies analysis and indicators evaluation. V. Gozzi

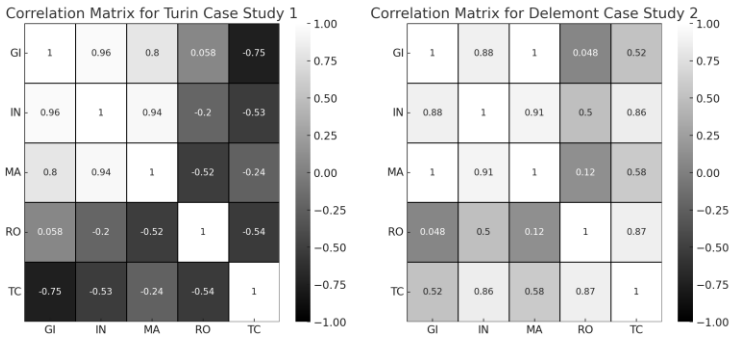

Figure 2. Case studies correlation matrices. Dark strong direct correlation, white strong inverse correlation. V. Gozzi

The correlation matrices summarize key observations on indicator interdependencies. IN and MA strongly correlate, confirming that easier inspection aligns with easier maintenance. GI and TC show no universal trend, highlighting context-sensitive trade-offs. RO and GI are nearly independent, suggesting that robustness can be enhanced without compromising sustainability. Meanwhile, RO and MA exhibit contrasting relationships, indicating that maintenance needs are not consistently tied to robustness. These findings emphasize the complex interplay between sustainability, cost, and structural performance, reinforcing the need for MCDM in bridge design.

4. Conclusions and Further Developments

This study presents a structured, data-driven framework to support conceptual bridge design by quantifying sustainability and resilience. Using a multi-criteria approach, it emphasizes the relationships between environmental, economic, and structural indicators, supporting informed early-stage decisions. Development will focus on standardizing the methodology and creating digital tools for integration into engineering workflows. Additionally, expanding the framework to include social, planning, and architectural aspects will promote a more holistic and context-sensitive design approach.

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