PEDESTRIAN BRIDGES – A HOLISTIC APPROACH IN RATING THEIR EFFICIENT USE AND SUSTAINABLE DESIGN

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Abstract

Pedestrian bridges are a unique type of bridges, vital elements of our communities' transportation infrastructure. Providing safe passage for users across traffic arteries and natural obstacles, they also enhance the overall quality of life through active transportation. Their aesthetic value often even surpasses the functional demands, making them the symbols of urban identity. There is a noticeable growing interest for not only Integrating these bridges into existing traffic infrastructure and achieving their aesthetically pleasing design but also aligning those two with sustainability imperative as an emerging key. Implementing a holistic approach in rating their efficient usage and sustainable design throughout the entire life cycle, by integrating environmental (LCA), economic (LCC) and social dimensions within a Life Cycle Sustainability Assessment (LCSA) framework is therefore a necessity. Based on conducted literature' search, this paper provides a brief overview and synthesis of the key steps for planning and design processes of pedestrian bridges, emphasizing the indicators of functionality, aesthetic and sustainability, with particular focus on its social aspects, identified within the S-LCA framework.

Keywords: pedestrian bridge, efficient use, sustainable design, holistic approach

1 Introduction

Pedestrian bridges significantly shape public space and contribute to its identity thanks to holistic design within transportation, urban, architectural, engineering and landscape context [1]. These bridges represent a critical component of the urban transportation infrastructure facilitating safe, convenient and efficient mobility of pedestrians and cyclists over natural or artificial obstacles [2]. Providing the increased movement of these vulnerable traffic participants across the city, this kind of link within traffic network can significantly improve connectivity between business, educational, commercial, residential and other urban areas, including those intended for leisure, and thereby generate positive economic benefits. These bridges assist in encouraging shift from vehicular traffic to healthier and more sustainable modes of transportation such as walking and cycling, thus engaging not only the physical activity of the residents and improve health, but simultaneously bringing a positive environment outcome to the city. Well-designed bridges which meet the required standards in providing high-quality infrastructure improve accessibility to work, education and other activities to all users, including those with mobility impaired or other disabilities. Integration into the surroundings and with other modes of transportation, pleasant experience of crossing and aesthetic which sometimes extends even beyond functionality are important attributes of these bridges. In that way, safety, economy, environment, health benefits, accessibility and integration might be the motivators to incorporate these bridges within urban environment, providing valuable decision criteria to urban planners and policymakers.

During the planning process, based on feasibility study prepared according to given objectives, the effects of several considered options should be assessed according to the criteria outlined, ranging from having significant advantages to significant disadvantages. Preferred option results from multi-criteria decision making. Construction methodology must be elaborated and impact of the proposed work on environment and landscape, as well [3].
This is a simplistic description of the planning phase from which the definitions of the project task (e.g. architectural and structural design) and definition of its framework (e.g. functional and economic aspects) result. As bridges in general are long-lived structures of great strategic importance, all choices and decisions made in the early stages of planning and designing consequently have long-term impact [4]. Since the entire engineering framework adjusts to the sustainability imperative, a holistic approach also in bridge construction integrates the principles of responsible development, emphasizing resilience, economic and social effects. Through a LCSA, environmental (LCA), economic (LCC) and social benefits (S-LCA) at the different stages of bridge's service life (figure 1) must be measured to select the best option by considering the pros and cons of each alternative over the entire lifespan (construction, operation and end-of-life stages). Enabling the design from sustainability aspects, this approach has been mostly focused on motorway bridges [5]. A comprehensive overview of LCSA research of these bridges, carried out over almost two decades, has recently been given and knowledge gaps were pointed out [4]. To the author's knowledge, comparable researches on sustainable design of pedestrian bridges are still much less represented [6, 7].
As functionality and aesthetic drives create challenges, pedestrian bridges' design significantly differs from the existing methods, common for vehicular bridges. This paper therefore shifts the focus toward specific LCSA indicators for the bridges, intended for pedestrian use only or mixed-usage with cyclists. Particularities of the planning and initial design considering effectiveness, aesthetic and sustainability, and the key indicators for S-LCA, as well, will be highlighted. They result from an extensive literature review within which many more sources have been investigated than it is evident from the number of cited references.

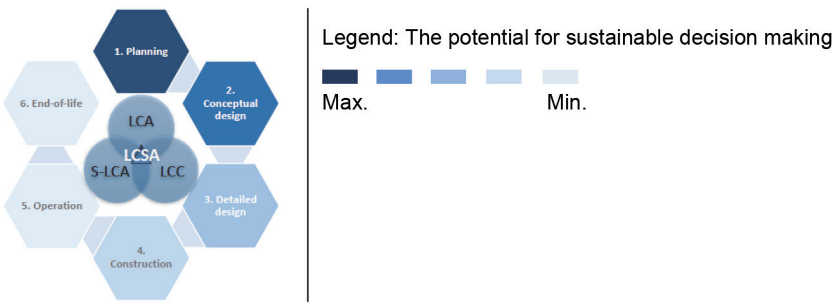

Figure 1 S-LCA involvement from the beginning of the decision-making process

2 Planning and conceptual design stages

Planning is a strategic framework that usually immediately precedes the conceptual (initial) design stage. By setting the focus on the functional requirements and feasibility, it defines project's scope, objectives and regulatory constraints within which the conceptual design must be carried out and fit into. Initial design is the most challenging phase during which essential features take form to optimize performances. It is thus a decisive to transform vision to life, to test and to evaluate selected options.

2.1 Functional and aesthetic considerations on pedestrian bridges

2.1.1 Functional objectives for effective use of pedestrian bridges

In order to be effective, pedestrian bridges must be must be a favourable option for use, and interdisciplinary preliminary research is thus essential to collect data and extract the relevant information. It involves traffic, planning and environmental studies, field and community surveys, as well. From the literature overview, it can be concluded that many studies have been focused to explore factors influencing the usage, perception and behavior toward pedestrian bridges in order to assess present status and suggest development orientation [2, 8-10]. Functional objectives focus on ensuring safe, convenient and accessible use. Effective implementation requires addressing user needs through location, design and maintenance.

Primary functional objectives [1, 8-10]:
- ensuring safety: separating user traffic from vehicular flow, reducing fatalities and accidents at high-risk locations (those with heavy traffic or high speeds)
- improving connectivity and accessibility: bridging gaps between key locations improves mobility especially if ramps, elevators and proper width are provided
- maximizing usage (efficiency): setting at user-desired lines and ensuring usage more convenient than at street level
- minimizing vehicular disruption: allowing continuous, uninterrupted traffic flow on busy roads, boosting overall transportation network efficiency
- providing comfort and convenience: encouraging usage through proper width and access, and design elements such as lighting and protection (e.g. roofing).

Key aspects for effective design and usage [1, 14, 15]:
- location analysis: placing close to user's-desired paths reduces detour without detraction from the existing routes
- reduced physical effort: increasing adoption (minimize steep stairs or ramps)
- structural integrity and safety features: including security measures, proper lighting, railing, and lane separation in case of mixed-use with cyclists
- aesthetics and user experience: attractiveness can make the bridge a symbol and landmark, improving the urban environment and encouraging use
- environmental integration: properly handling drainage to ensure water runoff and integrating the structure with the surrounding landscape.

2.1.2 Aesthetic objectives for effective use of pedestrian bridges

Aesthetic objectives focus on transforming functional crossings into structural art facilities, landmarks, and enjoyable, safe and visually harmonious additions to the landscape [1, 11]. The aesthetical values thus could be also measured in the extent of homogeneity and integration with surrounding, serving to meet functional needs of users [1, 12]. As the structural system forms the basis of the aesthetics, key objectives focus to achieve a balance between appearance and structural integrity, to improve the surrounding environment and enhance the overall users' experience at which the accessibility might be very important factor [1, 11]. More comprehensive overview and literature synthesis relevant for specific issues of accessible design, focused on stairs and ramps as critical element is given in [7].

Key aspects for aesthetic design [11, 13-15]:
- harmony with the environment: integrating with surroundings character, taking advantage of natural topography, and forming proportional to the environment

- visual transparency: a light, slender appearance minimizing visual obstruction
- creating a landmark: creating a form that defines the character of an area
- simplicity and clarity of form: shapes that clearly expressing the structural system are more aesthetically pleasing
- ergonomics and experience: the design should consider the user's perspective, creating a pleasant experience and providing panoramic views
- lighting as art: aesthetic lighting highlights the bridge's features, creates visual interest at night, and enhances safety
- expressing sustainability: eco-friendly materials and designs can contribute to the aesthetic appeal
- integration with infrastructure: ensuring that staircases, ramps, and elevators are designed to be part of the overall aesthetic, and not added as afterthoughts.

2.2 Developing conceptual design of pedestrian bridges

Criteria that drive pedestrian bridges' design therefore balances user needs (accessibility, safety, aesthetics) with site realities (geotechnical an environmental aspects) and technical requirements (materials, structure, drainage, lighting), focusing on seamless integration, durability, and compliance with codes for a successful, well-used public amenity, and not just a crossing. Key aspects include inclusive access (ramps/stairs), durable non-slip surfaces, ample lighting, clear wayfinding, and aesthetic harmony with surroundings, requiring interdisciplinarity (across engineering and architecture) and permitting (which is regulated on national level. Pedestrian bridges in general must be designed with careful and responsible consideration of safety and convenience, e.g. principles and requirements for design criteria, construction and maintenance requests, permitting and costs [13-18]. As functionality and aesthetic issues are the key predictors for effective usage, some of the current standards, manuals and guidelines, applicable on pedestrian bridges' design are listed here, providing the following information about essential principles of the design criteria, aesthetic and cost concerns:
- aesthetic guidelines for bridge design (SAD): a manual of aesthetic design on bridge components and categories [13]
- bridge aesthetic (NSW, AU): requirements, objectives, design principles and processes that guide the design of bridges [14]
- the Brief Dutch Design Manual for Bicycle and Pedestrian Bridges: contains considerations that precede the actual design, gives an insight into the Dutch regulations on loads and impact forces [15]
- CD 353 Design Criteria for Footbridges (UK): the requirements for design criteria for footbridges (general principles, layout and appearance, design and dimensional standards, parapets, enclosed bridges, drainage, etc.) [16]
- options for Designers of Pedestrian and Cyclist Bridges to Achieve Value-for-Money (NZ/AU): a summary of design considerations about the development, construction and routine maintenance costs of these bridges [17].

Design begins by identifying project's objectives and constraints and to involve the steps listed in table 1.

Table 1 Overview of main requirements and key steps of the design [15, 18]

Main requirements and indicators	
Functional requirements	Plan alignment, vertical profile, width, clearance, barrier-free access, railing dimensions, a drainage system and lighting
Aesthetic requirements	Overall geometry and position, superstructure type and form, pier placement and type, abutment location and height
Structural requirements	Sufficient strength and durability, robustness, deflection criteria compliance and minimal vibrations
Key steps	
Site analysis	Climate: can affect the choice – open bridge vs. enclosed, bridge piers and abutments type, as well Conflict analysis: any potential challenges or constraints on the design and construction must be identified Population density and needs: effective use must be appraised, economy and social impact, as well The surrounding environment: topography, hydrology, geology and ecology conditions
Design code and considerations	Hydrological and hydraulic analysis: Determining the water surface elevation for floods at the bridge site Geotechnical analysis: assessing of site and soil conditions, groundwater analysis and slope and stability assessment effects on foundation type, durability and stability of a bridge Traffic analysis: basis for projecting the traffic volume and usage Analysis of bridge types: Determines the suitability of a bridge typology and shape for a site Installation of precast vs. cast abutments, based on geotechnical analysis report Preliminary structure sizing helps to define overall size with realistic component dimension based on load analysis
Conceptual design configuration	Type of superstructure: depends on the required length and width of the bridge and the gap to be bridged as well Material selection: potential of prefabricated construction, duration and preservation/ maintenance requirements

3 LCSA framework and key considerations focus on S-LCSA

As an aesthetics is important attribute of these bridges making many the symbols of urban identity, it also affects the complexity of their design and fabrication, so construction can be challenging due the requirements such are: prefabrication the modular elements prior to erection/installation on the site, transportation issues of large elements, minimizing the disruption to normal traffic during erection and also durability and ease of inspection for maintenance. Effects of these requirements and structural performances on environment and economic must be assessed within initial stage using quantitative indicators for life cycle impact: global warming potential, total cost, material selection, robustness, inspection and maintenance. In recent study [6], the impact of these five indicators on sustainability was quantified by testing on two case-studies and the following conclusions are driven: regular inspection reduces complex maintaining; robustness and global warming potential do not correlate, so optimization might be material-independent for improved structural resilience, and cost-sustainability relationship is context-dependent (e.g. sustainable solutions are not always high-cost). The study also highlights the need to involve S-LCSA in initial design stage, too [6]. This might be difficult task because its impacts on community, well-being, accessibility and equity are less standardized and have mainly subjective nature, making difficult comparison across projects. At the other hand, an interest to push it into active design-stage tool, particularly for assessing sustainable materials (e.g. timber or repurposed composites) is growing.

Figure 2 Examples of timber and steel pedestrian bridges [19, 20]

3.1 Particularities of S-LCSA principles for pedestrian bridges

As S-LCA is used to evaluate the social impacts and benefits during lifespan of the bridge, aiming to fill the gap between technical, economic, and environmental assessments, by focusing on stakeholders the following are important [1, 4-7, 15]:

- local community: impacts on the immediate vicinity (noise pollution during construction), accessibility and connectivity improvements (access to schools/services/work), land-related conflicts and visual impact (aesthetics)
- society: broader impacts, public safety, visual impact, enhancing environment
- users: user-centric safety, time-savings, comfort (vibration) and accessibility
- workers: health and safety conditions (construction, repair and demolition).

Subjective nature of impacts makes quantitative assessment difficult and risky:

- accessibility and equity: how the bridge improves connectivity and mobility
- user comfort and safety: vibration caused by walking, ensuring structural design complies with comfort classes (reducing horizontal and vertical acceleration).

The following life cycle stages in S-LCA should be assessed:

- raw material acquisition: social conditions in the supply chain of materials
- manufacturing/construction: worker safety, local employment, and community disruption (noise, traffic detours)
- use phase: long-term impacts (accessibility, safety, community enhancement)
- end-of-life: safety during demolition, potential for recycle/reuse the materials.

4 Conclusion

Considering the efficient use can be concluded that is decisive how well the bridge serves its intended function of promoting sustainable urban mobility and connectivity. Thereby, the following is important to rate [derived from 1, 2, 7, 8, 15]:

- accessibility: easy access for all users (pedestrians, cyclists, people with disabilities) is critical to social sustainability and use, thus including physical accessibility (ramps, stairs, elevators) and integration with existing traffic links
- connectivity: how effectively links destinations, reduces detour, provides safe and uninterrupted passageway
- usage volume: quantifying user's traffic volume relative to potential demand is crucial to determine if fulfils its purpose or acts as underused urban barrier

- user comfort and safety: factors like lighting, dynamic stability (vibrations), security, and protection (roofing) enhance the user experience and use
- aesthetics and integration: visually appealing design that also blends with the surrounding environment improves community acceptance and use.

Considering the S-LCSA particular aspects can be concluded that accessibility, safety, user comfort, mobility and promoting of sustainable transportation options, inclusivity and urban cohesion are highly ranked. Consequently, key particularities related to the pedestrian bridges are the following [derived from 1, 7, 15, 16]:
- focus on vulnerable user experience: the ease of climbing stairs/ramps, perceived safety from crime, and protection from weather
- accessibility and social inclusion: ramps or elevators for elderly people, children, and people with disabilities are better option than high-step staircases
- local community impact: these bridges often have a greater impact on local community cohesion, potential to became a landmark or new public space
- safety vs. convenience: studies must account for this paradox – if the physical effort is required during use, users might prefer less safe street level crossing.

In comparison with other infrastructure projects (road bridges), the main differences in S-LCA for pedestrian bridges thus can be summarized as the following priorities:
- focus on user-centric social impacts (rather than vehicular traffic disruption)
- how the structure serves the user experience and social connectivity (rather than structural material or vehicular flow).

Acknowledgement

The conference fee was funded by the Faculty of Civil Engineering, University of Rijeka, Croatia.

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