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Sustainable Performance Index for Bridge Infrastructure: Integrating Environmental, Social, and Economic Dimensions for Holistic Sustainability Assessment

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ABSTRACT

This study presents a comprehensive evaluation framework of the Sustainable Performance Index (SPI) for bridge infrastructure, covering environmental, social, and economic aspects. The environmental dimension assesses the bridge's impact on natural resources, pollution control, and ecological preservation. The social dimension evaluates community connectivity, equitable access, user safety, and comfort, emphasizing inclusivity and well-being. The economic dimension measures the bridge's effectiveness in sustaining smooth transport of goods and services, reducing logistics costs, and supporting economic growth. SPI integrates these facets to provide a holistic sustainability assessment, guiding infrastructure development and maintenance towards balanced, long-term benefits for the environment, society, and economy. This multidimensional approach supports informed decision-making for resilient and sustainable infrastructure systems.

KEYWORDS: Sustainable Performa Index, Bridge Infrastructure, Sustainable Assessment

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1. INTRODUCTION

Bridge infrastructure assessment is a fundamental aspect in maintaining the safety, function, and continuity of the transportation system, which is critically important for development and the economy. Bridges that connect different regions require periodic performance evaluation to ensure that the structure continues to meet safety and service standards. However, conventional assessment methods have mostly focused solely on technical aspects and physical conditions, thus failing to capture long-term impacts and sustainability aspects that have become a primary concern in infrastructure management.

The phenomena of climate change, pressure on natural resources, and the need to build resilient and environmentally friendly infrastructure have driven the emergence of new approaches in infrastructure performance assessment. Bridge infrastructure must not only be durable from a technical standpoint but also support sustainable development goals by considering social, economic, and environmental aspects throughout its life cycle. Currently, there is a gap in bridge evaluation practices that are still limited to assessing physical damage and technical service life without taking broader sustainability factors into account.

The Sustainable Performance Index is a method designed to address these needs by providing a holistic assessment. This method integrates relevant technical, economic, social, and environmental indicators to offer a comprehensive overview of the condition and sustainable performance of a bridge. With this approach, managers and stakeholders can plan maintenance and infrastructure development more effectively and efficiently, while aligning with global demands for environmentally conscious and future-oriented development.

The urgency of this research arises from the need to fill the evaluation gap that integrates sustainability aspects comprehensively in the context of bridges, especially in Indonesia, which is experiencing accelerated infrastructure development. This research aims to apply and test the use of the Sustainable Performance Index as an evaluation tool capable of addressing these complexities and providing strategic recommendations for more sustainable and durable bridge management.

By understanding and implementing this index-based assessment, it is expected that bridge infrastructure management can be created that not only focuses on meeting technical safety standards but also supports resource conservation, reduction of environmental impact, and enhancement of socio-economic benefits for the broader community.

2. LITERATURE REVIEW

The sustainability assessment of bridge infrastructure has become a major focus in modern civil engineering research and practice, given the vital role of bridges in transportation systems and economic development. Recent studies emphasize the importance of an approach that covers the entire life cycle of bridges, including the design, construction, maintenance, and end-of-life disposal phases (life cycle assessment / LCA) to accurately measure environmental, social, and economic impacts [1]. Various sustainable performance assessment methods for bridges have been developed using multi-criteria decision-making (MCDM) approaches, such as AHP (Analytic Hierarchy Process), SAW (Simple Additive Weighting), TOPSIS, and PROMETHEE, which allow the integration of technical, economic, social, and environmental indicators into a comprehensive evaluation framework. These MCDM approaches are increasingly applied to support decision-making based on the interrelated factors throughout the bridge life cycle [2]. The literature also highlights the importance of using systematic and well-documented performance indicators for the objective assessment of bridge conditions during the operational and maintenance phases. These indicators can include the level of physical damage, load capacity, material sustainability, as well as social and environmental impact aspects that are often overlooked in conventional practice [3].

In addition to technical aspects, modern research emphasizes the importance of life cycle cost (LCC) analysis combined with the environmental aspects of life cycle assessment (LCA) for optimizing economically and environmentally friendly maintenance strategies. Studies show that alternative materials such as recycled steel, high-performance concrete, or composite materials can enhance durability while reducing carbon impact during the bridge's service life [4] Recent studies also highlight the lack of comprehensive evaluation of the end-of-life stage of bridges, which remains a gap in bridge sustainability assessments. This presents a significant challenge for truly full life cycle-oriented assessment, especially in the context of sustainable development in various countries, including Indonesia [5].

The development of a Sustainable Performance Index has become an alternative solution adopted to integrate these various important dimensions into a single framework that is easy for managers and policymakers to use. This index is expected to assist in prioritizing the maintenance and development of bridge infrastructure that not only meets technical requirements but also supports social, economic, and environmental protection goals [6]. Thus, research that combines life cycle thinking, multi-criteria assessment, and the development of sustainable performance indicators will make a significant contribution to more effective, efficient, and environmentally friendly bridge management, in line with the demands of global sustainable development [7]. This literature review provides a strong theoretical foundation and methodological framework for research on bridge infrastructure assessment using the Sustainable Performance Index in the referenced international article.

3. RESEARCH METHOD

This study aims to provide an assessment of bridges using the Sustainable Performance Index (SPI) method, with the main indicators covering Environmental, Economic, and social aspects, each consisting of several indicators representing the overall sustainability dimensions of bridges. The primary data used are questionnaires distributed to competent parties with good knowledge of various types of bridges, such as representatives from the Directorate General of Public Works of the Republic of Indonesia and operators specifically responsible for managing bridges in different regions across Indonesia.

Data processing is carried out according to the following steps:

- Summarize respondent answer scores from a Likert scale of 1–5 for each indicator (environmental, economic, social aspects).
- Calculate the average value for each indicator within each aspect.
- Aggregate the values.
- Normalize the indicator values.
- If indicator weights are available (from experts / AHP), multiply the average values by their respective weights.

Once the SPI results are obtained, they can be classified into sustainability level categories, such as:

- SPI 0.80 – 1.00 = Very Sustainable
- SPI 0.60 – 0.79 = Quite Sustainable
- SPI 0.40 – 0.59 = Less Sustainable
- SPI < 0.40 = Not Sustainable

4. RESULT AND DISCUSSION

The questionnaire was distributed to respondents online using Google Forms, followed by statistical analysis with SPSS using a Likert scale (values 1-5). A total of 40 respondents successfully completed the questionnaire, and all collected data were declared valid and can be used for analysis using the Sustainable Performance Index (SPI). The following is the average value of each indicator.

A. Environmental Aspects

Table 1. Average Value of Environmental Aspects

Indicators	Environmental Aspects	Average (Value Per Aspect/ 40)
A1	Eco-friendly materials	3,625
A2	Construction Energy Efficiency	4,175
A3	Low Pollution Maintenance	4,350
A4	Environmentally Friendly Drainage System	4,325
A5	Resilience to Natural Disasters	4,325
Average Environmental Aspects		4,160

Table 2. Normalization of Environmental Aspects

Indicators	Average	Normalization Value (Average-1/5-1)
A1	3,625	0,6563
A2	4,175	0,7938
A3	4,350	0,8375
A4	4,325	0,8313
A5	4,325	0,8313
Average Normalized Value of Environmental Aspects		0,79004

In the environmental aspect, most respondents chose Low Pollution Maintenance as the main indicator (0,8375). Low Pollution Maintenance in the context of Sustainable Performance Index (SPI) for bridge environmental assessment refers to maintenance practices that minimize pollution and environmental harm during the operational life of the bridge. This includes activities such as routine cleaning to prevent debris accumulation, controlling erosion around the bridge, using environmentally friendly materials and preservation chemicals, preventing contaminants from entering nearby water bodies, and managing structural repairs in a way that limits environmental impact. The aim is to maintain the bridge's structural integrity while reducing negative effects on surrounding ecosystems, air quality, and water resources, thereby supporting sustainability goals on the environmental aspect of the bridge's life cycle.

The detailed criteria for Low Pollution Maintenance within the Sustainable Performance Index (SPI) for bridge environmental assessment include:

1) Use of environmentally friendly chemicals and materials that have low toxicity and are biodegradable for maintenance activities.
2) Implementation of maintenance methods that minimize air pollutant emissions, such as dust and exhaust gases from machinery and support vehicles.
3) Proper management of maintenance waste to prevent contamination of water, soil, and surrounding environments.
4) Erosion and sediment control during maintenance work to protect water quality beneath the bridge.
5) Limited use of harmful substances like hazardous solvents or corrosive chemicals that negatively affect ecosystems.
6) Adoption of environmentally friendly technologies in maintenance processes, including energy-efficient and material-saving techniques.
7) Planning and executing maintenance with the full life cycle consideration of the bridge to reduce long-term environmental impacts.

These criteria ensure bridge maintenance preserves structural function while supporting environmental sustainability.

B. Economic Aspects

Table 3. Average Value of Economic Aspects

Indicators	Economic Aspects	Average (Value Per Aspect/ 40)
B1	Life Cycle Cost	4,225
B2	Efficient Operational & Maintenance Costs	3,975
B3	Supporting the Smooth Flow of Goods and Services	4,500
B4	High Economic Value for Regional Development	4,375
B5	Transparent and Accountable Asset Management	4,425
Average Economic Aspects		4,300

Table 4. Normalization of Economic Aspects

Indicators	Average	Normalization Value (Average-1/5-1)
B1	4,225	0,8063
B2	3,975	0,7438
B3	4,500	0,8750
B4	4,375	0,8438
B5	4,425	0,8438
Average Normalized Value of Economic Aspects		0,82254

Supporting the Smooth Flow of Goods and Services indicator has an SPI value of 0.8750. In the Sustainable Performance Index (SPI) assessment, particularly in the economic aspect, Supporting the Smooth Flow of Goods and Services means that bridge infrastructure must ensure efficient and unobstructed transportation. This is crucial so that the distribution of goods and services can occur quickly and effectively, which in turn supports economic growth and reduces logistics costs.

Some key criteria of this aspect are:

1) Bridges must be designed and maintained to handle traffic volumes according to needs, both in terms of vehicle numbers and types of goods transported.
2) Minimization of disruptions to traffic flow caused by deterioration of bridge condition or poorly coordinated maintenance.
3) The bridge's ability to reduce travel time, thereby accelerating the mobility of commodities and services.
4) Reduction in transportation costs and the risk of damage to goods during shipping due to poor bridge conditions.
5) Supporting the continuous operation of economic sectors relying on road transportation via the bridge.

Thus, the economic aspect in SPI evaluates the effectiveness of bridges in maintaining and improving the smooth flow of goods and services, contributing to regional and national economic stability and growth.

C. Social Aspects

Table 5. Average Value of Social Aspects

Indicators	Social Aspects	Average (Value Per Aspect/ 40)
C1	Connectivity and Community Access	4,550
C2	User Safety and Comfort	4,550
C3	Involving Community Participation	4,025
C4	There are no significant negative impacts	3,975
C5	Supporting socio-economic growth, surrounding communities	4,325
Average Social Aspects		4,285

Table 6. Normalization of Social Aspects

Indicators	Average	Normalization Value (Average-1/5-1)
C1	4,550	0,8875
C2	4,550	0,8875
C3	4,025	0,7563
C4	3,975	0,7438
C5	4,325	0,8313
Average Normalized Value of Social Aspects		0,82128

In the social aspect of the Sustainable Performance Index (SPI), the indicators "Connectivity and Community Access" and "User Safety and Comfort" have the same SPI value of 0.8875. Connectivity and Community Access within the social aspect of the Sustainable Performance Index (SPI) refers to the degree to which bridge infrastructure facilitates effective connections and access for the local community. This indicator evaluates how well the bridge enables people to reach essential services, social opportunities, economic activities, and other communities, thus supporting social inclusion and cohesion.

Specifically, Connectivity and Community Access means:

1) Providing reliable and inclusive access routes that reduce physical and social isolation.
2) Enabling diverse groups, including vulnerable and marginalized populations, to participate fully in community life.
3) Supporting local mobility by connecting residential areas with workplaces, schools, healthcare facilities, markets, and recreational areas.
4) Promoting equitable transport options so that all community members benefit from the infrastructure.
5) Facilitating integration within broader transport networks that enhance regional and social interaction.

This social indicator gauges the bridge's role in improving quality of life and community well-being by ensuring accessibility and connectivity. It reflects how infrastructure investments translate into tangible social benefits, fostering stronger, more resilient communities.

Meanwhile, User Safety and Comfort in the context of the Sustainable Performance Index (SPI) refers to the degree to which bridge infrastructure provides a safe and comfortable experience for its users. This indicator encompasses multiple factors:

1) Safety: Ensuring the bridge design and maintenance reduce risks of accidents, injuries, or fatalities. This includes structural soundness, adequate lighting, protective barriers, anti-slip surfaces, and safe pedestrian crossings.
2) Comfort: Enhancing the user experience by minimizing vibrations, noise, and exposure to harsh weather. Comfort also relates to ergonomic design features such as handrails, seating areas for resting, smooth walking surfaces, and shelter from sun and rain.
3) Accessibility: Facilitating access for people with disabilities, children, and elderly to ensure inclusive use of the bridge.
4) Psychological Comfort: Providing a sense of security and well-being while crossing, including visibility, aesthetic appeal, and cleanliness.

Overall, User Safety and Comfort in SPI assesses how well the bridge infrastructure supports secure, convenient, and pleasant movement for all users, contributing significantly to social sustainability and public satisfaction.

After obtaining all the normalized SPI values for each aspect, aggregation (combining) is performed to obtain the SPI score per aspect by calculating the average of all indicators within that aspect.

Tabel 7. SPI Value Aggregation

Indicators	Total Normalization (Normalization Value/5)	Sustainability
Environmental Aspects	0,79004	Quite Sustainable
Economic Aspects	0,82254	Very Sustainable
Social Aspects	0,82128	Very Sustainable

Based on the Sustainable Performance Index (SPI) evaluation, the bridge infrastructure demonstrates the following sustainability performance levels:

- Environmental aspect: *Quite Sustainable*
- Economic aspect: *Very Sustainable*
- Social aspect: *Very Sustainable*

The interpretation of each aspect is explained as follows:

1) Environmental Aspect – "Quite Sustainable"

The *Quite Sustainable* rating indicates that the bridge's environmental performance has incorporated sustainability principles**,** yet requires further improvement to achieve full environmental sustainability. The bridge project shows environmental awareness but has not completely optimized its ecological impact management.

Detailed interpretation:

a. Environmentally friendly materials have been utilized during construction; however, the use of recycled or locally sourced materials has not been maximized.
b. Waste management systems during construction and operation exist but are not yet fully integrated with long-term environmental monitoring, such as sediment control or water quality protection under the bridge.

c. Energy efficiency and carbon emission control could be enhanced through green technologies, such as energy-saving lighting or smart monitoring systems.
d. Ecosystem protection around the bridge area (including aquatic and terrestrial habitats) is considered, but long-term conservation programs are still limited**.**

Thus, a *Quite Sustainable* level reflects a moderate degree of environmental sustainability, where current practices are adequate but require further innovation and consistency to reach a "Very Sustainable" level.

2) Economic Aspect – "Very Sustainable"

The *Very Sustainable* classification in the economic dimension signifies that the bridge project provides strong long-term economic value, operational efficiency, and financial sustainability. It indicates that the infrastructure performs well in supporting economic growth and cost-effectiveness.

Detailed interpretation:

a. Construction, operation, and maintenance (O&M) costs are efficiently managed, resulting in optimal economic performance throughout the bridge's lifecycle**.**
b. The bridge significantly contributes to local and regional economic growth by facilitating logistics, reducing travel time, and enhancing access to productive areas.
c. Life Cycle Cost Analysis (LCCA) shows that although the initial investment is high, long-term maintenance efficiency ensures financial sustainability**.**
d. The project's financial management demonstrates transparency, accountability, and cost-effectiveness.
e. The bridge also supports local economic activities, such as trade, tourism, and increased land value in surrounding areas.

Therefore, a *Very Sustainable* rating in the economic aspect reflects that the bridge successfully fulfills the principles of economic sustainability**,** delivering both direct and indirect benefits to stakeholders and the broader community.

3) Social Aspect – "Very Sustainable"

The *Very Sustainable* rating in the social aspect shows that the bridge infrastructure positively contributes to social welfare, inclusiveness, and equity within the community.

Detailed interpretation:

a. The bridge improves accessibility and regional connectivity**,** allowing communities better access to essential services such as education, healthcare, and economic opportunities.
b. Public participation and community consultation were conducted effectively during the planning and construction phases, minimizing social conflicts.
c. The bridge enhances road safety, mobility, and comfort for users, benefiting both motorists and pedestrians.
d. The project generated local employment opportunities, both during construction and ongoing maintenance phases.
e. The community exhibits a sense of ownership and responsibility toward the infrastructure, reflecting trust and collaboration between citizens and the government.

Hence, a *Very Sustainable* social rating indicates that the bridge strongly supports socially inclusive and people-centered infrastructure development**.**

The results of the Sustainable Performance Index (SPI) assessment reveal that the bridge infrastructure achieves *Very Sustainable* performance in the economic and social dimensions, while the environmental aspect remains at the *Quite Sustainable* level. This difference reflects the current tendency of infrastructure projects in developing countries, where economic growth and social benefits are prioritized, while environmental considerations receive comparatively less emphasis in project planning and implementation:

1) **Environmental Sustainability Performance**

The "Quite Sustainable" rating in the environmental aspect indicates that sustainability principles have been partially integrated but not yet fully operationalized. Although eco-friendly materials and basic environmental management systems have been applied, the bridge's construction and maintenance activities still generate measurable environmental impacts, such as waste generation, increased energy consumption, and minor disturbances to the surrounding ecosystem. Several factors contribute to this condition:

a. Limited adoption of green technologies**,** such as recycled aggregates, energy-efficient lighting, or low-carbon concrete.
b. Insufficient long-term environmental monitoring, particularly for water quality, sediment transport, and biodiversity around the bridge site.
c. Budget allocation and policy priorities that still emphasize technical performance and cost efficiency rather than environmental innovation.

As a result, the environmental aspect lags behind other sustainability pillars, emphasizing the need for stronger integration between engineering design and environmental management frameworks.

2) **Economic and Social Sustainability Strength**

In contrast, the bridge achieves *Very Sustainable* status in economic and social aspects. Economically, the bridge has demonstrated strong performance through efficient life-cycle cost management and significant contributions to local and regional economic growth. The infrastructure enhances logistics, trade flow, and accessibility to productive zones, resulting in a high return on investment for both government and society.

Socially, the bridge provides equitable access, improves mobility and safety, and fosters community development. The active participation of local residents during planning and construction stages has built public trust and a sense of ownership. These findings confirm that economic and social sustainability are interdependent—as improved connectivity drives economic activity, it simultaneously enhances social welfare.

3) **Managerial and Policy Implications**

The disparity between environmental and socio-economic performance implies that environmental sustainability should be strengthened through managerial innovation and policy intervention**.** The following implications can be derived:

a. Strategic integration of green engineering into bridge design and maintenance, including renewable energy-based lighting systems and recyclable construction materials.
b. Implementation of continuous environmental monitoring programs, using smart sensors or GIS-based systems to track emissions, water quality, and ecosystem health.
c. Capacity building and awareness programs for engineers, contractors, and government officials to promote sustainable construction practices.
d. Policy reinforcement**,** where environmental sustainability indicators are made mandatory in infrastructure performance evaluation frameworks and public procurement systems.

4) **Toward Balanced Sustainability**

To achieve balanced sustainability, the bridge management authority should adopt a holistic sustainability approach**,** ensuring that environmental strategies evolve alongside economic and social gains. This can be achieved by aligning infrastructure policies with the principles of the Circular Economy **and** Green Infrastructure Development**,** which emphasize resource efficiency, emission reduction, and ecological restoration.

Overall, the SPI assessment highlights a progressive direction toward sustainable bridge infrastructure. However, a stronger environmental focus is essential to transform current "Quite Sustainable" performance into "Very Sustainable," thus achieving a truly integrated and resilient infrastructure system.

5. CONCLUSION AND POLICY RECOMMENDATION

5.1. Conclusion

The findings of the Sustainable Performance Index (SPI) assessment indicate that the evaluated bridge infrastructure demonstrates strong overall sustainability, with *Very Sustainable* performance in the economic and social dimensions, and *Quite Sustainable* performance in the environmental aspect. The bridge contributes significantly to regional economic development by improving logistics, reducing travel time, and stimulating local business activities. In terms of social sustainability, it enhances accessibility, safety, and public satisfaction while fostering community participation and employment opportunities.

However, the environmental dimension remains moderate, indicating that sustainability principles have not yet been fully embedded in construction and maintenance practices. Although efforts to manage waste, emissions, and resource use exist, the lack of advanced environmental technology and continuous monitoring systems prevents optimal environmental performance. These results highlight the imbalance among the three pillars of sustainability, emphasizing the need to strengthen the environmental aspect to achieve holistic and long-term sustainability in bridge infrastructure.

5.2. Policy Recommendations

Based on the results and analysis, several strategic recommendations can be proposed to enhance future infrastructure sustainability performance:

1) **Integration of Green Design Principles.**

Incorporate green engineering and low-carbon technologies in the design, construction, and maintenance phases of bridges—such as the use of recycled or locally sourced materials, renewable energy systems, and energy-efficient lighting.

2) **Implementation of Life-Cycle Environmental Management.**

Establish a comprehensive environmental management plan covering the entire life cycle of the bridge, supported by continuous monitoring of air, water, and noise quality to minimize ecological impacts.

3) **Institutional Strengthening and Capacity Building**

Promote capacity-building programs for engineers, project managers, and policymakers to improve knowledge and skills related to sustainable construction and environmental innovation.

4) Policy Reinforcement and Regulatory Alignment.

Embed sustainability indicators into national and local infrastructure policies. Governments should require environmental performance metrics in project evaluation, procurement, and maintenance stages.

5) Community Engagement and Awareness.

Strengthen public participation in the planning and monitoring of infrastructure projects to enhance social inclusiveness and ensure that sustainability practices are responsive to community needs.

6) Adoption of Circular Economy and Digital Monitoring Systems.

Encourage the transition toward a Circular Economy framework in bridge management by reusing materials and reducing waste. Employ digital tools such as IoT-based sensors and GIS for real-time performance tracking.

In conclusion, while the bridge infrastructure exhibits high levels of economic and social sustainability, environmental performance must be improved to achieve a fully sustainable infrastructure system. Strengthening policy integration, technological innovation, and stakeholder collaboration will be crucial to ensuring that future bridge projects align with the global agenda for sustainable and resilient infrastructure development.

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