COMPREHENSIVE ASSESSMENT OF ENVIRONMENTAL IMPACT AND LIFE CYCLE COSTS IN BRIDGE STRUCTURE DESIGN

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ANNOTATSIYA:

This scientific work investigates the integrated assessment of environmental risks and financial costs in the construction of transport infrastructure facilities, particularly bridge structures. The bridge construction sector in Uzbekistan is analyzed, and the cumulative environmental impact of construction activities on nature is identified. Based on international best practices, the life cycle cost (LCC) calculation method is improved, and a monetization model that converts environmental damage into economic indicators is proposed. An ecological and economic comparison of concrete, steel, and composite materials is carried out.

In recent years, significant developments have taken place in the field of transport infrastructure construction in Uzbekistan. Precast reinforced concrete structures are gradually being replaced by cast-in-place monolithic technologies, which improve structural strength and long-term durability. The use of steel–concrete composite systems in long-span bridges has also become increasingly widespread. In terms of digitalization, Building Information Modeling (BIM) and Bridge Management Systems (BMS) are being introduced into the design, construction, and maintenance processes. Studies indicate that these approaches can reduce design costs by approximately 10–15%. Furthermore, modern elastomeric bearings and seismic isolation systems are being implemented in structures located in seismically active regions to enhance their earthquake resistance and overall safety.

At the same time, a major limitation of local research is that environmental impacts are rarely converted into monetary values and therefore are not reflected in project budgets. Although the studies conducted by researchers such as Azizov, Inomov, and Boʻriyev have extensively examined logistics and material durability, a comprehensive methodology integrating environmental and economic assessment has not yet been developed.

Ensuring a balance between infrastructure development and environmental sustainability is one of the key challenges of modern engineering. Bridge structures are essential components of transportation networks; however, their construction and operation can have significant impacts on the environment. In accordance with the requirements of PQ-436 Resolution [1,2], reducing environmental impacts, promoting the efficient use of resources, and implementing energy-efficient technologies have become priority objectives in the construction sector. Nevertheless, conventional design approaches often prioritize economic and technical criteria, while environmental factors receive insufficient consideration during the decision-making process.

In addressing this challenge, the Life Cycle Assessment (LCA) approach proposed by Chris Hendrickson [3] and Arpad Horvath [4] plays a significant role. Research findings indicate that approximately 70–80% of the total environmental impact of bridge structures occurs during the material production stage, particularly due to the high carbon dioxide (CO_2) emissions associated with cement and steel manufacturing.

Contemporary studies have extensively examined the environmental and economic aspects of material selection. In particular, Susana Gervasio and Luis Simões da Silva [5] emphasize the necessity of evaluating construction materials based on their life-cycle performance. Similarly, Michael Pantelides [6] demonstrates that the use of alternative materials can significantly reduce environmental burdens. Furthermore, Vladimir Shestakov and Alexander Vasilyev [7,8] have investigated methods for improving bridge durability and reducing long-term maintenance and operational costs.

Therefore, it can be concluded that bridge design should incorporate environmental considerations alongside economic and technical criteria to achieve sustainable and efficient infrastructure development.

Environmental Impact of Bridge Construction:

Bridge construction is a complex anthropogenic process that simultaneously affects the atmosphere, hydrosphere, and soil environment. International Life Cycle Assessment (LCA) studies have shown that approximately 70–80% of the total carbon footprint of a bridge structure is generated during the material production stage. Cement manufacturing and steel metallurgy are the primary contributors to these emissions.

From a hydrological perspective, bridge piers installed within river channels can alter water flow velocities, affect sediment transport processes, and modify water quality characteristics. In addition, alkaline substances released during concrete works and the operation of construction equipment may enter water bodies, creating potentially harmful conditions for aquatic ecosystems

Figure 1. Technogenic Disturbance of Soil Layers at a Bridge Construction Site and Disposal of Construction Waste into the River Channel

Acoustic impacts should also be taken into consideration. During the construction phase, noise levels typically range from 90 to 120 dB, while during operation they range from 60 to 80 dB. Such noise levels can have adverse effects not only on human populations but also on local wildlife and ecosystems

Structure Type	Environmental Impact (CO_2 Emissions)	Economic Cost	Overall Assessment
Conventional Reinforced Concrete	High: Cement production generates significant CO_2 emissions.	Moderate: Lower initial cost, but maintenance expenses increase over time.	High environmental burden.
Steel Structures	Moderate: Steel is recyclable, but its production is energy-intensive.i	High: Continuous corrosion protection and maintenance are required	Suitable for long-span structures.
Composite / Lightweight Systems	Low: Reduced material consumption and lower transportation impacts.	Higher initial cost, but the most cost-effective option over a 50-year service lifer	A promising and rational solution for sustainable bridge construction

Table 1. Comparative Environmental and Economic Analysis of Bridge Structural Types.

In international practice, particularly in Scandinavian countries such as Norway, glued laminated timber (glulam)-based bridge structures are widely used. Life Cycle Assessment (LCA) studies conducted on the Mjøsa Bridge (Fink et al.) have demonstrated that timber-based systems can reduce CO_2 emissions by 40–45% compared to conventional alternatives.

In the United States, Accelerated Bridge Construction (ABC) technology enables the prefabrication of bridge components off-site followed by rapid on-site assembly. This approach significantly reduces construction-site noise and waste generation. In addition, Departments of Transportation (DOTs) require that project evaluations account for life-cycle costs over a service period of 75–100 years.

In Japanese practice, the use of weathering steel eliminates the need for surface painting and reduces life-cycle maintenance costs by approximately 25% over a 50-year service period.

In major bridge projects in China, solar energy systems and structural health monitoring technologies are increasingly being integrated into bridge infrastructure, enhancing energy efficiency and enabling real-time performance monitoring and maintenance management.

METHODOLOGY

Basic Structure of the LCC Model: In the selection of structural solutions for highway bridges, limiting the analysis only to construction-phase costs does not fully reflect the overall economic and environmental efficiency of the structure. Therefore, the application of a life-cycle approach is considered essential in the evaluation process.

The life cycle of a bridge covers the stages of raw material extraction, material production, construction, operation, and end-of-life decommissioning or demolition. Each of these stages is associated with energy consumption and resource use, which collectively determine the total environmental impact of the structure.

To determine the total financial burden of a bridge structure, the Life Cycle Cost (LCC) model is applied. This model is not limited to construction expenditures but includes all costs from the raw material stage through to demolition. The general formulation is as follows [10]:

$LCC = C_{cap} + C_{maint} + C_{env} + C_{user}$

Here, represents capital costs during the design and construction phase; denotes maintenance and operational costs during the service life; refers to the monetary valuation of environmental damage; and accounts for user costs, including travel time losses and additional fuel consumption caused by maintenance activities and traffic disruptions. The complete formulation, incorporating inflation and discounting effects, is expressed as follows:

$$LCC = C_{inv} + \sum_{t=1}^{T} \frac{C_{maint} + C_{oper} + C_{user} + C_{env}}{(1+r)^t} - \frac{S_v}{(1+r)^T}$$

In the formula:
r – discount rate (taking into account inflation and banking indicators);
Sv – residual value of parts that can be recycled at the end of the service life;
T – service life of the structure (years).
This approach expresses the main idea: the rational solution is not the bridge with the lowest initial cost, but the structure with the minimum total accumulated cost over its entire life cycle.

Capital cost	Conventional (%)	Rational (%)	Key aspect
Capital cost	70–80	60–65	Higher initial investment in rational designs

Capital cost	Conventional (%)	Rational (%)	Key aspect
Maintenance cost (Cmaint	15–20	10–15	Reduced due to durable materials and design optimization
Environmental cost (Cenv)	2–5	15–20	Lower emissions through LCA-based material selection
User cost (Cuser)	3–5	5–10	Reduced traffic disruption in optimized construction methods

* *In the rational approach, the relatively higher share of does not indicate an increase in environmental damage, but rather reflects the full inclusion of environmental impacts in monetary terms within the cost assessment framework.*

Table 2. LCC Components and Their Shares under Two Approaches

Ko'prik qurilishida material tanlash masalasi nafaqat muhandislik, balki ekologik qarordir. Xalqaro LCA ma'lumotlar bazalari asosida tuzilgan quyidagi jadval uch asosiy materialning asosiy ko'rsatkichlarini aks ettiradi.

Although High-Performance Concrete (HPC) contains a higher cement content, the overall

Material	CO_2 (kg/t)	Service Life (years)	Maintenance Interval (years)
Conventional concrete (C25–C30)	150–200	40–50	10–12
High-performance concrete (HPC)	250–300*	80–100	25–30

Material	CO_2 (kg/t)	Service Life (years)	Maintenance Interval (years)
Composite / stainless steel materials	1800–2000	100+	40–50

material demand is reduced due to improved structural efficiency. As a result, smaller cross-sectional dimensions can be achieved, which ultimately leads to a reduction in the total carbon footprint of the bridge.

Table 3. Environmental and Technical Parameters of Main Construction Materials

High-strength materials, when applied in bridge construction, allow for reduced cross-sectional dimensions of structural elements, resulting in a 20–30% decrease in material consumption. In addition, composite and steel materials can be recycled up to 90% at the end of their service life, which significantly reduces demolition and disposal costs.

The monetization of environmental damage refers to the conversion of ecological impacts into financial indicators. This approach helps reveal costs that are often "invisible" in traditional project budgeting. In accordance with the "polluter pays" principle, the following formulation is proposed [9]:

$$C_{CO_2}=\sum_{i=1}^{n}(M_i \times E_i) \times P_{carbon}$$

Here, denotes the total quantity of the type of material (in tons); represents the emission coefficient of the material (kg CO_2/ton); and is the international or national carbon price per ton of CO_2 (typically 25–40 USD).

In addition, costs related to earthworks and land reclamation (), construction waste disposal (), and noise protection measures are also included in the overall environmental cost assessment.

To determine the rational solution, the following objective function is proposed for minimization:

$$F_{total}(x)=C_{inv}(x)+C_{user}(x)+C_{env}(x)\rightarrow min$$

Here, represents the set of decision variables, including material type, structural system, span length, and other design parameters.

The optimization process is carried out under the following technical and regulatory constraints:
[6/14/2026 8:33 AM] Admin二: Strength condition: (stresses must not exceed allowable limits in accordance with ShNK 2.05.03-22).

Environmental constraint: The total project emissions must not exceed the predefined carbon quota, as required by PQ-436 regulations.

Budget constraint: Initial construction costs must remain within the allocated budget.

The algorithm consists of the following steps: first, alternative structural solutions are generated; then the Life Cycle Cost (LCC) is calculated for each option; environmental impacts are monetized; the break-even point is determined within a 12–15 year range; and finally, the alternative with the minimum value of is selected as the rational solution.

Sensitivity analysis is also conducted to evaluate how variations in carbon pricing and discount rates may affect the final decision. The results indicate that as environmental taxation increases, the economic advantage of rational (eco-optimized) solutions becomes more pronounced.

CONCLUSION

The conducted research demonstrates that the use of modëern technologies and innovative structural solutions in bridge engineering in Uzbekistan is gradually developing. However, it has been identified that the current design practice still lacks a fully integrated framework for the combined assessment of environmental and economic factors. The study also shows that approximately 70–80% of the total environmental impact of bridge structures is generated during the material production stage, confirming that material selection is one of the most critical aspects of environmental management.

The developed Life Cycle Cost (LCC) model covers a service life of 50–100 years and enables a comprehensive assessment that includes not only initial construction costs but also maintenance, repair, operational expenses, and environmental impacts within a unified framework. By monetizing environmental effects, the long-term economic efficiency of the rational design alternative was evaluated, showing that it is approximately 31% more cost-effective over a 50-year period compared to conventional solutions.

Furthermore, the proposed multi-criteria optimization model enables evidence-based decision-making at the early design stage. This model simultaneously considers material consumption, CO_2 emissions, operational costs, and structural efficiency. As a result, it can be concluded that in the context of Uzbekistan, a rational bridge design refers to a structural solution with minimal environmental impact, optimized material usage, and the lowest total life-cycle cost over long-term operation.

REFERENCES.

1) O'zbekiston Respublikasi Prezidentining PQ-436-sonli Qarori "2030-yilgacha O'zbekiston Respublikasida 'yashil iqtisodiyot'ga o'tish dasturini tasdiqlash to'g'risida". Toshkent, 2022.
2) O'zbekiston Respublikasi Prezidentining PQ-199-sonli Qarori. Transport infratuzilmasini rivojlantirish bo'yicha chora-tadbirlar.
3) Hendrickson C., Horvath A. Economic and Environmental Evaluations of Life-Cycle Cost Analysis Practice // Environmental Science & Technology. – 1998. – Vol. 32, No. 7.
4) Gervasio H., Simões da Silva L. Comparative life-cycle analysis of steel-concrete composite bridges // Engineering Structures. – 2008. – Vol. 30, No. 10. – P. 2818–2828.
5) Pantelides C.P. Environmental impact of bridge construction materials // Journal of Bridge Engineering. – 2015.
6) Karimova A.B., Abdurasulova M.T. Methodology for Assessing Embodied Carbon in Bridge Structures // Engineer International Scientific Journal. – Vol. 1, No. 1. – 2026.
7) Karimova A.B., Abdurasulova M.T. Minimizing environmental impact in transport infrastructure // Journal of Multidisciplinary Sciences and Innovations. – 2025. – P. 861–865.
8) Azizov Q.X., Inomov A.A., Bo'riyev Sh.A. O'zbekistonda ko'priksozlik sohasining rivojlanish istiqbollari. – Toshkent: Fan, 2020.
[6/14/2026 8:33 AM] Admin二: 9) Ponsioen T.C., et al. Monetization of life-cycle based environmental impacts // The International Journal of Life Cycle Assessment. – 2023. – Vol. 28. – P. 412-428.
10) ISO 15686-5:2017 – "Buildings and constructed assets — Service-life planning — Part 5: Life-cycle costing". (Bu xalqaro standart bino va inshootlarning hayotiylik sikli xarajatlarini hisoblashning asosiy qoidalarini belgilaydi.