

# Sustainable Practice and Cost-benefit Analysis in Bridge Maintenance

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## ABSTRACT

Bridges are the hinge between cities and regions, and their health status and maintenance efficiency have a profound impact on economic activities and people's daily life. Due to the increasingly prominent problem of aging infrastructure, the limitations of traditional maintenance methods in terms of cost and efficiency have gradually emerged, which is urgent to improve through new technologies and methods. Moreover, the improvement of environmental sustainability issue has prompted engineering projects to pay more attention to ecological benefits. Therefore, this paper probes into the integration of sustainable practice and cost-benefit analysis in bridge maintenance, in order to identify and promote effective strategies, and then promote the sustainable development of bridge maintenance.

## KEYWORDS

bridge maintenance; sustainable development; cost benefit

Bridges are the key component of traffic network, and their maintenance directly affect the traffic safety, economic circulation and regional development. As the global infrastructure enters a phase of large-scale upgrading, methods and technologies for bridge maintenance are also evolving, and maintenance costs and environmental impacts are becoming key concerns for decision makers. Traditional maintenance strategies often focus on short-term cost benefits, but ignore the long-term environmental responsibility and sustainability. Balancing economic benefits and environmental responsibility has become a major problem in bridge maintenance. Therefore, this paper discusses the comprehensive consideration of economic benefits and environmental sustainability of bridge maintenance, in order to provide a new perspective for bridge maintenance, and help relevant departments to develop both economic and environmental strategies to meet the emerging challenges.

## 1 Current Status of Bridge Maintenance

### 1.1 Evolution of Maintenance strategies

The evolution of maintenance strategies reflects the interaction between the bridge engineering maintenance concept and the technological progress. Historically, bridge maintenance has focused on responding to dominant damage, and relied on periodic checks and repairs to maintain the functionality and safety of the structure. But with the development of engineering and materials science, as well as the promotion of sustainability goal, maintenance strategies is gradually shifting to a preventive and condition monitoring orientation.

Modern bridge maintenance strategies the include structural health monitoring system and the data-driven maintenance decision support systems, which enable maintenance operations to be implemented based on real-time data and accurate predictive models, so as to optimize the resource allocation, extend the service life of bridges, and reduce the ecological footprint.

The integration of structural health monitoring technology improves the sensitivity of fault detection and conducts a quantitative assessment of damage evolution trends through continuous data analysis. In addition, by comprehensively considering the direct costs, potential risks and environmental impacts in the maintenance process, life cycle cost analysis supports the optimal maintenance decisions under budget constraints, which promotes the efficient use of resources and the fulfillment of environmental responsibilities, and ensures the long-term stability of public infrastructure and the maximization of economic benefits<sup>[1]</sup>.

### 1.2 Current Implementation of Maintenance Technology

The current implementation of bridge maintenance technology reflects the integration of modern engineering progress and emerging technologies. Specifically, maintenance works rely on advanced diagnostic tools and predictive maintenance strategies that provide bridge managers with precision and efficiency. Real-time monitoring technologies, such as optical fiber sensing and wireless sensor networks, have been widely deployed in key structures to achieve continuous monitoring of bridge status. These systems can capture small structural changes and provide data support for damage warning. The application of big data analysis and machine learning algorithm enhances the ability to extract

useful information from massive monitoring data and optimizes the decision-making process maintenance. In addition, non-destructive testing technologies such as ultrasonic testing, magnetic flux leakage detection and infrared thermography technology have become an integral part of routine maintenance, which improves the safety and efficiency of testing and reduces maintenance costs. Through these techniques, maintenance teams can accurately identify structural defects and potential risks, and thus develop more targeted maintenance programs<sup>[2]</sup>.

## **2 The Theoretical Framework of Cost-benefit Analysis**

### **2.1 Basic Principle: Cost-benefit Analysis**

Cost-benefit analysis is a method to evaluate the overall economic benefits of a project, which is widely used in the decision-making process of infrastructure projects. Based on the systematic comparison of the relationship between the direct and indirect economic benefits brought by the project and the corresponding costs, this principle aims to determine whether the project is worth investment and how to optimize the allocation of resources to achieve the maximum economic benefits.

In the field of bridge maintenance, the application of cost-benefit analysis covers traditional direct costs, such as repair and replacement costs, and extends to indirect costs and benefits, including the economic impact of operational disruption, the potential environmental impact of maintenance activities, and the long-term benefits through improved structural reliability.

At the same time, the cost-benefit analysis must also consider the time value and use the net present value method to evaluate the current value of future cash flows to ensure the financial accuracy and foresight of the analysis. In practice, decision-makers need to evaluate the costs and benefits of various potential schemes, and use sensitivity analysis to explore the impact of changes in key parameters on project economic benefits. In this way, cost-benefit analysis can provide scientific and systematic decision-making support for the selection of bridge maintenance strategies and resource allocation, and effectively guide the rationalization of public investment<sup>[3]</sup>.

### **2.2 Cost-benefit Model for Bridge Maintenance**

The cost-benefit model for bridge maintenance integrates multiple parameters to accurately evaluate the economic rationality and social benefits of maintenance investment. This model provides a comprehensive decision supporting tool by quantifying the direct impact of maintenance activities on bridge functionality and safety and their indirect effects on traffic flow<sup>[4]</sup>. The construction of the cost-benefit model extends the traditional cost-benefit analysis framework to the assessment including full life cycle costs, which covers the full costs from construction, operation, maintenance to final decommissioning, as well as the benefits brought by these stages, in order to ensure a comprehensive consideration of economic sustainability in the decision-making process.

With the increasing popularity of predictive maintenance strategy, this model integrates predictive analysis based on the performance degradation model to enhance the foresight and pertinence of maintenance strategies. In addition, the cost-benefit model uses the risk analysis method to assess the impact of uncertain factors on cost benefits, thereby enhancing the applicability and robustness of the model, which enables bridge managers to identify critical risk points and develop optimal maintenance strategies based on economic and safety criteria.

### **2.3 Application of Cost-benefit Analysis to Bridge Maintenance Strategy Formulation**

Cost-benefit analysis provides decision-makers with a tool to evaluate the economic benefits and social impacts of different maintenance programs in the formulation of bridge maintenance strategies. This analysis method emphasizes the balance between maximizing economic benefits and minimizing cost expenditures in maintenance activities to ensure the maximum return on investment and reducing long-term operating costs.

On the one hand, by applying cost-benefit analysis to bridge maintenance, managers are able to make a comprehensive cost forecast and assess the potential impact of maintenance activities on the safety, reliability and service life of the bridge. They also take into account the indirect impact of maintenance activities on the surrounding environment and the community, such as economic losses and social inconvenience caused by traffic disruptions.

On the other hand, by using the cost-benefit analysis tool, decision makers can choose the most appropriate maintenance time and method by comparing the short-term maintenance cost with the long-term loss caused by delayed maintenance.

Moreover, the cost-benefit analysis supports the comparison of multiple schemes and provides decision-making support to help managers choose the one with the best cost and maximum benefit from multiple maintenance schemes.

### **3 Integrated Strategies for Sustainable Practice**

#### **3.1 The Use of Green Materials and Technologies**

The use of green materials and technologies has gradually become a major strategy to promote the sustainable development in the field of bridge maintenance, in order to reduce environmental impact, optimize energy use, and extend the service life of bridge structures. Specifically, green materials such as high-performance concrete and recycled steel have been widely used in the construction and maintenance of bridges due to their durability and environmentally friendly properties. Green technologies include the use of ecological coatings and low-carbon emission technologies, which can help to reduce the release of hazardous substances during maintenance and improve the efficiency of maintenance operations. For example, the use of ecological coatings can reduce the emission of volatile organic compounds and extend the service life of bridge components through their enhanced corrosion resistance, thus reducing the need for frequent material changes. When using these green materials and technologies, maintenance managers need to conduct a comprehensive cost-benefit analysis to ensure that the technologies and materials used can be economically viable, provide both environmental and economic benefits throughout the bridge's life cycle, and provide solid support for achieving the green development goal<sup>[5]</sup>.

#### **3.2 Balance the Economic Efficiency and the Environmental Impact**

The selection of bridge maintenance strategies should be based on the comprehensive consideration of cost-effectiveness and ecological footprint to ensure a balance between the long-term financial sustainability and environmental responsibility. On the one hand, rising environmental standards and increased public concern for sustainable development have led to bridge maintenance requiring cost efficiency and minimal disruption to the ecosystem. Although the initial investment of the selection of low-carbon technologies and materials is high, in the long run, this selection can reduce carbon emissions, reduce the cost of future environmental improvement, and improve the public's acceptance of the project. Cost-benefit analysis should calculate direct financial expenses, such as materials and labor costs, and also estimate environmental costs, such as potential economic losses and ecological restoration costs caused by pollution emissions. In this way, bridge maintenance plans can select the best environmental technologies and materials within budget, thereby collaboratively improving the economic and environmental goals. On the other hand, the application of system dynamics models and life cycle assessment tools can accurately analyze the long-term economic and environmental impacts of various maintenance options, and help decision makers to make comprehensive and forward-looking choices, which enhances the scientific nature of decision making and strengthens the project's commitment to environmental sustainability.

#### **3.3 Application of Sustainable Technology Driven by Policies and Norms**

Policies and norms have played a guiding role in bridge maintenance, and set a new benchmark for the sustainable development in the industry. Specifically, government and industry regulatory agencies have begun to develop standards and policies, in order to promote the widespread use of environmentally friendly materials and low-carbon technologies in public infrastructure projects. These policies and norms often include strict requirements for material selection, environmental standards for construction processes, and energy efficiency indicators in long-term maintenance, which stipulate the use of certified green building materials and emphasize the use of energy saving and emission reduction technologies in bridge design and rehabilitation. Through these regulations, project managers are motivated or compelled to adopt more environmentally friendly technical solutions to reduce the negative environmental impact of engineering activities. In addition, some government departments promote the implementation of sustainable technology by providing tax incentives, subsidies or financial support, which reduce the initial cost of adopting new technologies and accelerate the market acceptance and application of green innovative technologies. Through the implementation of these policies and norms, sustainable technology is substantially promoted and applied in the field of bridge maintenance, which demonstrates the strategic consideration of policy makers for the future development of urban infrastructure.

### **4 Conclusion**

This paper identifies the necessity of sustainable practice and the key of cost-benefit analysis in bridge maintenance, discusses the application of green materials and technologies and their dual benefits to the environment and economy, and reveals the role of policies and norms in promoting the application of sustainable technology through systematic analysis. Therefore, these technologies and methods should continue to be promoted and optimized, and policy support

should be strengthened to ensure the environmental sustainability and the maximization of economic benefits of bridge maintenance strategies.

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