Enhancing Cost Prediction and Estimation Techniques for Sustainable Building Maintenance and Future Development

Subjects: Engineering, Civil

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Building maintenance is crucial, yet predicting financial resources for it remains challenging, particularly during the design and construction phases. This research aims to analyze and synthesize existing studies on maintenance cost estimation, with a focus on identifying key trends, methodologies, and sustainability considerations. The review finds that most studies emphasize educational and office buildings, while limited attention has been given to infrastructure such as bridges and roads. Moreover, growing attention is being directed toward early-stage maintenance cost estimation and integrating sustainability principles into cost prediction models. The findings underscore that incorporating sustainability factors in maintenance planning enhances long-term performance, reduces lifecycle costs, and supports future-ready building management. The study concludes by highlighting the need for more comprehensive, sustainability-oriented frameworks to improve the accuracy and applicability of maintenance cost estimation in the built environment.

maintenance costs prediction models buildings building maintenance cost estimation regression analysis artificial neural networks machine learning sustainable maintenance

Not so long ago, the construction cost was expressed only through the capital costs of acquiring land ownership, design costs, obtaining a building permit, and building construction costs. Today, there is more and more talk about the construction costs that will appear after the building is used, i.e., after obtaining a use permit [1]. All buildings are built to last as many years as possible, and the economic life of a building is an average period of 30 to 50 years [1][2]. Of course, the economic life is different for a family house, a building, or a bridge. Service life is the time after construction/installation during which the building or its parts meet or exceed the required behaviour or property [3]. The economic life is reached when the building no longer meets requirements from an economic point of view, i.e., when there is a variant that meets the intended function at lower costs [1]. However, proper and timely maintenance is essential for the structure (building, bridge, road) to be usable during its lifetime and to be used safely [4]. Adequate and regular maintenance refers to implementing a suitable, economically efficient strategy that anticipates potential defects or failures, thereby highlighting the importance of preventive maintenance [5].

Maintenance is carried out so that the building or some part of it retains its original purpose and so that all its users can be guaranteed safe use [6], that is, in order to meet the basic requirements for the building, such as mechanical resistance and stability, safety in the event of fire, preservation of hygiene, health and the environment, ensuring

safety and accessibility during use, noise protection, energy management and heat conservation, and sustainable use natural sources [7]. In the life cycle of a building, the period of use of the building lasts the longest, and for this reason, proper maintenance of the building is essential because this is where costs appear that may not be economical. Nowadays, it is increasingly visible that engineers, architects, and investors pay more and more attention to reducing the costs of maintenance and use of buildings or, more importantly, to reducing the total costs of projects, while this was not the case earlier because attention was paid exclusively to reducing construction costs [8]. Maintenance activities comprise various systematic measures designed to uphold the operational performance of a facility, safeguard user safety, and maintain the asset in satisfactory condition to prolong its lifespan [4][9][10]. If maintenance were not carried out on time and to a sufficient extent, the building would collapse relatively quickly. Building maintenance itself, especially when managing several buildings (e.g., city housing fund, university building group), should be carefully programmed in order to optimize investments and achieve optimal allocation of funds to priority operations [9].

Building maintenance costs include the costs of necessary work, materials, and other related costs that occur when maintaining a defined level of easement of a building, and include the costs of corrective, preventive, and reactive maintenance of the entire building or its parts [11].

Given the current research trends, it is important to acknowledge the significance of sustainability within the context of building maintenance [12][13]. Integrating sustainability into the maintenance of buildings goes beyond just saving money; it encompasses the wider effects on the environment and society. Sustainable maintenance approaches strive to minimize resource utilization and decrease waste generation, hence reducing the carbon emissions associated with buildings during their entire lifespan [14][15]. This includes the utilization of sustainable materials for repairs, the incorporation of energy-conserving equipment, and the adherence to environmental rules during maintenance operations. Furthermore, the practice of sustainable maintenance encourages the reuse and reutilization of building materials, thereby improving the durability and flexibility of constructions. Integrating sustainability into maintenance techniques not only improves the economic lifespan of buildings but also promotes environmental conservation and the well-being of future generations [16][17]. This comprehensive strategy guarantees that buildings maintain their functionality, safety, and environmental responsibility by connecting maintenance methods with global sustainability objectives [18].

In order to be able to plan financial resources for maintenance for the next year or the next few years, it is essential to estimate and determine the maintenance costs because proper maintenance of buildings is only possible with sufficient funds. By using a model for estimating building maintenance costs in the early design phase, it is possible to rationalize maintenance costs, plan the exact future costs, and prevent or reduce the impact of business interruptions due to maintenance needs.

Despite the growing awareness of the importance of maintenance, research on cost prediction and estimation has mostly focused on construction rather than post-construction phases. Construction cost estimation models are generally based on well-defined quantities, materials, and labor inputs within a limited project timeframe, whereas maintenance cost prediction must account for long-term uncertainty, degradation rates, user behavior, and the

impact of environmental conditions. This fundamental difference makes maintenance cost forecasting inherently more complex and less predictable. Furthermore, few studies have comprehensively reviewed and compared the existing approaches to maintenance cost estimation, particularly from a sustainability perspective. Given that maintenance activities contribute significantly to a building's total life-cycle cost and environmental footprint, there is a pressing need to consolidate current knowledge, identify methodological gaps, and propose directions for more sustainable and data-driven prediction models. Therefore, this review aims to address this gap by critically analyzing the existing literature on maintenance cost estimation techniques, highlighting their limitations, and emphasizing how integrating sustainability principles can enhance accuracy, efficiency, and long-term value in building management.

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