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Application of Life Cycle Costing Models for Evaluating Operating Costs in Large Construction Projects

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Abstract: The article examines the application of Life Cycle Costing models for assessing and managing operational costs in large-scale construction projects. It analyzes the development of the Life Cycle Costing concept, its theoretical foundations, and practical applications. Special attention is given to the impact of Life Cycle Costing models on decision-making processes, as well as methods for accounting for risks and uncertainties. A comparative analysis of various models is conducted, highlighting their advantages and limitations. An original classification of LCC models is proposed based on their analytical complexity and suitability for different project contexts. A case-based simulation is presented to demonstrate how scenario analysis and uncertainty modeling affect long-term cost outcomes. The study results emphasize the importance of utilizing Life Cycle Costing to optimize costs and improve construction efficiency in the long term.

Keywords — project life cycle, operational costs, operation, construction, Life Cycle Costing.

INTRODUCTION

The prediction of operational costs is a significant aspect of efficient large construction project management. In the past decades, as construction projects grew in complexity and size, there was a demand for more profound and detailed analysis of all the costs of the entire life cycle of constructed objects. The life cycle of a construction encompasses design phases, construction stages, operational procedures, maintenance needs, and ultimate disposal of the materials, with enormous financial outlay in each. Traditional cost estimation methods often fail to provide a comprehensive assessment, which can lead to increased financial and strategic challenges for developers and investors involved in large-scale projects.

The Life Cycle Costing (LCC) method is a very promising technique for carrying out an efficient analysis of operating costs. The system facilitates the accommodation of up-front capital investment along with the projection of maintenance and operating costs throughout the whole lifecycle of the facility. The use of LCC provides more accurate data for informed decision-making at every phase of the project, and thus it is an indispensable tool in assessing and reducing operating costs.

The objective of this study is to assess the existing LCC models and their applicability to establishing running costs in large construction projects. The paper will take into account the evolution of the LCC concept, the theoretical basis of the various models, and their application in various types of construction projects. Additionally, account will be taken of the problems and limitations that are encountered by practitioners in applying these methods.

To accomplish this objective, the techniques of comparative analysis and a systems approach will be applied, which will enable the synthesis of current methodologies and identification of the best models to be applied to different kinds of construction projects.

MAIN PART. HISTORY AND DEVELOPMENT OF THE LCC CONCEPT

The LCC concept emerged in the mid-20th century, when it became obvious that traditional cost assessment methods, focused only on initial investments, did not provide a complete picture of the cost of operating facilities. In construction, where operational costs can be several times higher than initial costs, the need to consider all stages of the life cycle of the facility – from construction and design to operation and disposal – increased more and more important.

The LCC concept was initially introduced in the US defense industry in the 1960s, where there was a need to assess the long-term costs of maintaining and operating weapons and infrastructure facilities. At that time, the LCC methodology was focused on increasing the efficiency of using state resources and minimizing costs in the long term. As the concept developed, it was adapted to other industries, including construction, where it began to be actively used in the 1970s.

By the 1980s, LCC methodology had become a prominent decision-making and planning instrument in construction, particularly for complex and large projects where operating costs are of particular interest. The 1980s also saw the initial substantial move toward capturing the risks and uncertainties involved in operating costs, enabling the prediction of changes in cost during the assets' life cycle more precisely [1]. This resulted in further sophisticated and advanced models that factored in considerations such as erratic energy prices, different codes and standards, and advances in construction materials and technologies.

Since the 1990s, the LCC method has been further evolved to include environmental and social factors. In order to satisfy the demands of sustainable development and energy-saving buildings, models have been designed that include not just financial costs, but environmental costs as well, e.g., carbon footprint and use of renewable resources [2]. Hence, now LCC is an integrated approach that not just facilitates the management of running expenses effectively, but also takes broader aspects of the life cycle of

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objects into account.

FUNDAMENTALS OF LCC MODELS

The concept behind LCC models emphasizes that the cost of operating an asset is influenced not only by its initial expenses but also by the cumulative costs incurred throughout its entire life cycle. This approach includes several key aspects, ranging from initial costs such as design and construction to operating and disposal costs (fig. 1).

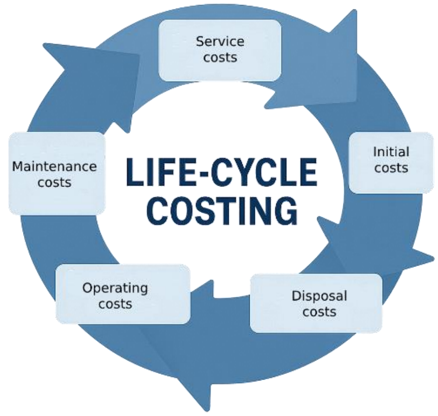

Fig. 1. LCC model [3]

The basis of LCC is to determine the total cost of an item, not just production costs, but also an estimate of all expenses that will arise in operation. For this purpose, the method of discounting is applied, whereby all future costs are discounted to the present value so that proper valuation of the impact of various factors on the final cost of the object can be made [4]. Discounting is especially effective for forecasting long-term expenditures, where the impact of items such as inflation or fluctuation in the price of resources can have a significant bearing on the final cost.

Historical LCC model classifications typically focus on whether cost inputs are fixed or variable, or whether discounting techniques are employed. These dualisms fail to reflect the increased sophistication of construction projects and the broader range of factors influencing long-term cost behavior. To transcend this limitation, we propose a new three-level taxonomy of risk approaches based on the depth of risk integration and the degree of contextual responsiveness. This system distinguishes between: **static LCC models**, which consider only initial and running costs and fail to make provision for uncertainty; **dynamic LCC** models, which utilize discounted cash flow analysis, scenario planning, and sensitivity testing; and **integrated LCC models**, which integrate financial, environmental, technological, and regulatory uncertainty and are applicable to projects involving high sustainability or ESG requirements (fig.2).

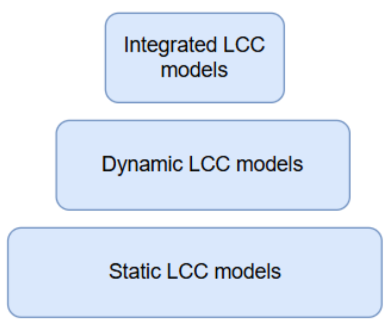

Fig. 2. Conceptual scheme illustrating the maturity hierarchy of LCC models

This classification gives a convenient template for correlating the choice of cost model with the strategic characteristics of a project. For example, Static models may suffice in early design phases or for recurrent facilities, while Integrated models are needed for large-scale, long-term infrastructural projects exposed to fluctuating legal, environmental, and market condition.

COMPARATIVE ANALYSIS OF MODELS

There are various LCC models, each having its own attributes and areas of application depending upon the type of construction projects and the objectives of the analysis. The main variance between them lies in the accuracy in taking into consideration different parameters such as risks, uncertainty and environment. For the purpose, different approaches can be recognized, amongst which the most common are fixed cost models and variable cost models.

Fixed cost models assume all the operating costs of an asset as exogenously given upfront and do not vary in the lifetime of the asset. It is a simpler approach to apply but is not able to capture possible changes in the cost of resources or technical characteristics

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of the asset, leading to errors while making long-term predictions. These models are typically used in the initial design stage, where the accuracy of the predictions is not so critical [5]. The advantage of these models is that they are simple and can be used in various projects, but they cannot always reflect the real costs of operation.

In contrast, variable cost models are more complicated but exact. They encompass the usage of methods such as cash flow discounting and uncertainty accounting. Such models allow for precise accounting of changes in the economic environment, shifts in resource prices, and possible changes in legislative and technological requirements [6]. These models allow different sets of circumstances to develop, thereby making them more suitable for large and long-term projects where accuracy of computation is the most important factor.

Comparison of the models shows that the use of more advanced and adjusted techniques, such as variable cost models, allows for a more accurate outcome in situations of uncertainty and risk. However, in short-term projects or when there are no prospects for modifications in operating costs, fixed cost models may prove to be economically more reasonable. It must be considered that the accuracy of the results depends directly on the quality of the original data and the choice of an appropriate model for a particular project.

To provide a more systematic understanding, the models can be comparatively evaluated across several critical criteria, such as analytical accuracy, flexibility, implementation cost, risk consideration, and practical suitability. Table 1 presents a summary comparison of three primary LCC model types, including static, dynamic, and integrated approaches.

Table 1

COMPARATIVE ASSESSMENT OF LCC MODEL TYPES BASED ON KEY ANALYTICAL CRITERIA

Criterion	Static LCC models	Dynamic LCC models	Integrated LCC models
Cost accuracy	Low – average-based	Medium – forecasting + discounting.	High – includes multidimensional analysis.
Risk consideration	None	Partial (economic factors).	Comprehensive (financial, technical, legal, environmental).
Project suitability	Basic/short-term projects	Medium complexity, long-term planning.	High-risk, ESG-oriented, strategic infrastructure projects.

This comparative table highlights that whereas static models have simplicity and minimal implementation costs, they are devoid of adaptability and risk considerations. Dynamic models can be the compromise, yielding higher accuracy and moderate use of uncertainty. Integrated LCC models, although more complex and resource-expensive, are most facilitative of decisions for high-risk or sustainability-oriented projects.

DECISION MAKING IN CONSTRUCTION

Models LCC play a significant role in construction project decision-making at different levels. Among the key areas of LCC application is its influence on technology, material, and building method selection, which establishes long-term operational costs. Investors and designers are able to take into account not just initial costs through LCC but also subsequent costs related to maintenance, repairs, and energy efficiency of buildings.

One of the major benefits of LCC is that it helps choose the most cost-saving options in constructing projects in terms of long-term operation expenses. For example, in a comparison of two options in construction technology or material, LCC helps establish which option will be more economical in the long run even if one option is expensive in the short run. This is very critical when people are weighing saving energy and building in an environmentally friendly way. In such situations, cost of operation can form a very large percentage of the project cost.

Additionally, LCC influences risk management in construction projects. Considering potential changes in operating procedures and maintenance enables more precise prediction of deviations from initial estimates. Therefore, LCC models assist in the identification and avoidance of risks associated with uncertain operating costs, for example, regulatory reforms or volatility in material and energy prices. The approach reinforces financial stability while promoting long-term project sustainability.

It should be noted that effective application of LCC relies on good-quality data, so there is a requirement to track the operating parameters of the facilities on a continuous basis. Additionally, the use of digital technologies and predictive analytics has the potential to enhance data quality, enabling more precise cost estimation and decision-making throughout the asset's life cycle.

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Applied Modeling: A Life Cycle Cost Comparison of Engineering Alternatives

For a direct illustration of real-life application of LCC models to building schemes, the costing model for an instance of the building with administrative space of 18,000 m² was hypothetically done and an exercise simulated comparing two other engineering proposal alternatives of the system heating and ventilation as to whether either of them would make economic sense or not when their life-long monetary return per unit asset-operating-years basis is placed on the costing criteria.

The simulation entailed a comparative evaluation of two engineering alternatives for a massive administrative block's heating and ventilation system. Option A consisted of a conventional gas boiler system with less initial capital expenditure but higher operating expense each year. Option B consisted of a heat pump system with in-board heat recovery, with higher initial expenditure but significantly reduced energy consumption and operating expenses in the long run.

To compare these options, two different LCC analyses were employed. The first utilized a simplified reduced-form model involving constant annual operations throughout the duration of the project life cycle. The second implemented a more complex discounted cash flow model with an assumed discount rate of 6% to factor in the timing value of money over a project operating life lasting 25 years.

The principal cost assumptions and resulting values for both alternatives, calculated using the two LCC approaches, are summarized in table 2.

Table 2

LCC BETWEEN CONVENTIONAL AND ENERGY-EFFICIENT HVAC SYSTEMS

Parameter	Option A (gas)	Option B (heat pump)
Initial capital cost (USD)	240,000	410,000
Annual operating cost (USD)	38,000	19,500
Total cost over 25 years (undiscounted)	1,190,000	897,500
LCC (discounted at 6%) (USD)	755,000	676,000

The modeling was based on standard LCC formulas. The present value of operating costs was calculated using the annuity present value formula:

$$PV = C_{op}\left(\frac{1-(1+r)^{-N}}{r}\right), \quad (1)$$

Where:

C_{op} – annual operating cost;

r – discount rate (6%);

N – lifetime (25 years).

The total LCC for each option was calculated by summing the initial investment and the discounted operating expenses.

A sensitivity scenario was also analyzed to evaluate the impact of energy price escalation. Assuming a 5% annual increase in gas prices, the financial advantage of the heat pump system grows significantly, reducing the life cycle cost gap by more than 25% in favor of Option B.

The model simulations clearly show that by making larger initial investments, energy-efficient systems such as heat pumps can have lower life-cycle costs. This emphasizes the application of LCC models in facilitating economically and ecologically sound decision-making in significant building projects.

ACCOUNTING FOR RISKS AND UNCERTAINTIES IN LCC

One of the principal elements of the LCC model application is the management of risks and uncertainties sure to be encountered when running construction projects. Risks could be identified with a list of factors, such as change in the economic state, change in the prices of resources, change in matters of regulation, and technical and environmental risks, able to influence the cost of operating facilities materialistically. Forecasting these changes and correctly assessing their impact on long-term costs is an important task when using the LCC (table 3).

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Table 3

TYPES OF RISKS AND THEIR IMPACT ON LCC [7,8]

Type of risk	Description	Impact on LCC	Mitigation methods
Economic	Inflation, currency fluctuations, financial crises.	Increase in material costs.	Use of discounting, hedging strategies.
Technological	Obsolescence of materials and technologies.	Increased expenses for modernization.	Selection of flexible and upgradable technologies.
Environmental	Climate changes, new eco-standards.	Additional costs for compliance.	Investment in sustainable technologies.
Legal	Changes in legislation and regulations.	Need for project adjustments.	Monitoring regulatory changes.
Operational cost risks	Rising costs of resources (electricity, water).	Increase in total expenses.	Implementation of energy-efficient solutions.

To accommodate uncertainty, the LCC model employs vast-scale stochastic modeling techniques, one of which is the Monte Carlo method, which allows various scenarios with varying levels of uncertainty to be simulated. The technique allows for the estimation of the probability of occurrence of specific events and its impact on the facility's total cost of operation. For example, uncertainty in energy costs or repair costs can make a significant difference in the estimated operating costs, and modeling techniques allow engineers to factor this aspect into the equations.

It is important to closely monitor the uncertainty that is created by laws and environmental regulations changing because these types of changes can necessitate a large sum of extra money to retrofit the facility to meet new standards. Another important factor is the change in the need to repair or maintain the facility, which will greatly add to operating costs.

Attention to risks and uncertainties makes forecasts more accurate and lessens the possibility of flawed management decisions. However, it must be realized that perfect information for risk modeling is not always present, and all projections contain some margin of error. In order to lessen these risks, there is a need to keep revising information and adjusting models based on developments in the external environment.

To illustrate the application worth of risk modeling, a simple scenario analysis was conducted to estimate the impact of energy price inflation on life cycle costs. With a 4% per annum rate of increase in the cost of electricity over a period of 25 years, the aggregate operational cost for an energy-using building increases by more than 40% compared to a fixed-price basis. With an overlay of stochastic modeling (e.g., Monte Carlo simulation), the calculated LCC distribution also indicates a high variation of outcomes with a potential range of 90% probability having ±15% variation around the median point. This justifies the imperative consideration of uncertainty in long-term investments, particularly where energy-sensitive is the situation for infrastructure.

CONCLUSION

The application of LCC models to construction projects offers significant benefits through enabling the more accurate forecasting of long-term operational expenditures and supporting very informed decision-making throughout the asset's life. In addition to the initial capital expenditures, LCC models take into account future spending on maintenance, repairs, energy consumption, and end-of-life disposal. This study proposed an integrated typology of LCC models by their project suitability and analytical maturity, which allows methodological complexity to be matched with the strategic goals of construction planning.

The economic efficacy of using advanced LCC models, particularly under the circumstance of price uncertainty and fluctuation, was also demonstrated using a case simulation and comparative analysis. Scenario-based calculations, including expected energy price inflation and risk modeling techniques such as Monte Carlo simulation, illustrated the necessity for external variable consideration. Success in any LCC application, however, strongly depends on input data quality and the ability to model uncertainty in a formal and realistic way. As LCC methods continue to develop, their future enhancement must target the incorporation of digital technology and sustainability principles to assist robust, affordable, and ecologically sound construction outcomes.

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