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Evaluation of pavement life cycle cost analysis: Review and analysis

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Abstract

The cost of road construction consists of design expenses, material extraction, construction equipment, maintenance and rehabilitation strategies, and operations over the entire service life. An economic analysis process known as Life-Cycle Cost Analysis (LCCA) is used to evaluate the cost-efficiency of alternatives based on the Net Present Value (NPV) concept. It is essential to evaluate the above-mentioned cost aspects in order to obtain optimum pavement life-cycle costs. However, pavement managers are often unable to consider each important element that may be required for performing future maintenance tasks. Over the last few decades, several approaches have been developed by agencies and institutions for pavement Life-Cycle Cost Analysis (LCCA). While the transportation community has increasingly been utilising LCCA as an essential practice, several organisations have even designed computer programs for their LCCA approaches in order to assist with the analysis. Current LCCA methods are analysed and LCCA software is introduced in this article. Subsequently, a list of economic indicators is provided along with their substantial components. Collecting previous literature will help highlight and study the weakest aspects so as to mitigate the shortcomings of existing LCCA methods and processes. LCCA research will become more robust if improvements are made, facilitating private industries and government agencies to accomplish their economic aims.

Keywords: Life-Cycle Cost Analysis (LCCA); Pavement management; LCCA software; Net Present Value (NPV)

Contents

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1. Introduction

Nowadays, highway pavement construction, maintenance and rehabilitation costs are rising dramatically. It is essential for highway agencies to utilise tools and approaches that facilitate proper decision-making by applying economics and operations research such as Life-Cycle Cost Analysis (LCCA) to achieve economically reasonable long-term investments. LCCA is a method based on principles of economic analysis. It improves the estimation of the total long-term economic viability of different investment options [1]. This method finds significant application in pavement design and management [2]. A number of agencies employ the LCCA approach to estimate the economic feasibility of pavement designs over the long haul. Thus, it is very important for agencies to realistically evaluate pavement economics in order to provide suitable input to the LCCA.

As a concept, it was in the 1950s that benefit-cost analysis (BCA) was initially applied as a selection factor for various pavement design options. Then in the 1970s, LCCA principles started being implemented in some key projects at the local and national state levels for pavement design and pavement type selection [3]. As presented in Fig. 1, the aim of LCCA represents the extent and details of the next steps. All managers and stakeholders should completely collaborate so that full effectiveness can be achieved [4].

Considering the mostly inadequate funding under normal circumstances, road authorities are consistently challenged with funding projects due to resource insufficiency [5]. Moreover, with the increasing demand for new road infrastructure, the demand for efficient management of old and new roads is on the rise as well, along with safety demands, accessibility and the implementation of advanced traffic management systems for decreasing socio-economic costs by mitigating maintenance-related environmental effects, traffic issues, and losses. Maintenance backlogs nonetheless increase too [6]. Road authorities thus emphasise more on better efficiency and lower expenses due to limited funds. Since maintenance expenditures normally comprise half the annual road infrastructure funds, it is very important to prioritise efficiency in road maintenance [5,7]. Thus, with respect to road objects, life-cycle costs (LCCs) are regarded as having higher priority than simply investments. Hence, road authorities are expected to realise the importance of LCCA and maintain a calculation system [8]. LCCs are also deemed to be a restraint in road design selection or the assessment of tenders [9,10]. When calculating LCCs, both road authority costs and costs of socio-economic nature should be taken into account. Road agency (authority) costs comprise expenses for planning, construction, design, maintenance, and rehabilitation. All these costs are usually the government's responsibility to cover using tax earnings. Socio-economic costs comprise agency costs, user costs (e.g. delay costs, accident costs and vehicle operation costs), and environmental costs [7,11].

2. Literature review

2.1. Historical background

The American Association of State Highway Officials (AASHO) introduced the concept of life-cycle cost-benefit analysis in its "Red Book" in 1960. The LCCA was intro-

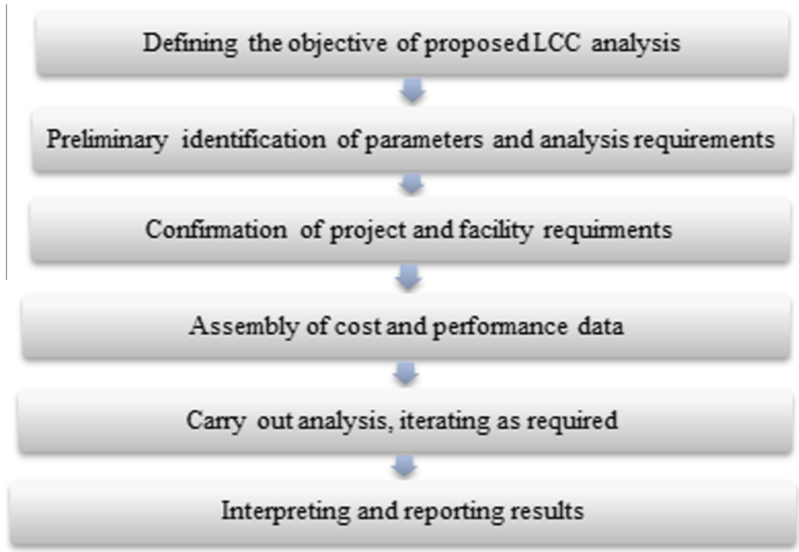

Fig. 1. Core process of LCCA.

duced for highway investment decisions, and as such, formed the notion of economic evaluation of highway upgrades during the planning stage. The next progress step was made by Winfrey [12] who combined data available on the cost of vehicle operations in a system to be utilised when highway planners are developing life-cycle costing processes. Moreover, two projects in the 1960s introduced the utilisation of LCC principles for pavement type selection and pavement design. In the first project, the Centre for Highway Transportation Research and the Texas Transportation Institute (TTI) developed the Flexible Pavement System (FPS), a computer-based approach for analysing and rating alternative flexible pavement designs through the overall life-cycle cost [13]. The second project was by the National Cooperative Highway Research Program (NCHRP), which examined the promotion of the LCCA concept [14]. Subsequently, the Rigid Pavement System (RPS) was developed by Texas DOT, which is identical to FPS with regard to how Life-Cycle Cost Analysis of rigid pavements is carried out. RPS also ranks alternative designs according to their total life-cycle costs [15].

The use of LCC concept is supported in the different AASHTO Pavement Design Guide editions [1,16], which also include detailed discussions regarding costs that should be considered in LCCA. The current study presents an overview of the basic life-cycle costing theories, with explanations of the various user and agency costs associated with highway pavement projects, as well as the discount rates and economic feasibility of systems [17,18].

2.2. Obligations and legislative requirements

In 1991, LCC application during the design and construction of tunnels, bridges or pavements was mandated by the Intermodal Surface Transportation Efficiency Act [19]. The FHWA stimulated state departments of transportation to carry out LCCA of all pavement projects having costs above US$25 million [18]. As per the National Highway System (NHS) Designation Act of 1995, state highway agencies are supposed to perform an LCCA of every NHS "high-cost usable project segment" [20]. It is legislatively presented in section 303 of the NHS Designation Act that LCCA is an approach for analysing the total economic value of a feasible project segment by evaluating the initial costs and discounted future costs like maintenance, rehabilitation, reconstruction, resurfacing, and restoring costs, over the entire life of the project.

Although LCCA is formally required in certain situations, the FHWA consistently encourages its implementation when evaluating all key investment decisions. This is because such analysis could improve the efficiency and effectives of investment decisions irrespective of whether particular LCCA-mandated requirements are satisfied or not [17]. The requirement for highway agencies to perform LCCA was removed by the 1998 Transportation Equity Act for the 21st century. Nonetheless, utilising LCCA as a decision support tool is still advocated in the FHWA policy, stressing that the outcomes are not exactly final decisions. This means that the logical analytical framework of this kind of analysis is as significant as the LCCA results themselves [21]. It is the objective of TEA-21 to increase knowledge of LCCA by applying certain notions, as presented in Fig. 2.

Walls and Smith presented technical instructions and suggestions in the FHWA Interim Technical Bulletin regarding the most suitable method of performing LCCA in pavement design [21]. The Bulletin is aimed at state highway agency personnel who perform and/or evaluate pavement design LCCAs. It is specifically related to the technical aspects of continuing economic efficiency possibilities of other prospective pavement designs. Risk analysis is also included as a probabilistic

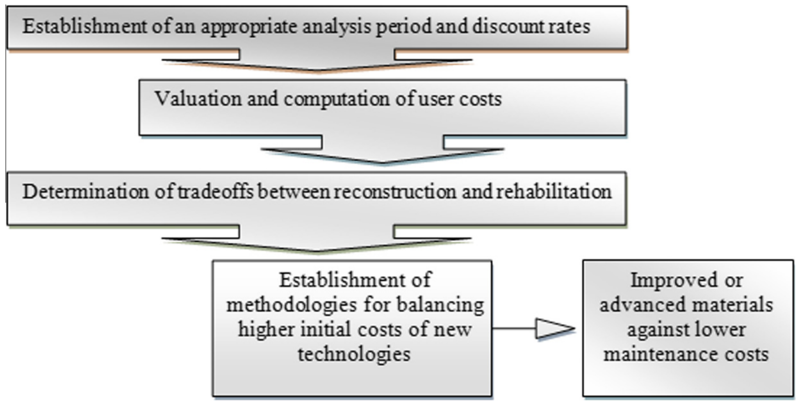

Fig. 2. Process of LCCA by TEA-21.

method for understanding unpredictability in the design process [18].

2.3. LCCA models

Huvstig [22] analysed different LCCA calculation models implemented by road authorities. The models were QUEWZ (Australia), Highway Design and Management (HDM I to IV) developed by The World Bank, COMPARE (Great Britain) and Whole Life Costing System (USA). These models are basically implemented for the design and construction of roads and pavement types. LCC has been suggested as a factor to consider during road design selection or alternatives assessment [23,10]. However, since it is difficult to calculate LCC for road objects with the dearth of reliable information and calculation approaches, the LCC has less critical importance when assessing alternatives [24]. The inadequacy of investment and maintenance-related data is caused by road authorities' failure to have organised and systematic processes for data collection or follow-up throughout the stages of planning, design, construction and maintenance. These deficiencies are ultimately due to the scarcity of consensus and comprehensive LCC approaches to correctly compute the user costs and environmental costs as precise as agency costs. In some circumstances, LCCs even result in rising investment costs. The bases of current deterioration models are experience and empirical models [25]. Nevertheless, these models could produce satisfactory results only if past and future situations would remain the same. This is quite a rare situation considering road construction, because a number of factors like the use of heavier vehicles, traffic development and new types of tires impact road conditions [7]. The Sweden Road Administration (SRA) has tested the minimum annual LCC as an award criterion [26]. The outcomes of SRA study are signified rising investment costs that lead to negative budgetary implications. Also, it is indicated that this may be due to the exploitation of circumstances by contractors who emphasise on costly solutions with speculative guarantees that cannot be verified or rectified until it is too late. It should be understood that LCC models are mainly for structural road design as tools for selecting the most economically reasonable solutions in the context of investment and maintenance. Many of the models do not consider geometrical road design, although such design method provides road alignment and road restraint systems that affect costs during road life-cycle [27].

2.4. LCCA effectiveness in pavement design, maintenance and rehabilitation

The Federal Highway Administration (FHWA) guidelines are published in order to examine the various cost effectiveness of pavement rehabilitation design approaches [21,28]. The model framework applied in Anderson's study [28] contained four stages: a pavement condition and analysis module, suitable maintenance and rehabilitation approaches, computing the costs and benefits of all approaches and selecting approaches on a network basis. The study incorporated relationships that link maintenance costs with the pavement serviceability index (PSI) and user cost with the PSI according to road classification. Lampty et al. [2] presented beneficial tips regarding the development and assessment of maintenance approaches. Their study report indicated that the model was basically developed for rehabilitation strategy analysis, but it can be changed to address preventive maintenance practices as well.

Gorvetti and Owusu-Ababio [29] utilised LCCA principles in a study that examined possible pavement design alternatives. The LCCA principles served to assess the benefits and costs of one particular design for flexible and rigid pavements separately over their respective life cycles. They indicated that current LCCA processes could comprise some pavement designs not taken into account in the initial LCCA development. In 1984, the long-term pavement programme (LTPP) and strategic highway research programme (SHRP-related) were initiated. The purpose was to provide tools to better understand pavement behaviour and to aim for efficient management of highway infrastructure without large increases in funds [30–32]. The research involved an extensive and detailed study of numerous real pavement and field conditions to find out about maintenance practices, the impact of climate, construction practices, material variations and long-term load effects. One segment of the LTPP study included specific pavement studies #4 (SPS-4) experiments, which were particularly developed to analyse the success of common preventive maintenance treatments of rigid pavements. It was anticipated that quantifying the ability of various maintenance treatments to prolong the service life or decrease distress rates would be facilitated by analysing the pavement performance data achieved from the sites or the family sites [30]. The purpose of the experiment was also to investigate how different environmental regions, traffic rates, pavement types (plain or reinforced), subgrade types (course-grained or fine-grained) and base types (stabilised or dense granular) impact the preventive maintenance of rigid pavements.

The FHWA stated that the lowest LCC option might not exactly be the most ideal, since there are other factors that must also be taken into account, such as available budget, risk, and political and environmental concerns [33–35]. Moreover, the LCCA provides information that is critical to the total decision-making process but it does not offer the final answer [36]. According to the FHWA, as per a recent survey of state practices, some type of LCCA is utilised by 28 of 38 responding states in their pavement investment decision-making [37]. It was also indicated that less than half of these 28 states included user costs in their LCCA. In comparing the survey outcomes with a similar attempt made in the past, Peterson [38] showed that the states are gradually accepting and implementing LCCA concepts during pavement design.

Road authorities are required to focus on decreasing costs and improving efficiency, since maintenance costs constitute a large portion of annual road infrastructure expenditure. Universally, road authorities can only carry out new road projects and adequately maintain current roads by lowering costs and enhancing efficiency, as funds for road infrastructure have been continually declining [5].

2.5. LCCA effectiveness in preservation treatments

In LCCA, the effectiveness of pavement maintenance or rehabilitation is a major input. Short-term analysis of treatment effectiveness may be done, for instance the decline in deterioration rate or performance improvement [39], or there could be long-term assessments. Such assessments of preservation effectiveness are more pertinent to LCCA. One of the three approaches presented in Fig. 3 is mainly used for the long-term evaluation of the effectiveness of preservation treatment (usually over the entire treatment duration).

Effectiveness can be measured by forecasting how much extension is available in the remaining service life through the preservation treatment. This means the time remaining till the pavement weakens to a specific threshold level, which is also stated as the treatment service life or treatment life. Treatment life can be measured through performance curves (made from past data), or by using expert opinion and a treatment performance threshold. Compared to these two methods, the area-under-the-curve method is much more data intensive but is based on simple logic. There are numerous benefits of a well-kept pavement; however, it is quite difficult to quantify the benefits in monetary terms. The area under the performance curve can serve as a substitute for user benefits. Kher and Cook [40] employed the area under the performance curve for the Ontario Ministry of Transportation and Communications' Program Analysis of Rehabilitation System as a substitute for user benefits. Also, the area under the condition-time curve was utilised as a measure of performance when developing budget optimisation methods for PAVER (U.S Army Corps of Engineers' Pavement Management System) [41]. Joseph [42] also applied this curve in combination with road section length and average annual daily traffic (AADT) in order to compare the cost-effectiveness of preventive maintenance strategies. The area under the pavement performance curve was employed by the New York State Department of Transportation for comparing the cost-effectiveness of alternative preventive maintenance approaches [43]. In the PSI-ESAL loss concept (where the performance measure is Pavement Surface Index (PSI) and the "time" scale is signified by cumulative loadings applied to the pavement), benefits are denoted by the area under the PSI-load curve [44]. A funding allocation process for the San Francisco Bay Area Metropolitan Transportation Commission was developed using the area under the performance-time curve concept [32].

3. Evaluating the benefit and cost-effectiveness

Cost-effectiveness evaluation is a method of economic evaluation. It involves comparing what is sacrificed (i.e. the cost) to what has been gained (effectiveness) so the alternatives can be evaluated. Measuring cost-effectiveness may be done for the short or long term. Between long-term and short-term evaluation, the cost-

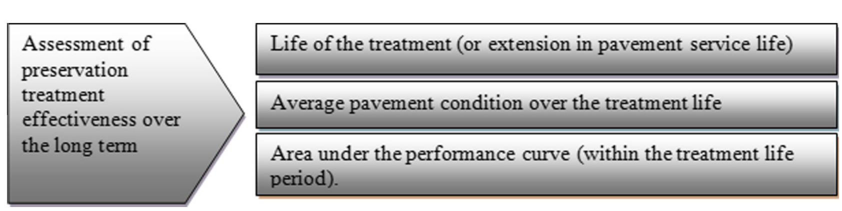

Fig. 3. Three different methods to measure assessment of preservation treatment effectiveness.

effectiveness concept might be regarded as more suitable for long-term evaluation. From the view of the economist, effectiveness evaluation can be performed in two ways: first, to attain maximum benefits from a certain level of investment (the maximum benefit approach), and second, to determine the minimum cost for the effective treatment of problems (least cost approach). The first method is applied very frequently in capital investment decision-making, while the second method is more suitable for maintenance cost assessment.

3.1. Maximum "BENEFIT" approach

This method is typically applied for the assessment of capital investment projects, since these activities usually comprise a single big investment that is linked with considerable unpredictableness and where each alternative's cost is the same. Hence, it is quite difficult to evaluate the exact benefits. It is also usually hard to determine measures of effectiveness for such projects and quite complex to describe because of the long duration of the activities and spillover effects [45,46]. Many research works have been conducted over the past two decades to describe the measures for assessing capital improvement benefits. Several benefits include: tort liability, decrease in travel time, improved motorist comfort and safety, decreased or deferred capital expenditures through capital preservation, vehicle operating and maintenance costs, and reduced pavement deterioration rate [43].

3.2. Least Life-Cycle Cost approach

Pavement maintenance investments normally have lower values and take comparatively less time to complete capital improvements. Moreover, their effects are observed soon after completion. The least cost method can be regarded as the most adequate when short-term assessment of corrective maintenance "investments" is to be carried out, because all alternatives are believed to lead to the same benefits.

3.3. Combination of cost and benefit approaches

When assessing pavement preservation, maintenance and reconstruction, using a combination of least cost and maximum benefit is advocated. NCHRP Synthesis 223 indicates that both gains accrued by users and the costs spent for the provision of those benefits should be taken into account [43]. According to the study, a benefit-cost analysis could be done when the costs and benefits are quantifiable in monetary terms. Among the best tools for measuring the effectiveness of different maintenance activities are the LCC and benefit analysis, whereby all factors are converted into economically measurable units [38]. It is claimed that cost reduction is the benefit, which is implied in the term "Life-Cycle Cost Analysis." In pavement management, LCCA has been applied either as the least annualised life-cycle return that is calculated in perpetuity [44], or as the least present worth of the life-cycle cost and benefit [47]. To evaluate the cost-effectiveness of network level maintenance and rehabilitation processes, a basic type of LCCA approach was used [48]. Moreover, the effect of deferring the maintenance and rehabilitation of pavements as per data received from U.S military installations was measured via life-cycle costing [46].

4. LCCA approaches

LCCA entails two approaches that may be used, which are the probabilistic and deterministic approaches. Input variables are considered discrete fixed variables in the deterministic approach (for instance, design life = 20 years). However, it is observed that a certain level of uncertainty lies within the input values of any LCCA. If prediction is present with engineering analysis, there will be some level of uncertainty, which is mainly due to four reasons [49]:

- First, uncertainty is caused by randomness, meaning that the measured or observed values would have different frequencies of occurrence and variation.
- Regional construction variation is the second reason for uncertainty. For instance, the data collected for location "A" cannot be used to assess any condition in location "B."
- Uncertainty across human factors is another reason for uncertainty. Factors include imperfect estimation or modelling.
- Finally, a lack of data may be a reason behind uncertainty, whereby it is possible to omit a variable due to limited data.

Uncertainties can be managed with various methods, including risk analysis (the probabilistic approach) or sensitivity analysis [50]. Sensitivity analysis is used during model development, when the effects of several input parameters need to be analysed. Several areas of uncertainty must be known during the decision-making process, which may not be known as part of this type of analysis [51]. The probabilistic approach is utilised with input variables and computer simulation for the characterisation of risk with the outcome in the case of risk analysis. If all inputs are analysed probabilistically, the LCCA system is deemed much more powerful and valid [52].

4.1. Sensitivity analysis

In order to understand the variables affecting the final outcome at the largest level, the sensitivity analysis method is used. Christensen et al. [53] reported that by using this process, the model variables can be identified and also the ranking of the considered options can be changed by determining the breakeven points. Rehabilitation timing, discount rate and unit cost of materials are some of the factors that have significant influence [54]. If a change occurs in a model variable like the discount rate, it would have an effect on the ranking of feasible design options, but no dominant alternative design options would emerge. Also, the effect of a single model variable on the analysis outcomes can be judged through sensitivity analysis, but it is not possible for engineers to attain the simultaneous and combined influence of several model variables on LCC results and rankings. Lastly, there is no exploration of the presence of particular values, as probability distributions are not assigned to variables. Hence, risk analysis facilitates addressing these issues [53].

4.2. Risk analysis

Probability values have been used to describe variables instead of point values, ensuring that no variables are left unexplored. A simultaneous effect of several model variables on the outcome is also observed, as the sampling techniques take into account the variability effect present in the input parameters. Lastly, it is still possible that a dominant outcome may not be observed. A descriptive and clearer image of the associated outcome is presented by assigning a probabilistic distribution to the variables [53]. Many sources have presented information regarding risk analysis introduction, sampling concepts, relevant probability and comparison-related measures [49,55]. It is possible for the analyst to assign probability distributions to specific input variables when using risk analysis. To check how close the data set distribution is to the hypothesised theoretical distribution, the goodness-of-fit test can be performed once sufficient data is present [56]. The construction variables can best be described by the lognormal distribution as compared to the generally presumed normal distribution. The lognormal distribution is followed by pavement thickness and pavement material costs. The results may be altered if normal distribution is used instead of lognormal distribution. For instance, a cost difference of $62,000/km was observed when normal distribution was applied rather than lognormal [56].

5. LCCA assessment and methodology

In the long term, the economic viability of pavement designs is calculated with LCCA. This method is utilised by several agencies because it is essential to realistically analyse pavement economics in order to state an objective input to the LCCA [57]. The comprehensive LCCA methodology is shown in Fig. 4.

For the economic evaluation of projects, many economic indices are available. The internal rate of return (IRR), equivalent uniform annual cost (EUAC), benefit/-cost ratio (B/C) and Net Present Value (NPV) are the most commonly used indices. Within the analysis environment, the level and context of analysis determine the kind of indi-

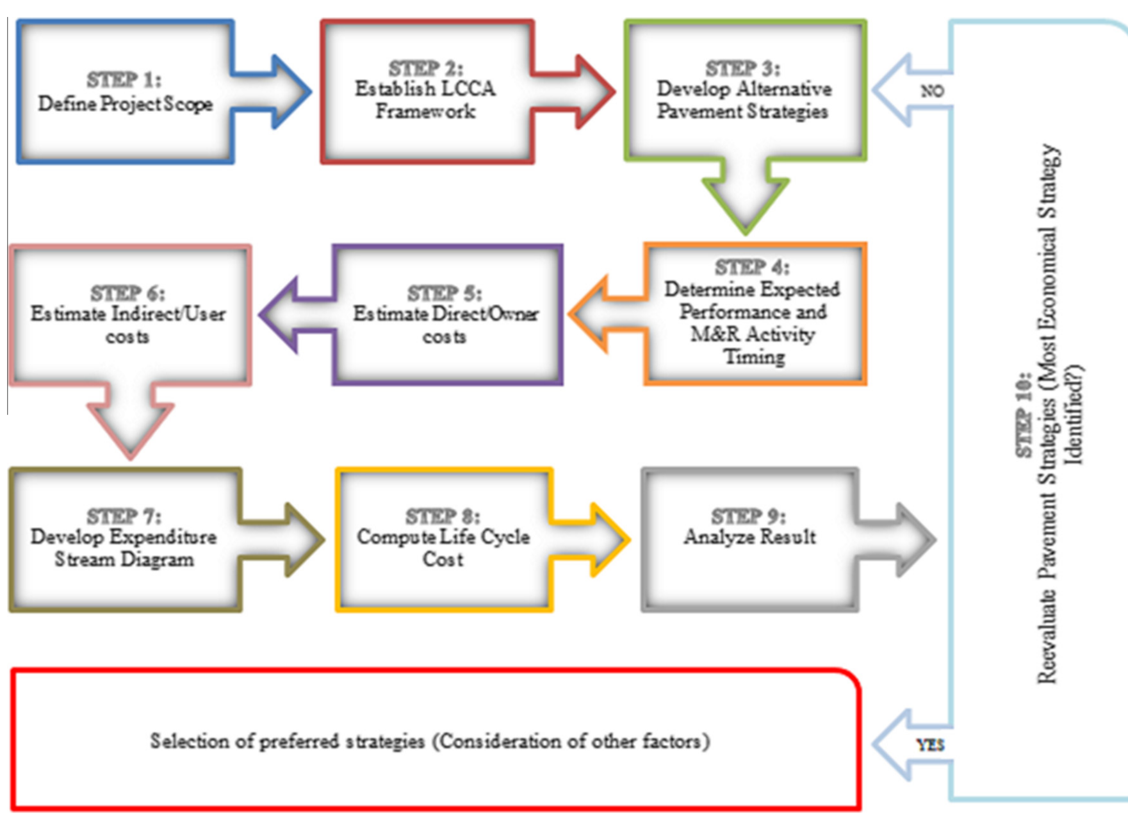

Fig. 4. Methodology for conducting airport/highway pavement LCCA.

cator to be used by a transportation agency. In developing nations, the IRR is the preferred economic indicator as the discount rate is very uncertain [58].

The selected analysis period needs to be compared in terms of performance period establishment, costs of each alternative and activity timing. The equivalent uniform annual costs (EUAC) or the Net Present Value (NPV) is used for this purpose [21]. NPV and EUAC are the most common indicators used today [52]. The projected value in terms of the present value of money is used for the initial costs, maintenance and rehabilitation costs and salvage value being used, as shown by the expenditure stream diagram in Fig. 5. The discount rate factor is then applied to calculate the time value of money.

Eq. (1) can be applied for a pavement case, as NPV is considered a popular economic computation [3,59,60].

$$NPV = Initial\ Cons.Cost + \sum_{K=1}^{N} Future\ Cost_K \left[\frac{1}{(1+i)^{n_k}}\right] - Salvage\ Value\left[\frac{1}{(1+i)^{n_e}}\right] \quad (1)$$

where:
N = number of future costs incurred over the analysis period,
i = discount rate in percent,
n_K = number of years from the initial construction to the K^{th} expenditure,
n_e = analysis period in years.

Present and future expenditures are converted to a uniform annual cost in order to present the equivalent uniform annual costs (EUAC). When budgeting is carried out annually, this is a preferred indicator. Eq. (2) states the formula for EUAC [60]:

$$EUAC = NPV\left[\frac{(1+i)^n}{(1+i)^n - 1}\right] \quad (2)$$

where:
i = discount rate,
n = years of expenditure.

As shown in Fig. 6, costs are divided into two basic categories: direct/owner costs and indirect/user costs, both of which are subdivided again.

5.1. Initial cost

The initial construction cost is presented in unit prices from bid records of projects constructed in previous years and only representative prices must be used. Unit prices may be taken out from the overall cost of previous projects if the representative costs are not available. The start-up

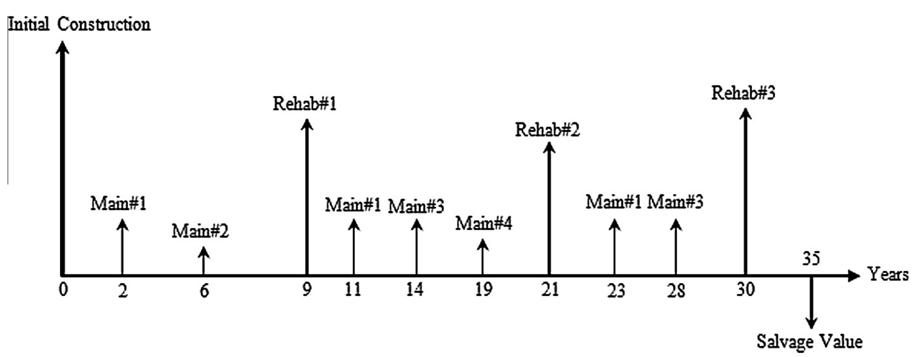

Fig. 5. Example of expenditure stream diagram.

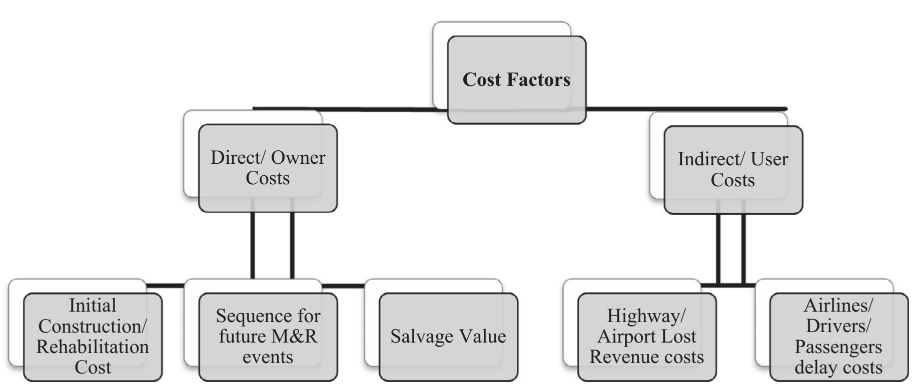

Fig. 6. LCCA cost factors in highway/airport.

cost can be taken into consideration as well as part of the LCCA. Hence, the annual budget limits an agency and there is a need to investigate the expenditures' short-term implications and the long-term influence of pavement type decision [57].

5.2. Determining the performance periods and activity timing

LCCA outcomes are very much affected by activity timing and performance period. Both user and agency costs are impacted. Historical experience and analysis of pavement management systems (PMS) help present pavement performance design-life [60]. The performance must be recorded at regular intervals from initial construction until reconstruction. By applying the concept of Perpetual Pavement, it is observed that reconstruction takes place longer (30–50 years) than normal time period. The analysis period proposed by the Asphalt Pavement Alliance (APA) is 40 years or more and it also requires for each pavement option to have at least 1 rehabilitation activity [61]. The Alliance follows the 35-year minimum policy brought forward by the FHWA. Judgement or actual construction and pavement management data set must be used in forecasting the magnitude of the first rehabilitation. According to the APA [61], information was collected from 50 state highway agencies and the result clearly showed that the first overlay was required after 20 years from initial construction and during the performance period. The average observed period for the same interval was 15.7 years. The average performance period observed from the first to the second overlay for 50 US states was another 12 years. Hence, the average time from the first construction to the second overlay was 27.7 years. The figures were extracted for asphalt overlay performance from a long-term pavement performance study by the FHWA. It indicated that the overlays lasted 15 years and some lasted 20 years until significant distress signs were noted [57,62]. In the mid-1990s Superpave was implemented and in the 1990s some of the agencies were using the Stone Mastic Asphalt (SMA), which is why a number of performance enhancements have not been completely realised [63].

5.3. Maintenance and rehabilitation costs

Maintenance and Rehabilitation (M&R) is another matter that requires attention. Preventive maintenance strategies appear to be much more cost effective compared to conventional maintenance strategies [64]. It is difficult to determine maintenance costs because there is usually an absence of efficient record keeping and differentiation between maintenance actions cannot be achieved. Hence, tools to help users define the effects of preventive maintenance are required [65]. Compared to the initial construction and rehabilitation costs, the maintenance cost of an LCCA has limited effect. Historical records of the actual pavement costs and activities must be utilised if these costs are present in the LCCA procedure [66]. An artificial increase in LCC would take place if there were unsuitable and frequent maintenance activities like rehabilitation [57]. Lamptey et al. used a threshold to recommend a set of rehabilitation and pavement maintenance strategies [2].

5.4. Salvage value

Beyond the analysis period, some pavement structure can still be serviced; however, if the condition is beyond maintenance, action needs to be taken. If the assets still have a useful life at the end of the life analysis period, the salvage value or residual value must be determined [58]. There are two components to the salvage value. One part is the residual value, which refers to the net value from pavement recycling [21]. The second part is the serviceable life, which is the pavement alternative remaining life when the analysis period expires. During LCCA, salvage value is the term normally used, but in the case of FHWA, the term "remaining service life" (RSL) is preferred. This helps differentiate the fact that the pavement will remain in service after the analysis period has expired. The salvage value can also be taken as the percentage of initial pavement construction cost [57].

5.5. Discount rate

When long-term public investments are being analysed, costs are compared at several points of time for which discount is necessary [67]. A dollar spent in the future is considered of lesser worth than a dollar spent today, which is why it is said that time, has money value. Hence, it is essential to convert the costs and benefits stated at different points of time to the costs and benefits that would happen at a common time [68]. Discount rate is the rough difference between the interest and inflation rates and it indicates the real value of money over time [3]. The mathematical relationships between interest rate, inflation rate and PW are presented in Eqs. (3) and (4).

$$PW = C \times \left[\frac{(1 + i_{inf})}{(1 + i_{int})}\right]^n \tag{3}$$

or:

$$PW = C \times \left[\frac{1}{(1 + i_{dis})}\right]^n \tag{4}$$

where:

PW = present-worth cost ($),
C = future cost in present-day terms ($),
i_{inf} = annual inflation rate (decimal),
i_{int} = annual interest rate (decimal),
n = time until cost C is incurred (years),
i_{dis} = annual discount rate (decimal).

Research has shown that if data are collected over a long period of time, the real time value of money would only be 2–4% [49,69,70]. It has also been stated that the OMB

Circular A-94 discount rates should be used when possible, especially with a probabilistic LCCA. To determine the LCCA and the mean value of probabilistic normal-distribution LCCA, the most current annual real discount rate based on a long-term (10, 20 or 30 years) treasury rate must be used [3].

6. Pavement LCCA tools and programmes

6.1. Existing LCCA packages

Approaches for pavement Life-Cycle Cost Analysis have been developed in the last few decades by various organisations, agencies and other intuitions. Some have even developed computer programmes for their LCCA approaches in order to further extend the analysis. This section includes a description of the nominated LCCA software for pavement design and management (Table 1).

Other pavement companies use different LCCA computer software and methodologies, including methods for Alabama [46], Pennsylvania [71], and non-automated methodologies for Ohio [72], Australia [73] and Egypt [74]. Highway work zone lane closures are evaluated using the QUEWZ model (Queue and User Cost Evaluation of Work Zones) [75,76].

6.2. Merits and limitation of LCCA methodologies and software packages

LCCA models are subject to certain limitations. User cost exclusion is one of the limitations in analysis. Highway users incur these costs, which include delay costs, vehicle operating costs (such as fuel, tires, engine oil, and vehicle maintenance) and any other accident costs. User cost is excluded in several LCCA methods and software as quantification is difficult and there are disputed values associated with user cost. Pavement LCCA models suffer from the limitation of not considering preventive maintenance treatment within strategy formulation. LCCA researchers and practitioners argue that preventive maintenance is a new preservation strategy for pavements and data on long-term benefits still need to be collected. Presently, only certain models are able to quantify the long-term effectiveness of preventive maintenance treatment. This is done in the form of service life extension or a performance jump. Hence, it is seemingly challenging to include preventive maintenance in LCCA. It is also observed that users find the accounting of LCCA input parameters complicated, which is why they do not consider it during the process. The LCCA models treat the input variables discretely and the single deterministic result is computed through the best-guess process of the fixed values for each input parameter. The various input parameters affect the model results, which is why evaluation is done with sensitivity analysis. The uncertain areas that may be crucially affecting the decision-making process are not shown as part of the sensitivity analysis. Hence, it is difficult to observe which option consists of the lowest true LCC [21]. The uncertainty problem can be managed by LCCA through the risk analysis procedure. This would allow decision makers to weigh the probability of any potential outcome. In contrast to most LCCA packages, the current FHWA package includes LCCA probabilistic approaches.

7. LCCA state-of-the-practice

7.1. United States

For the pavement type selection process, most states use the LCCA. The level of implementation, however, varies to a large extent. The state-of-the-practice in the US needs to be captured along with documenting the degree of LCCA usage. For this purpose, several efforts have been made by Peterson [37], AASHTO [16] and Zimmerman et al. [52]. LCCA methodologies and principles have been analysed by DOTs and research institutions in order to enhance knowledge and research, the same as Ozbay et al. [58], Beg et al. [77], Jung et al. [78], Cross and Parson [79] and Temple et al. [80]. The current state-of-the-practice has been analysed and several reports have been presented by state DOTs at the US government level (e.g. Goldbuam [81], VDOT [82], PENNDOT [83] and West et al. [84]). User costs, rehabilitation data, agency determination and unit costs as part of the analysis along with other aspects are mentioned in the reports. Enhancement of LCCA knowledge levels has mostly been contributed by the University Transportation Centre for Alabama, the University of Texas at Austin [85], Southwest Region University Transportation Centre, the Kentucky Transportation Centre and University of Kentucky, and the University of Alabama [86]. The FHWA and the American Concrete Pavement Association (ACPA) also have a vital role. The LCCA guidelines can be observed in the LCCA bulletin presented by the ACPA [87] and FHWA [88].

7.2. Europe

Economic model development for evaluating LCCA of pavements was officially researched by the Forum of European National Highway Laboratories in October 1997. It was known as the PAV-ECO (Economic Evaluation of Pavement Maintenance – Life-cycle Cost at the Project and Network Levels) and it ceased in October 1999. A consortium of partners including the Technical Research Centre of Finland (Finland), University of Cologne (Germany), Laboratoires Central des Ponts et Chaussées (France), Danish Road Institute (Denmark), Anders Nyvig A/S (Denmark), Via-group SA (Switzerland), Transport Research Laboratory (United Kingdom) and the Laboratoires des Voies de Circulation LAVOC-EPFL (Switzerland) undertook the PAV-ECO Project. The project was managed by the Danish Road Institute [89]. Comparisons of the life-cycle costs at the project level for different maintenance strategies can be carried

Table 1
Comprehensive LCCA packages.

Software Package	Year	Producer	Life-cycle Costs				Descriptions
			Initial Construction	Rehabilitation	User Cost	Salvage Value	
DARWin	N/A	AASHTO	•	•		•	Project level assessment
TEXAS DOT RPS/FPS	1968	Centre of Highway Research of Texas Transportation	•	•		•	Latest version consists of user cost
HDM	1977	World Bank	•	•	•		The HDM updated new versions
LCCP/LCCPR[1]	1987	University of Maryland			•		The programs comprise of user operating costs associated with pavement roughness
EXPEAR	1989	University of Illinois[2]	•	•			Project level assessment
PRLEAM	1991	University of Waterloo	•	•	•	•	Most focus on cost-effective rehabilitation improvement approach
LCCOST	1991	Asphalt Institute	•	•	•	•	Routine maintenance (optional) is also considered
MicroBENCOST	1993	Texas Transportation Institute	•	•			Under the NCHRP Project 7-12
ACPA LCCA[3]	1993	ACPA	•	•	•	•	Risk analysis is used to make sure a 90% confidence level
CAL-B/C	2000	California Department of Transportation	•	•	•		A first spreadsheet format (MS Excel)
REALCOST	2004	FHWA	•	•	•	•	First Probabilistic and comprehensive software
D-TIMS	2006	Indiana Department of Transportation	•	•	•		Provides the recommendations for the treatment for the specific distresses
IDAHO DOT LCCA	2008	Idaho Transportation Department	•	•			Units across the English and metric system can also be converted
APA LCCA	2011	APA	•	•	•	•	The software using the work zone duration and the hourly traffic distribution

[1] The rigid and flexible pavements were analysed through the programs.
[2] The EXPEAR computer program was developed by the University of Illinois under a FHWA project.
[3] The Winfrey's Economic Analysis for Highways (1969) and NCHRP Report 133 are used by the ACPA spread sheet to extract the user costs employing values.

out within the PAV-ECO Project framework. This includes user and agency cost calculations spread over the selected analysis period. The PAV-ECO project also provides network and project-level traffic simulation models as well as the factors affecting traffic forecasts. To establish an effective maintenance strategy, user, agency and social costs are all considered. Crash, vehicle operation and user lost time costs are part of user costs. CO_2 emissions and air pollution comprise social costs. The European VOC model range was analysed during the project in order to check the suitability of life-cycle cost model inclusion for European roads.

7.3. Canada

The University of Saskatchewan Civil Engineering Professor Dr. Gordon Sparks conducted an LCCA survey in Canada. There is also extensive use in Alberta for pavement type selection and different reconstruction alternative evaluation as well as material selection. Alberta addresses uncertainty through risk and sensitivity analysis. Rehabilitation, reconstruction and asset management applications are carried out by Saskatchewan LCCA methods. Vehicle operating cost is the only user cost component being used. Deterministic and probabilistic approaches are both employed by Saskatchewan. For 8 years, Manitoba used the LCC method for its asset management system. Pavement construction project planning and design was done via LCCA (for instance pavement type selection) along with asset management. An alternative bid process is presently applied in Manitoba. Passenger and driver value of time, delay and vehicle operation costs are the user costs present in the analysis. Right-of-way costs, environmental/emissions costs and socio-economic costs (for instance improved infrastructure benefits) are also included in the analysis as external costs. LCC methods have been used in Ontario for over 25 years. The LCCA has been applied to 90% of pavement designs. Analysis is carried out to include user costs in the LCCA. Risk and sensitivity analyses are both used in Ontario [90].

For many years, LCC methods have been extensively used in Quebec. LCC has been applied for pavement selection type since the year 2000. User delay costs and agency costs are factors used in the analysis. The analysis also addresses uncertainties using the FHWA RealCost program. A uniform system for all construction and rehabilitation projects along with VOC are to be included as part of future plans. By the year 2007, an asset management system was to be implemented by New Brunswick. Initial costs and on-going preservation costs are criteria used for New Brunswick. Uncertainty is addressed with risk and sensitivity analysis. For pavement type selection, LCC methods are used in Nova Scotia. It was shown there is high sensitivity to some variables when LCCA results were analysed (for instance discount rate).

8. Conclusions

Use of LCCA must be carried out appropriately and data utilised must be from existing records that are accurate in terms of initial costs, salvage value, rehabilitation timing and costs as well as discount rates. Data are available for some aspects, but other data need to be analysed and documented by the agencies themselves. It is essential to understand that LCCA is only a tool and the results must not be taken as decisions. Several other factors apart from LCCA must be taken into account when deciding which kind of pavement should be considered. The LCCA process comprises several assessments, predictions and assumptions. Differences in inputs can considerably impact analysts' confidence with the LCCA results. Input accuracy is essential for all aspects. The precise estimation of pavement performance, traffic for more than 30 years in the future and future costs by analysts determines the reliability of LCCA results. In managing forecast uncertainties, the probabilistic risk analysis approach is gaining popularity. It allows to quantitatively capturing input parameters, helping to provide LCCA results. A large part of literature also states that LCCA implementation is as complicated as selecting the correct discount rate and agency costs, quantifying non-agency costs as user costs, securing credible supporting data including traffic data, estimating the salvage value and useful life, modelling asset deterioration, and estimating maintenance costs, effectiveness and travel demand throughout the analysis period. During major rehabilitation and construction activities, the vast majority of LCCA only use delay costs as part of user costs.

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