International Journal of Advanced Research and Multidisciplinary Trends (IJARMT)
An International Open Access, Peer-Reviewed Refereed Journal
Impact Factor: 6.4 Website: https://ijarmt.com ISSN No.: 3048-9458

Review on Novel approach to design of variability in flexible Highway pavement life cycle cost analysis

Chetan Kalme, Professor Shashikant B. Dhobale
Department of Civil Engineering,
Jawaharlal Institute of Technology, Borawan Dist. Khargone

ABSTRACT
Life cycle cost analysis of existing road is becoming more significant to determine the proper time of maintenance and the proper action, which should be taken for maintenance. An efficient maintenance policy is essential for a cost-effective, comfortable and safe transportation system. But, the decision to maintain the road facilities, consider a number of possible ways from routine maintenance action to reconstruction of the road network. Moreover, an economic analysis of a road network is dependent upon a number of factors, which are responsible for deciding road serviceability level. Optimization model is an analytical model, which helps to make a cost benefit analysis and compare that with various possible alternatives to give out the best possible activity within the allocated budget, before being carried out in field work.
Keywords: Life cycle cost analysis, Optimization model, Maintenance, Rehabilitation, IRI.

I.INTRODUCTION

Road authorities of all around the world are finding and innovating ways to cope with the high cost of road network maintenance, the increasing demands of road users and the changing traffic type and volume. The road network plays a vital role in contributing to the economic, social, cultural and environmental development of the country. A well-maintained road is needed to make the network sustainable for future generations. Improving road maintenance management has become a key factor in developing nations like India.

User safety, traffic volumes, climatic conditions, soil characteristics, long-term economic performance, and all other regional conditions of the project area are the factors that affect the pavement type. There exist three types of pavement structures which are namely flexible, rigid, and composite.

Flexible pavements are those comprised of bituminous layer(s) as a surface course at the top exposed to traffic loads directly, and underneath base and subbase courses form the layering system of this type of road. The base course of flexible pavement is typically designed with “bituminous materials” or “granular materials”, whereas subbase layers in the pavement are traditionally selected as “crushed stone type” or “sand & gravel type”. On the other hand, rigid pavements are those whose layering components are concrete slab as a surface course, an underneath base course, and/or subbase course, respectively.

An important point to be focussed on is that the traffic load transfer system over roadbed soil for these two pavement types is different. In flexible pavement, traffic load from the exposed surface layer toward roadbed soil is distributed over a smaller area due to the physical characteristics of this pavement type. On the contrary, the load is spread on a wider area of the subgrade due to the stiff structure of the surface layer in rigid pavements. The load-transferring mechanism of a Portland cement concrete slab is not different from that of a concrete beam resting on an elastic foundation due to the high flexural strength of this binding material.

II. RESEARCH MOTIVATION

It is clear from the above study that there is no specific schematic for life cycle cost analysis process. Any general form for any roads can be taken into action. It is obvious from all the literature reviewed in this study that in spite of adapting different types of optimization models, there were some common factors of same centrality. Another thing is that life cycle cost analysis is more economically effective process for rigid pavements than flexible pavements.

Considering the mostly inadequate funding under normal circumstances, road specialists are consistently challenged with funding projects thanks to resource insufficiency. Moreover, with the growing demand for brand new road infrastructure, the demand for efficient management of old and new roads is on the increase also, together with safety demands, accessibility and also the implementation of advanced traffic management systems for decreasing socio-economic costs by modifying maintenance-related environmental effects, traffic issues, and losses. Maintenance backlogs nonetheless increase too. “Road authorities thus emphasize more on better efficiency and lower expenses thanks to limited funds. Since maintenance overheads normally comprise half the annual road infrastructure funds, it's vital to rearrange efficiency in road maintenance” [5&6]. Thus, with relation to road objects, life-cycle costs (LCCs) are considered as having a higher priority than simply investments. Hence, road authorities are expected to appreciate the importance of LCCA and maintain a calculation system. LCCs are deemed to be a restraint in road design selection or the assessment of tenders. When calculating LCCs, both road authority costs and costs of socio-economic nature should be taken into consideration. Road agency (authority) costs comprise expenses for planning, construction, design, maintenance, and rehabilitation. Of these costs are usually the government's

International Journal of Advanced Research and Multidisciplinary Trends (IJARMT)
An International Open Access, Peer-Reviewed Refereed Journal
Impact Factor: 6.4 Website: https://ijarmt.com ISSN No.: 3048-9458

accountability to hide using tax earnings. Socio-economic costs comprise agency costs, user costs (e.g. delay costs, accident costs and automobile operation costs), and environmental costs. The **Present Value Method** in Flexible Highway Pavement Life Cycle Cost Analysis (LCCA) is a widely used approach to assess the total cost of a pavement over its entire service life, accounting for both initial and future costs. This method involves converting all future expenditures (such as maintenance, rehabilitation, and replacement) into their present value by applying a discount rate, which reflects the time value of money.

The key steps in the Present Value Method are:

1. **Identify All Costs**: These include initial construction costs, routine maintenance costs, rehabilitation costs, and eventual replacement costs over the pavement's life cycle.
2. **Determine the Time Horizon**: Establish the expected service life of the pavement, typically spanning several decades.
3. **Apply the Discount Rate**: Future costs are converted to present value using a discount rate, which represents the opportunity cost of capital or the rate at which future costs are discounted. This ensures that the costs occurring at different times are comparable in today's terms.
4. **Calculate the Total Present Value**: The total life cycle cost is obtained by summing the present values of all future costs and the initial construction cost.
5. **Compare Alternatives**: The Present Value Method allows for the comparison of different pavement alternatives by standardizing costs in present-day terms, helping to identify the most cost-effective choice over the entire life span.

This method helps decision-makers evaluate different pavement designs, materials, and maintenance strategies by providing a clear financial picture of long-term costs, enabling more informed and cost-effective decisions in highway infrastructure management.

III. PROBLEM STATEMENT

In this study the motive was to develop a model for the following cases

- Low traffic growth
- Moderate weather in term of rainfall
- Stable area development

RISK ANALYSIS

Probability values are wont to describe variables rather than point values, ensuring that no variables are left unexplored. A simultaneous effect of several model vari- ables on the result is additionally observed, because the sampling techniques take under consideration the variability effect present within the input parameters. Lastly, it's still possible that a dominant outcome might not be observed. A descriptive and clearer image of the associated outcome is presented by assigning a probabilistic distribution to the variables. Many sources have presented information regarding risk analysis introduction, sampling concepts, relevant probability and comparison-related measures. It is feasible for the analyst to assign probability distributions to specific input variables when using risk analysis. to test how close the info set distribution is to the hypothesized theoretical distribution, the goodness-of-fit test are often performed once sufficient data is present. the development variables can best be described by the log- statistical distribution as compared to the widely presumed distribution. The lognormal distribution is followed by pavement thickness and pavement material costs.

IV. LITERATURE REVIEW

[1] Abdelhalim Azam et al. Integrating environmental goals in the construction of infrastructure has attracted great attention over the past two decades. The use of construction and demolished waste materials (C&D) as a base layer for pavement structures gained popularity as a sustainable alternative to virgin aggregates (VA). An experimental testing program was designed to investigate several recycled materials as a potential replacement to VA in flexible pavements base layer. The testing program included routine tests, matric suction, static, and repeated load triaxial tests to measure the general engineering properties and evaluate the material performance under static and cyclic loading. The results of the laboratory testing program were employed to predict the pavement performance utilizing different combinations of C&D waste as a base layer for flexible pavement structures using the AASHTOW are Pavement ME Design at different climate conditions. The sustainability of using C&D material as a partial or full replacement of VA base material in pavement construction was evaluated by using the life cycle assessment (LCA) approach. The results showed that all the C&D materials yielded a much thinner base layer compared to the natural VA achieving the same pavement performance. Moreover, the reduction in the thickness is more significant in cold and wet climatic conditions rather than the hot and dry climatic conditions. LCA results revealed that the VA base layer had the highest environmental impact

on all tested categories. VA materials, used as a base layer, show 65% higher global warming potential compared to C&D materials as a base layer in all climatic conditions.

[2] Shriram Marathe et al. This study investigates the development and performance of agro-industrial waste-based air-cured alkali-activated concrete composites (AC) for sustainable high-strength rigid pavement applications. The calculated amounts of liquid sodium silicate and sodium hydroxide flakes were used with an adequate quantity of water to prepare the alkali-activator solution. Agro-Industrial by-products, including ground granulated blast furnace slag (GGBS), construction and demolition (C&D) waste, and sugarcane bagasse ash (SBA), were utilized to develop AC mixes and the mechanical properties, micro-structural behaviour, and life cycle impacts were studied. Optimized AC mixes containing 50% recycled aggregates (RCA) (with 50% natural coarse aggregates) and 15% SBA (with 85% GGBS) demonstrated superior compressive, splitting-tensile, and flexural strength, while significantly reducing embodied energy and carbon emissions. Microstructural analysis through XRD, SEM, EDAX, and TGA confirmed the formation of stable alumino-silicate hydrate phases, contributing to enhanced mechanical strength performances. The life cycle analysis results indicated considerable environmental benefits compared to traditional Portland Cement based pavement concrete counterparts. This research presents a sustainable solution for pavement infrastructure, aligning with circular economy principles by promoting the reduction of resource consumption and greenhouse gas emissions.

[3] Fei Lu et al. This paper delivers an in-depth risk analysis of asphalt pavement structural strength in the cold Qinghai-Tibet Plateau region. It encompasses a wide range of risk factors, including environmental conditions, traffic dynamics, pavement structures and materials, and various human-related factors. These risk factors are quantified using probability distributions, with emphasis on the changes in their mean and variance to simulate the effects of risk. A novel risk metric, termed “CV_{all}”, is introduced to encapsulate the cumulative risk associated with each random variable. The paper describes the risk in the load and resistance equations, which govern the asphalt pavement strength, using the probability density function distribution. This approach takes into account the variation coefficient of each parameter. The study highlights that the risk related to the pavement structure number following freeze-thaw cycles significantly influences the reliability of pavement structural strength. These insights are particularly crucial for highway design, construction, and maintenance in cold regions, where the durability and longevity of pavement are paramount.

[4] Peyman Babashamsi et al. 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.

[5] Paola Dalla Valle MEng et al. This research presents a method that accounts for variability in the principal design input variables for fully flexible highway pavements and assesses their effect on pavement performance. Variability is described by statistical terms such as mean and standard deviation and by its probability density distribution. Statistical characterisation of the variation of asphalt layer thickness, asphalt stiffness and subgrade stiffness is addressed. A model is then proposed that represents an improvement on the method of equivalent thickness for the rapid and repeated calculation of performance life. A Monte Carlo analysis is used to estimate pavement performance life to account for uncertainty of input variables and to calculate the probability of failure of a pavement structure. The output is a statistical assessment of the estimated pavement performance. Rather than the single deterministic result that would be derived by considering average values of input variables, a range of values and probabilities is found for any particular outcome. The probabilistic approach offers a way of incorporating risk assessment considerations that are vital for whole-life-cycle economic analysis and decisions. The paper investigates how variability affects the life-cycle cost of a pavement over a 60-year analysis period.

[6] Mehrdad Asadi Azadgoleh et al. Oil-Based Drill Cuttings (OBDC) are one of the hazardous wastes of the oil and gas industry. In this study, Reclaimed Asphalt Pavement (RAP), OBDC and Fly Ash (FA) geopolymer were used in Cold Central Plant Recycling (CCPR) mixtures. The dynamic modulus test was used to appraise the viscoelastic properties of CCPR mixtures. The Toxicity Characteristic Leaching Procedure (TCLP) test was also utilized to investigate the long-term contaminants leaching. In addition, a cradle-to-grave Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA) were conducted to evaluate the potential environmental burdens and economic costs of pavement structures containing CCPR mixtures. Moreover, Multi-Criteria Decision-Making (MCDM) analysis using four different methods was performed to determine the optimal sample. The results revealed that the recycling of OBDC and RAP in stabilized CCPR mixtures with FA geopolymer can improve the viscoelastic properties and prevent the leaching of contaminants from these waste materials. Furthermore, recycling of the mentioned waste materials in CCPR mixtures has caused a significant reduction in global warming, acidification, eutrophication, smog, respiratory effects, Human toxicity, ecotoxicity, and cumulative energy demand up to 41%, 36.6%, 73%, 43%, 47%, 34%, 73%, and 13%, respectively. Additionally, using CCPR mixtures containing the OBCD, RAP, and FA geopolymer in the pavement structure has led to economic benefits of up to 31% compared to the conventional pavement system.

[7] Qindong Yang et al. Pavements are susceptible to accelerated deterioration due to changing climate conditions, leading to increased maintenance and excess fuel consumption through pavement-vehicle interaction. China's diverse climates raise concerns about the environmental and economic sustainability of flexible pavements amid climate change and the effectiveness of preventative maintenance strategies. This study examines climate change's potential impacts on long-term pavement performance, greenhouse gas (GHG) emissions, and costs, employing the Mechanistic-Empirical Pavement Design Guide method. The calibrated World Bank's Highway Development and Management Model 4 assesses the impacts of surface characteristics on vehicle fuel consumption. Life cycle assessment and life cycle cost analysis quantify GHG emissions and costs. Results reveal significant pavement deterioration in Southeast and Central China. Preventative maintenance strategies reduce fuel consumption, with GHG emissions and cost savings from smoother driving conditions outweighing those

from maintenance. These insights stress the importance of proactive maintenance strategies for mitigating climate-induced deterioration and enhancing sustainability.

[8] Mohammad Reza Heidari et al. Sustainable development requires decision-making systems based on sustainability criteria and overpassing just economic and financial criteria. Integration of life-cycle cost analysis (LCCA) and life-cycle assessment (LCA) to select pavement alternative is a solution to address economic and environmental issues simultaneously. While most of current methods related to sustainable design of pavements consider environmental parameters as economic factors i.e. cost, this paper takes the two criteria of carbon emissions and energy consumption into account. Moreover the presented method considers the embedded managerial flexibilities which are available due to existing uncertainties in pavement project valuation procedure. Agency costs, user costs, carbon emissions, and energy consumption are considered as the main criteria, and Monte Carlo simulation (MCS) technique is used with a recursive procedure for analyzing flexibility in each time step of pavement life-cycle. For making the best decision in each time step and the best overall alternative, technique for order of preference by similarity to ideal solution (TOPSIS) is used, and the best alternatives are reported. The model is applied in a highway project in Iran to demonstrate its capabilities to analyze the sustainability of different asphalt and concrete alternatives for pavement projects. Various alternatives of the two pavement types are compared and it is clarified that the best asphalt alternative has lower life-cycle costs but more carbon emissions and much more energy consumption. Selection of concrete pavement instead of asphalt pavement in last decade in Iran, will approximately 35% increase related costs but it will result in about 2,000,000 tons of carbon emissions reduction and 700,000 GJ reduction in energy consumption annually.

[9] Surya Teja Swarna et al. Presently, there is strong consensus that significant temperature and weather changes are fast approaching as a result of climate change. Pavements will be significantly affected by increased temperatures, precipitation, and flooding, and will require present design methodology to be modified accordingly. Several climate change adaptation strategies are easily available to agencies including upgraded asphalt binder grades, increased Hot Mix Asphalt (HMA) thickness, modified mix gradations, and stabilized base. The objective of this study is to investigate Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA) for climate change adaptation strategies across various locations in Canada, from a Global Warming Potential (GWP) perspective. All analysis was completed leveraging

the Athena Pavement LCA software and the LTPP database. The investigated scenarios were (i) a baseline asphalt pavement with no climate change, (ii) a baseline asphalt pavement with climate change, and (iii) an asphalt pavement adapted to withstand climate change, appropriate to the level of changes experienced by the specific location. The study revealed that although there are initial increases in both cost and emission to administer these adaptation strategies, they are offset over the life of the pavements. Increasing the HMA thickness and using stabilized bases were the most expensive and the highest emitting among the investigated strategies, but they are only necessary for extreme coastal climate change regions including British Columbia and Newfoundland. British Columbia is expected to observe a near 30% increase in agency costs to effectively adapt their pavements to climate change. However, these initiatives were found to decrease the overall global warming potential by nearly 10% in comparison to not adapting. The other examined locations, although not returning as drastic of changes, followed similar trends. The conclusions find that climate change adaptation strategies are highly beneficial from the standpoint of both an LCA and LCCA for all of the investigated locations.

[10] Omran Maadani et al. This paper presents findings about the influence of projected data from the Canadian regional climate model on the performance of flexible pavement, building upon the results from previous work where the data were generated and published, in which a general trend of decreasing the design life was observed. Projected temperature is the most important extreme climate impact on flexible roads. Adopting a conservative approach demonstrated that two extreme events of maximum mean annual air temperature and maximum summer average air temperature resulted in significant reduction of 25 years road design life. The observed trend indicates a severity range of 7%–15% in terms of design service life loss when considering events every year compared to every 5 years. The findings revealed a reduction in pavement design life by 34%, 50%, 73%, and 90% for historical, short, intermediate, and long-term life cycles in the city of Windsor, respectively.

V. CONCLUSIONS

Flexible Highway Pavement Life Cycle Cost Analysis (LCCA) offers several key benefits for transportation agencies and decision-makers. By providing a comprehensive assessment of all costs associated with a pavement’s lifespan, LCCA enables more informed decision-making, allowing for the selection of the most cost-effective pavement design or maintenance strategy. This method helps optimize resource allocation by considering not just the initial construction costs, but also long-term maintenance, rehabilitation, and replacement costs. Additionally, LCCA supports sustainability by identifying options that offer better performance over time, potentially reducing the frequency of costly repairs and extending the pavement's service life. Furthermore, by factoring in variables such as traffic growth, environmental conditions, and material cost fluctuations, LCCA helps account for uncertainties, offering a more realistic view of future financial needs. Overall, LCCA promotes better budgeting, cost-efficiency, and long-term infrastructure planning, ultimately contributing to improved road quality and reduced taxpayer burden.

Reference

1. Azam, A., Gabr, A., Ezzat, H., Arab, M., Alshammari, T. O., Alotaib, E., & Zeiada, W. (2024). Life cycle assessment and pavement performance of recycled aggregates in road construction. Case Studies in Construction Materials, 20, e03062.

2. Marathe, S., Sheshadri, A., & Sadowski, Ł. (2024). Agro-industrial waste utilization in air-cured alkali-activated pavement composites: Properties, micro-structural insights and life cycle impacts. Cleaner Materials, 100281.

3. Lu, F., & Si, W. (2024). Reliability risk modelling of asphalt pavement structure performance under the impact of freeze-thaw cycles. Case Studies in Construction Materials, 20, e03054.

4. Babashamsi, P., Yusoff, N. I. M., Ceylan, H., Nor, N. G. M., & Jenatabadi, H. S. (2016). Evaluation of pavement life cycle cost analysis: Review and analysis. International Journal of Pavement Research and Technology, 9(4), 241-254.

5. Dalla Valle, P., & Thom, N. (2017). Inclusion of design variability in flexible highway pavement life-cycle cost analysis. Proceedings of the Institution of Civil Engineers-Construction Materials, 170(4), 211-222.

6. Azadgoleh, M. A., Mohammadi, M. M., AzariJafari, H., Santos, J., Ahmadi, A., Alavi, M. Z., & Ayar, P. (2024). A comparative life cycle assessment (LCA), life cycle cost analysis (LCCA), mechanical and long-term leaching evaluation of road pavement structures containing multiple secondary materials. Journal of Cleaner Production, 458, 142484.

7. Yang, Q., Cao, Z., Shen, L., Gu, F., Santos, J., Qiao, Y., ... & Chu, C. (2024). Impacts of climate change on environmental and economic sustainability of flexible pavements across China. Resources, Conservation and Recycling, 206, 107589.

8. Heidari, M. R., Heravi, G., & Esmaeeli, A. N. (2020). Integrating life-cycle assessment and life-cycle cost analysis to select sustainable pavement: A probabilistic model using managerial flexibilities. Journal of Cleaner Production, 254, 120046.

9. Swarna, S. T., Hossain, K., & Bernier, A. (2022). Climate change adaptation strategies for Canadian asphalt pavements; Part 2: Life cycle assessment and life cycle cost analysis. Journal of Cleaner Production, 370, 133355.

10. Maadani, O., Shafiee, M., Shirkhani, H., & Hiedra Cobo, J. (2024). The impact of extreme weather events of projected Canadian regional climate model data on flexible pavement. Canadian Journal of Civil Engineering.