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Flexible Pavement Life Cycle Cost Analysis by Using Monte-Carlo Method and the Suggestions for Developing Countries

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Abstract: Flexible Road pavement plays an essential role in developing an effective, economic, and safe operation road network of any country. In Vietnam, a developing country, the selection of a suitable flexible pavement structure is always a challenge due to fiscal limitations. The traditional determinant method (TDM) by which pavement structures are selected mainly on the basis of initial construction costs and traffic load has been used for many years in the nation. This paper presents the use of Monte Carlo simulation to analyze the entire flexible pavement life cycle cost. Data including initial and maintenance costs and road user costs were collected from several different types of existing flexible pavement in Nghe An province, Vietnam. Random variations of several main inputs were explored in order to develop density distribution functions. These functions then were used as the bases for Monte Carlo simulation. One million simulation runs were implemented and the Net Present Values (NPVs) among pavement types were compared under the light of risk analysis. Research results showed that TDM method provided bias and uncertain results compared to that of Monte Carlo one. In terms of long- term pavement performance, a low-cost pavement structure should not always be considered as a wise selection. Some other suggestions for a developing country as Vietnam were also included.

Keywords: Pavement life cycle cost, Monte Carlo simulation, flexible pavement

1. Introduction

Flexible pavement management and maintenance systems represent one of the critical constituent elements inside the life cycle of transportation infrastructure and associate with socio-economic, environmental, and political issues. The selection of a flexible pavement structure to suit each region's conditions has always been a remained issue due to the fiscal limitations and, at the same time identifying complex projects that can be risky across different phases and perspectives. In this case, the project must be based on a certain methodology that allows managers to identify and quantify risks and costs, taking into account a flexible road pavement project is usually a large one, requiring many resources and having a big-time span. Because of various flexible pavement structure components, hence, the decision-making process is the decisive factor to estimate realistically project life cycle cost. Therefore, the life cycle cost analysis (LCCA) should be applied in the initial stage. Accordingly, different cost categories (e.g., construction costs and rehabilitation costs) will be compared on an equal basis in consideration of total economic value. The long service life of

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flexible pavement forces decision-makers to adopt long-term evaluation methods in road management. Over the past decade, with the development of the sustainability concept, LCCA has been widely used to evaluate highway projects' value in a variety of applications. Mohammad et al., (2020) used LCCA in defining maintenance and rehabilitation strategy. One of the most remarkable projects is the application of LCCA in pavement design carried out by the Federal Highway Administration in 10 states of the United States as an analysis tool for quantification of the cost difference of alternative investment options for a given project, namely investment decisions in the field of transportation and roads. The model includes all possible inputs such as the actual cost of initial construction and maintenance into the analysis and weighs each occurrence's probability to determine future costs for risk pavement management (Walls and Smith, 1998). A representative LCCA includes the following procedure: a preparatory strategy and decision in establishing parameters and alternatives that are to be taken into consideration by the LCCA, estimate costs for each alternative, compare alternatives by typically using standard metrics like Net Present Value (NPV) and analyze the results usually using sensitivity analysis or re-evaluate alternatives (Walls and Smith, 1998).

LCCA has been developed during the last decade and even computer programs have been created to help managers in using LCCA as an option for decision support. Babashamsi et al., (2016) analyzed the alternatives of LCCA and the existing decision-support tools or software packages based on it. They conducted a comprehensive analysis to consider the current practice status of the LCCA in the USA, Europe, and Canada and concluded that the differences in inputs can substantially influence the results and the reliability of analysis and, in the end, the chosen alternative.

We place value as the primary driving force behind turning a project into a successful one by taking the quote from Deloitte (Patchin and Mark, 2012) is “Value is a function of risk and return. Every decision either increases, preserves, or erodes value”. This becomes an essential issue in flexible road pavement projects that are usually characterized by a large number of resources involved, a considerable time investment, and a variety of factors that may lead to risks and the project's failure if those risks are disregarded or not assessed. Risk analysis is the process of evaluating the probabilities and consequences of risk events if they are identified (MITRE, 2017). Risk analysis represents the process of risk identification, assessment, and measurement to reduce them to acceptable levels (Stoneburner et al., 2002). The risk analysis approach is widely used to identify and/or avoid potential costs and to consider that proactive management within a project can accurately identify the risks and allocate funds and resources according to the project's limited budget requirements.

In this paper, a methodology of flexible pavement LCCA is introduced that reflects risk analysis correlated with the computation's input factors. Subsequently, a case study is then carried out to examine the influence of risk analysis on estimating the life-cycle cost of the different alternative selection of flexible pavement design. By exposing these uncertainties are often concealed in the traditional determinant method of LCCA, the analysts can provide decision-makers with suggestions on the risks linked with different action plans and the possibility of actual results. By adopting this method, planners can choose the most cost-effective solutions that deliver tremendous long-term benefits to the flexible pavement life cycle. The last section provides a discussion on the usefulness of the proposed method and its refinement directions. Finally, some suggestions for developing countries as Vietnam were also included.

2.1 Traditional Determinant Method

The assessment objectives of flexible pavement LCCA include the owner’s construction and rehabilitation costs and the economic, time, and safety costs of the road user in the life cycle (FHWA, 1998). The Federal Highway Administration made a coordinated effort to use life-cycle cost analysis (LCCA) in highway pavement design (FHwA, 1998). Yu et al., (2013) pointed out that LCCA is a tool for assessment of total costs, which takes into account construction, maintenance, and user costs. Abaza (2002) developed an optimal flexible pavement LCCA model. The pros of this method are simple to develop and easy to understand. Hicks et al. (1999) presented various pavement life-cycle design strategies and made reasonable comparisons between traditional mixtures and asphalt rubber pavement materials. Labi and Sinha (2005) & Peshkin et al. (2005) investigated the cost-effectiveness of various life-cycle preventive maintenance levels. Chan et al. (2008) assessed the LCCA practices of the Department of Transportation in Michigan. For other sectors, Hajare and Elwakil (2020) established the tradeoff between initial investment and long-term benefits for various energy-saving measures by integrating the LCCA approach and energy simulation. Gopanagoni and Velpula (2020) developed an analytical approach to LCCA of a green construction's complete existence for 80 years. Ozbey et al. (2004) founded that more than 80% of states in the U.S use LCCA, at least for some projects.

The traditional determinant method (TDM) by which flexible pavement structures are selected mainly based on initial construction costs and traffic load has been used for many years. Cost elements are predictable and risk factors from construction, maintenance, and rehabilitation process in flexible pavement life cycle. TDM models commonly utilize discrete input factors known as a conventional best hypothesis of each parameter. However, inherent uncertainty correlated with each input factor is not considered. Consequently, the analyst defines each input factor's values based on a series of "best hypothesis" and then estimates a single deterministic result.

While it is possible to perform limited sensitivity analysis in which different combinations of input are selected to assess their influence on the analysis results qualitatively, but even in sensitivity analysis, this deterministic approach to

LCCA can also hide areas of uncertainty that can be an essential part of the decision-making process. Therefore, this approach's problem is that information can enhance decision is often ruled out due to stakeholders take advantage of the uncertainty inside the LCCA inputs, and strenuously argue the validity of the outcomes. Due to a lack of appropriate information, a significant probability distribution may not be established for possible outcomes of a specific input factor in many cases. As a supplement to TDM, the Monte Carlo Simulation (MCS) allows to collate the uncertainties in the input factors and returns certain results.

2.2 Probabilistic Method

Strategic long-term investment decisions under a short-term budget constraint compel transport agencies to consider risks and uncertainties (implicit or explicit) as criteria in the evaluation process of alternative pavement design.

In recent years, researchers have utilized the LCCA approach to establish mathematical expectations of flexible pavement projects based on risk consideration to maximize the flexible pavement life-cycle benefits. In practice, the difference between LCCA results and road management costs explains the importance of probabilistic LCCA to better estimate actual costs. For instance, the guideline for probabilistic LCCA introduced by Tighe (2001) shows that LCCA of pavement can be used as a deterministic approach by merging the mean, variance, and probability distribution of typical construction variables. Wilde et al. (1999) used risk assumptions and the Monte Carlo Simulation technique to evaluate rehabilitation activities. Reigle et al. (2005) developed a probabilistic and derives model that considered probability distributions, such as road surface cost and thickness. Eravi and Esmaeeli (2014) developed a fuzzy method to analyze the cost and pavement performance during the project life cycle and select the best alternative road design strategy by using the multi-criteria decision-making (MCDM) method. Setunge et al. (2005) developed a life cycle benefit/cost analysis method for highway projects based on uncertainty using Monte Carlo simulation to repair highway bridges.

In terms of risk analysis, the disadvantage of TDM is its poor ability to analyze the uncertain input variables. Risk analysis is a technique to identify the areas of uncertainty usually hidden in LCCA's traditional determinant approach. It allows decision-makers to weigh the possibility of any particular outcome. It is also known as the statistical test method. The risk analysis approach utilizes the probability description of uncertain variables by applying MCS to describe the risk outcomes. By incorporating all possible input variables into the analysis process and weighing the probability of each input variable's occurrence, the risk analysis discusses the validity of the LCCA results in order to make the best decisions for flexible pavement design alternatives.

Monte Carlo simulation (MCS) is a tool for analyzing phenomena containing risk factors to obtain approximate solutions. A series of random risk variables are drawn from each input distribution to obtain the probability distribution results by doing the MCS. That process was through iterations to obtain a sufficiently large set of empirical outcomes. Finally, the analysts capture the results of each iteration for later statistical analysis.

3. Proposed Methodology

The life cycle of flexible pavement is defined as the time interval between two successive construction circumstances. Maintenance and rehabilitation solutions are executed within the flexible pavement life cycle. The LCCA process requires several inputs such as agency cost, user cost, determine activity profile, and annual user cost profile. However, project construction and maintenance costs may not be maintained as predicted. During the pavement life cycle, traffic demand may differ from the forecast, and the discount rate may vary over time. Such variations will lead to changes in the cost of the entire project life cycle.

Fig. 1 demonstrates the fundamental risk analysis method in LCCA. It depicts the NPV formula typically used as the economic indicator in an LCCA. The risk analysis approach uses random sampling from probabilistic descriptions of uncertain input variables to generate a probabilistic description of results. By performing the Monte Carlo simulation, thousands, even tens of thousands of samples are randomly drawn from each input distribution to select values from the probability distribution that describes the range of possible outcomes along with a probability weighting of occurrence.

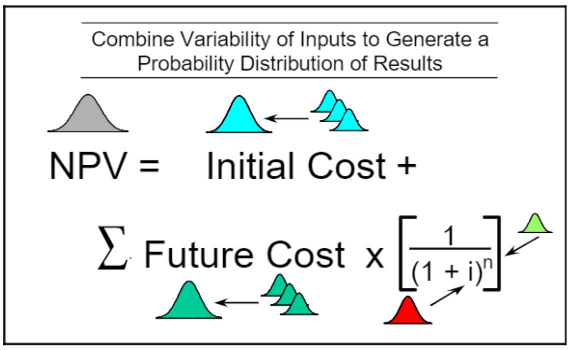


Fig. 1 - Computation of NPV using probability and simulation (Walls and Smith, 1998)

Interpretation of risk analysis results goes beyond a simple comparison of which alternative on average costs less by including an analysis of the likelihood that any particular outcome will occur. By using statistical calculations to determine characteristic statistical features (mean, variance, etc.) of the results, we can observe the level of the project's expectation with each random given value from the accumulative probability distribution function. Therefore, the risk of a project is commonly described by the accumulative probability distribution function.

With risk analysis results, the decision-maker knows not only the full range of possible values but also the relative probability of any particular outcome actually occurring. This is precisely the information that the decision-maker needs in order to make an educated decision.

In developing countries as Vietnam, the cheapest flexible pavement structure is used to be selected because of the fiscal constraints and the lack of methodology to take risk analysis into selection.

4. A Study in Nghe An Province

A study was implemented in Nghe An province to consider the impacts of using probability-based flexible pavement LCCA approaches on computing the costs of individual pavement alternatives. Four typical road pavement structures, namely A, B, C, and D, that are mostly used not only in Nghe An but also in many other provinces in Vietnam were selected as shown in Table 1.

The relevant data for each type of alternatives were randomly collected from 20 existing highways in Nghe An. These data include the initial construction costs, maintenance and rehabilitation costs, traffic volume, the historical frequencies of maintenance and rehabilitation works. The road user costs were assumed to be the product of traffic volume and the average value of time cost due to the delay caused by road maintenance activities. The economic discount rate was selected in the range of 10%-12%, the values that are commonly used in Nghe An.

Table 1 - Typical pavement structures used in Nghe An province

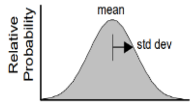
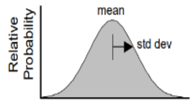
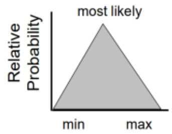
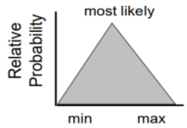
Typical pavement type	Layers (*t*)	Thickness (*cm*)
A	Asphaltic layer-Fine Aggregate	5
	Asphaltic layer-Medium Aggregate	7
	Crushed stone-base layer	25
	Crushed stone-subbase layer	30
B	Asphaltic layer-Medium Aggregate	7
	Crushed stone-base	18
	Crushed stone-subbase	22
C	Asphaltic layer-Medium Aggregate	5
	Crushed stone-base layer	15
	Crushed stone-subbase layer	25
D	Bitumen Slurry layer	2 (average)
	Macadam base	12
	Macadam subbase	15

The first step in conducting a Monte Carlo simulation process is to determine the structure and configure layout of the issues. This usually includes the process of reducing the issues to the most basic components which can be described in the form of an analytical model. The flexible pavement LCCA model is commonly delineated by the formula of NPV:

$$P = V_0 + \sum_{k=1}^{N} C_k \left[\frac{1}{(1+i)^{n_k}} \right] \tag{1}$$

Whereas: P= Net Present Value (NPV) of the studied project; V_0= Initial cost; C= future cost in the pavement life-cycle (see Table 1); i= Discount rate; N= Year of expenditure.

Table 2 - Summary of the probability distributions

Variables	Distribution Type	Distribution Form and Parameters	Illustration
Initial Cost	Normal	Normal (mean, std dev) Alt A – Normal (1980.00, 143.96) Alt B – Normal (1912.50, 186.33) Alt C – Normal (1465.00, 156.21) Alt D – Normal (1207.50, 136.27)	
Future Maintenance Costs and Road User Costs	Normal	Normal (mean, std dev) Alt A – Normal (3100.00, 312.69) Alt B – Normal (2925.00, 586.84) Alt C – Normal (2544.44, 602.05) Alt D – Normal (2116.67, 690.21)	
Pavement Service Life – Rehabilitation	Triangular	Triang (min, most likely, max) Alt A – Triang (9.00, 12.00, 13.00) Alt B – Triang (7.00, 9.00, 10.00) Alt C – Triang (6.00, 8.00, 9.00) Alt D – Triang (4.00, 6.00, 7.00)	
Discount Rate	Triangular	Triang (min, most likely, max) Alt A – Triang (10, 11, 12) Alt B – Triang (10, 11, 12) Alt C – Triang (10, 11, 12) Alt D – Triang (10, 11, 12)	

The sensitive analysis must be used before applying risk analysis to identify the key variables in the evaluation model and help the analyst select the critical risk variables that explain most of the project's risk. The probability distribution is commonly used in flexible pavement life-cycle cost analysis is multivalued distribution. Based on the simulation results whose inputs are the database collected from the four typical pavements as mentioned above, different hypotheses and the goodness-of-fit sequences for searching the suitable probability distribution for each input were implemented. Table 2 summarizes the probability distributions of the inputs for the model using in this study.

Given the probability distribution of the aforementioned inputs, the Monte Carlo simulation was developed to select the best flexible pavement design alternative. By running 1,000,000 iteration simulation, the probability distributions NPV of the four pavement alternatives were developed, namely A, B, C, and D. Fig.2 shows the probability distribution of the NPVs in the form of a histogram, where the probability is the area under the curve. According to Fig.2, the entire range of possible outcomes is aligned with the estimated probability of each outcome occurring. The main advantage of the histogram is that it easily shows the changes in mean values. The wider the distribution, the greater the variability. As shown, the outcome for Alternative B, C, and D are less certain than Alternative A.

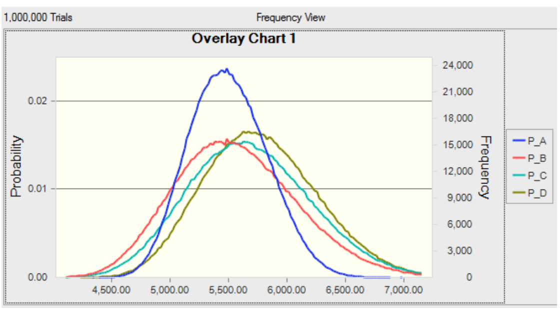


Fig. 2 - Histogram NPV for 04 alternatives

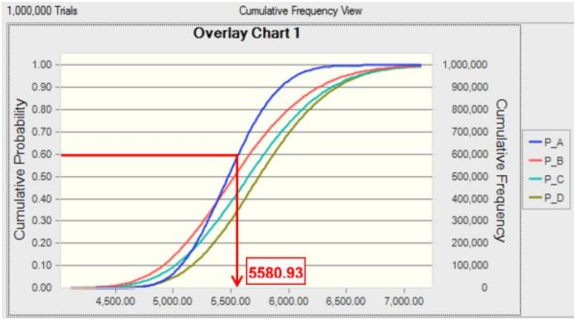


Fig. 3 - The cumulative risk status of NPV for 04 alternatives

Fig. 3 illustrates the risk status for 04 Alternatives in the cumulative frequency curves. Accordingly, the probability that the project life cycle cost of Alternative A is less than VND 5,580.93 million is as high as 60%, while this value of Alternative D is rather low, only 35%.

It should be noted that of the 04 pavement types, the initial cost for Alternative A is the highest, and that of Alternative C is the second-lowest. All of them meet the required structural modulus given the traffic volume, which is assumed to be 3,000 vehicles/day at the end of the pavement service life. Therefore, if the selection is based on the traditional determinant method, Alternative A will be easily rejected, and Alternative D will be selected. In developing countries as Vietnam, due to fiscal constraints, the selection of the cheapest initial cost for a pavement structure is easy to understand, and it would lead to a wrong decision under the light of the probabilistic method as presented. In general, the probabilistic provides much more information than the simple deterministic one. The risk assessment reveals areas of vagueness for stakeholders who are responsible for decision making. Under the light of the latest information provided in this paper, stakeholders have the chance to take such measures to minimize exposure to the risk.

5. Conclusion

This study introduces an application of Monte Carlo simulation, a probability approach, to the traditional determinant method in flexible pavement design. The primary contribution to the body of knowledge of this study is to indicate that there is always a risk in the cost analysis of flexible pavement projects. The case study conducted in Nghe An province exposed the benefits of the method of simulation over the traditional deterministic approach. In place of using a specified number for each life cycle hypothesis, the MCS model enables life cycle assumptions using a set of values for input variables with their variations in nature. This study represents an efficient approach for risk prioritization and resource management involving the examination of a series of simulation experiments. Essential factors such as costs, time, quality and the impact of risks on them are used to determine degrees on which a project should efficiently adjust its budget.

Finally, an indispensable requirement to use the Monte-Carlo model is to have sufficient databases for analysis and evaluation. Therefore, based on the study, the further suggestion for developing countries is that the agency competencies need to have specific orientation in storing the valuable source of databases. These are very important to flexible pavement life-cycle cost analysis, especially in the context that Vietnam, as well as developing countries, where the poor capacity of monitoring and keeping pavement database is obvious.

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References

Abaza, K. A. (2002). Optimum flexible pavement life-cycle analysis model. J. Transp. Eng., 128(6), 542–549.

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, 241- 254.

Chan, A., Keoleian, G., and Gabler, E. (2008). Evaluation of life-cycle cost analysis practices used by the Michigan Department of Transportation. J. Transp. Eng., 134(6), 236–245.

Federal Highway Administration FHwA. (1998). Life-cycle cost analysis in pavement design—In search of better investment decisions. U.S. Department of Transportation, Washington, D.C.

Gopanagoni, Varshini & Velpula, Sree. (2020). An analytical approach on life cycle cost analysis of a green building. Materials Today: Proceedings. 10.1016/j.matpr.2020.04.226.

Hajare, Ayushi & Elwakil, Emad. (2020). Integration of Life Cycle Cost Analysis and Energy Simulation for Building Energy-Efficient Strategies Assessment. Sustainable Cities and Society.

Hicks, R. G., and Epps, J. A. (1999). Life cycle cost analysis of asphalt rubber paving materials. Final Rep. Volumes 1 and II to Rubber Pavements Association, Tempe, Ariz.

Mardani, Abbas & Jusoh, Ahmad & Zavadskas, Edmundas. (2015). Fuzzy Multiple Criteria Decision-Making Techniques and Applications – Two decades review from 1994 to 2014. Expert Systems with Applications.

MITRE. Risk Impact Assessment and Prioritization. (2017). Https://www.mitre.org/, last accessed 2020/10/15.

Mohammad, Heidari & Heravi, Gholamreza & Nezhadpour Esmaeeli, Asghar. (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. 10.1016/j.jclepro.2020.120046.

Labi, S., and Sinha, K. C. (2005). Life-cycle evaluation of flexible pavement preventive maintenance. J. Transp. Eng., 131(10), 744–751.

Patchin C., Mark C. (2012). Risk Assessment in Practice, Committee of Sponsoring Organizations of the Treadway Commission (COSO).

Peshkin, D. G., Hoerner, T. E., and Zimmerman, K. A. (2005). Optimal timing of pavement preventive maintenance treatment applications. NCHRP Rep. No. 523, National Academies, Washington, D.C.

Reigle, J. A., and Zaniewski, J. P. (2005). Risk-based life-cycle cost analysis for project-level pavement management. Transportation Research Record. 1816, 34–42.

Setunge, S., et al. (2010). Whole of life cycle cost analysis in bridge rehabilitation. Rep. No. 2002-005-C-03, RMIT Univ., Melbourne, Australia.

Stoneburner G., Goguen A., Feringa A. (2002). Risk Management Guide for Information Technology System, National Institute of Standards and Technology, Special Publication 800-30.

Tighe, S. (2001). Guidelines for probabilistic pavement life cycle cost analysis. Transportation Research Record. 1769, 28–38.

Walls J., Smith, M. Life-Cycle Cost Analysis in Pavement Design Federal Highway Administration, Report no. FHWA-SA-98-079, Washington D.C., USA (1998).

Wilde, J. W., Waalkes, S., and Harrison, R. (1999). Life cycle cost analysis of Portland cement concrete pavements. FHWA/TX-00/0-1739-1, Univ. of Texas at Austin, Tex.

Yu, Bin & Lu, Qing & Xu, Jian. (2013). An improved pavement maintenance optimization methodology: Integrating LCA and LCCA. Transportation Research Part A: Policy and Practice.