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EXTENDED DECISION-MAKING FRAMEWORK FOR SUSTAINABLE PAVEMENT MANAGEMENT

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Abstract

Sustainable pavement management (SPM) is characterized by economic, environmental, and social factors, which are respectively evaluated by life-cycle cost analysis (LCCA), life-cycle environmental assessment (LCEA), and life-cycle social assessment (LCSA). Despite current progress on SPM, several opportunities for improvements remain. This paper proposes an extended decision-making framework that integrates LCCA, LCEA and LCSA modules that can be used to select optimal pavement design and maintenance strategy in SPM at the project level. In the pavement LCEA module, the use phase is incorporated into SPM, including three elements of rolling resistance, albedo, and lighting. An approach for performing LCSA is developed and social impact indicators are identified in the pavement LCSA module. Based on the outputs of the three modules, the framework combines the analytic hierarchy process and a technique for order preference by similarity to ideal solution.

Keywords: Sustainable pavement management, life-cycle, cost analysis, environmental assessment, social assessment, decision-making

1. INTRODUCTION

Currently, there is an increased focus on sustainable development, but “sustainability” is a broad concept as every organization has its own definition and methodology. In the transportation infrastructure field, the Federal Highway Administration (FHWA) defined sustainability as "a sustainable highway should satisfy lifecycle functional requirements of societal development and economic growth while striving to enhance the natural environment and reduce consumption of natural resources". It is evident from the definition that sustainable development needs to integrate economic, environmental, and social factors. In addition, sustainable transportation projects are required to satisfy the whole life cycle from conception through the construction, use, maintenance, and rehabilitation stage (Carolina et al 2015).Therefore, the multidimensional life-cycle approach is suitable for use in sustainable pavement management (SPM), which includes life-cycle cost analysis (LCCA), Life-cycle environmental assessment (LCEA) and Life-cycle social assessment (LCSA).

Pavements comprise an important portion of the transportation infrastructure, which has a significant effect on the environment and society. Therefore, sustainability is widely considered in pavement management systems. Stakeholders in the pavement sectors have been seeking new engineering solutions to move toward more environment-friendly pavement management practices, such as use of warm mix asphalt, applying in-place recycling techniques, and implementing preventive treatments (Santosa et al. 2007, 2015). However, the environmental benefit of new techniques is not equivalent to achieving the goal of sustainability for pavement practices since sustainability incorporates economic, environmental, and social factors. Therefore, defining sustainable measures is the critical step of performing sustainability into pavement management.

In previous studies, there were more focus on economic and environmental factors that are incorporated into pavement management to enhance sustainability (Nathman et al. 2009, Nicuță et al. 2013, Liu et al. 2015).Only a few studies have focused on integrating social impacts at a particular segment of the pavement project. For example, Sundeep (2016) proposed a decision-making approach that integrates LCCA, LCEA and LCSA for selecting sustainable pavements in Texas. The study achieved the following contributions: (1) deficits in pavement life-cycle environment assessment were incorporated into the proposed framework, which included developing a model for calculating environmental impacts of traffic delays during the maintenance phase and a methodology for normalization in environmental life-cycle impact assessment, (2) an approach for social life-cycle assessment was conducted, where traffic noise was identified as a social impact indictor, and(3) a group decision model integrating analytic hierarchy process(AHP), data envelopment analysis, and particle swarm optimization technique was performed for the decision making. However, there are still some gaps in the SPM framework proposed by Sundeep (2016), such as overlooking several parameters in the LCCA module, omitting the use phase/components in LCEA, and ignoring the uncertainty of the input parameters. Overall, SPM is still at an immature stage and further research is still needed. Therefore, beyond the further progress of LCCA and LCEA, it is necessary to develop some new approaches and application of SLCA and decision-making model to complete and optimize the methodologies for SPM.

The purpose of this paper is to present an extended SPM framework that incorporates several novel aspects to fill some gaps in existing SPM analysis. Specifically, based on previous studies, the extended decision-making framework for SPM at the project level, which integrates LCCA, LCEA, and LCSA, is proposed. In the LCEA module, the use phase is incorporated into SPM, including three elements: rolling resistance, albedo, and lighting. In addition, uncertainty analysis is included in the LCEA module using Monte-Carlo simulation. A new approach for performing LCSA is developed and social impact indicators are identified in the LCSA module. Subsequently, a decision-making model that combines AHP and technique for order preference by similarity to ideal solution (TOPSIS), along with sensitive analysis, is conducted to select the optimal design strategy for SPM.

2. LITERATURE REVIEW

Sustainable pavement management is the application of sustainability considerations to traditional pavement management systems. These systems transform the available data into useful information, including economic, environmental, and social impacts to help with the decision-making process in a structured way.

2.1 Life-cycle cost analysis

Economy is one of the sustainability pillars and in pavement management, life-cycle cost analysis (LCCA) is performed for the economic element over its service life, which builds on the true principles of economic analysis to evaluate the cost based on the net present value (NPV) concept (Torres and Yepes 2014).The American Association of State Highway Officials (AASHO) presented the concept of LCCA of pavement projects in 1960. Then, some researchers and organizations developed the process and application for pavement type selection and pavement design (Babashamsi 2016). In 1991, the Intermodal Surface Transportation Efficiency Act mandated to adopt LCCA for the design and construction of bridges, tunnels, and pavements. In 1995, FHWA made LCCA compulsory for national highway projects costing more than $25 million, but this policy was annulled in1998 due to the Transportation Equity Act (Babashamsi 2016). However, FHWA further developed the methodology and application of pavement LCCA and still identified LCCA as a helpful tool in highway design and management for decision makers (FHWA 1998). The National Highway System Designation Act identified LCCA as an effective approach for analyzing the total economic cost of a project segment by calculating the initial costs and discounting future costs such as maintenance and rehabilitation (M＆R) strategies during the whole life cycle of the projects. Literature surveys indicated that the use of LCCA in transportation projects has increased. According to Chan et al. (2008), more than 40 states in the USA performed LCCA during the pavement selection process. However, there is some main drawbacks in LCCA, such as lack of uncertain analysis for input parameters, consideration of preventive maintenance, and inclusion of user cost (Babashamsi 2016).

2.2 Life-cycle environmental assessment

A common modeling approach to measure the environmental burden is LCEA that evaluates environmental performance using a series of different metrics, such as energy consumption, conventional air pollutants (e.g., SOx, NOx, and CO), and greenhouse gas emission. According to the International Organization for Standardization, LCEA addresses the environmental impacts throughout products' life cycle from the purchase of raw materials to the production, use, treatment, and recycling, until its final disposal (ISO 2006).ISO14040 series guidelines are the basic methodology for LCEA which is being used in various fields, including pavement management.

Since the first pavement LCEA was put forward in the mid-1990s, this method has been steadily used to quantify the environmental impacts for pavement projects. Studies have been achieved through a large number of publication and summarized into two parts: (1) comparison and selection of pavement type associated with environmental aspect, which concrete and asphalt materials are the common pavement options (Santeroa et al. 2011a, 2011b) and (2) there were a growing tendency to evaluate the environmental impacts of new materials and construction technologies for pavement, such as reclaimed asphalt, warm and half-warm mix asphalt, cold in-place recycling asphalt (Mazumder et al. 2016).

Pavement LCEA is still in progress and no standard framework to be adopted by transportation agencies. Typically, a pavement LCEA is divided into five phases: raw materials and production, construction, use, maintenance, and end-of-life (EOL) (Santeroa et al. 2011a). Current studies vary from system boundaries for pavement LCEA due to a lack of identical understanding of environmental impacts on pavement activities and difficulty in acquiring relevant data. As a result of these difficulties, the majority of pavement LCEA studies have been applied to raw materials and production and construction phase, as well as the maintenance phase of the pavement (Santeroa et al. 2011a, 2011b). Only a few studies included use and EOL phases and the existing pavement LCEA is not completely included all phases and components of the life cycle (Santeroa et al. 2011a). The omission of use phase from current studies is perhaps the most deficient from a system boundary perspective and often contribute greatly to the overall life-cycle impact, thus potentially changing the conclusions for a given pavement project. Santero et al. (2011a) represented the traffic delay during the construction and maintenance phases, use phase, and EOL phase are the most important gaps in pavement LCEA. AzariJafari et al. (2016) considered important challenges and opportunities should be improved for pavement LCEA methodologies, include inventory collection, environmental impact assessment and interpretation stage. Sensitivity and uncertainty analysis should be highly recommended in the pavement LCEA by Santeroa et al. (2011b). Beyond the system boundaries and typically omitted phases and components, existing pavement LCEA is still lack of consensus upon the functional unit and environmental indicators that hinder comparison and aggregation of pavement LCEA results, importantly limit their effectiveness in a decision-making process (AzariJafari et al. 2016).

2.3 Life-cycle social assessment

Life-cycle social assessment is a technique that is used to evaluate the social and socio-economic aspects of product and their potential positive and negative impacts referred to different groups of stakeholders along with their life cycle (UNEP 2009).LCSA is still at its infancy stage and current studies adopted the combined approach of ISO 14040 series guidelines with four steps similar to LCEA and UNEP Guidelines to develop LCSA, include 5 stakeholders, 6 impact categories, 31 subcategories, more than 100 inventory indicators, and impact assessment (Arcese et al. 2016). There has been some theoretical discussion about how to perform a LCSA, but the methodology is still immature. The current challenges in the theoretical part of LCSA are related to the lack of standard methodology, social-impact databases, multi-disciplinary expertise, selection and analysis of social impact indicators, functional unit definition and system boundaries, and impact assessment (Hewage and Sadiq 2015).

In addition, there are insufficient practical cases to apply and study LCSA (Arcese et al. 2016). Several studies have focused on products while less attention is related to services, including construction activities (Sundeep2016). Dong and Thomas (2015) developed a social life-cycle assessment model for building construction projects in Hong Kong and identified health and safety (worker) as the most important social aspect. Gerva'sio (2013) proposed a social life-cycle analysis for the evaluation of motorway bridges and considered user cost (e.g. vehicle operation costs, driver delay cost, and accident cost) as a social impact.

In the pavement field, LCSA is still at the blank stage and only a few cases have implemented the concept in pavement management. As previously mentioned, Sundeep (2016) considered traffic noise as a social impact indictor, where the impact pathways approach was adopted to calculate social impact using social cost and social emission for construction and maintaining noise barriers. Therefore, there is enormous room for further development of LCSA in pavement management, including the methodology and practical application.

2.4 Multi-criteria decision analysis

Traditionally, Multi-criteria decision analysis (MCDA) is considered as an effective tool for selection of alternative projects that have multi-attribute criteria, such as economic, environmental and social factors, and assist with decision-making process (Ouma et al. 2014).Nonetheless, it is noted that MCDA technique is suitable for dealing with the problems whose alternatives are predefined and are to be ranked by the decision makers.

One of the most widely applied method which belongs to utility theory type is AHP that was developed by Saaty (1990). A weight for each level of a hierarchy is established with numerical ratings (1~9) by pairwise comparisons (Saaty 1990).Due to its simplicity and flexibility, AHP has been applied in many fields, such as engineering, business, food, and ecology and government (Seyhan and Mehpare 2010). In pavement field, there are some studies related to pavement maintenance prioritization, maintenance and construction quality evaluation and pavement performance evaluation (Jahanian et al. 2017, Farhan and Fwa 2009).

TOPSIS method was originally developed by Hwang and Yoon (1981), which is a multiple criteria method to identify solutions from a finite number of criteria. The basic principal is that the optimal alternative should have the shortest distance from the positive ideal solution and the farthest distance from the negative ideal solution. As a well-known classical MCDA method, TOPSIS has widely applied in different fields. Behzadian et al. (2012) reviewed 266 published papers related to TOPSIS, nine application areas were categorized, such as "Design, Engineering and Manufacturing Systems", "Health, Safety and Environment Management".

3. PROPOSED SPM FRAMEWORK

Sustainable pavement management can be implemented at three levels:(1) project level, that technical decisions are made concerning pavement type selection and design, construction practice, material type, maintenance strategies,(2) network level, which analyzes a set of pavements in order to rank and schedule the works for their maintenance under budget constraints, and (3)strategic-level, which establishes general management objectives, maintenance policies and the available resources (Torres and Yepes 2014). In this paper, the extended SPM framework develops three criteria (LCCA, LCEA, and LCSA) and a multi-criteria decision-making model to optimize the alternative pavement design and maintenance strategies at the project level, as shown in Figure1.

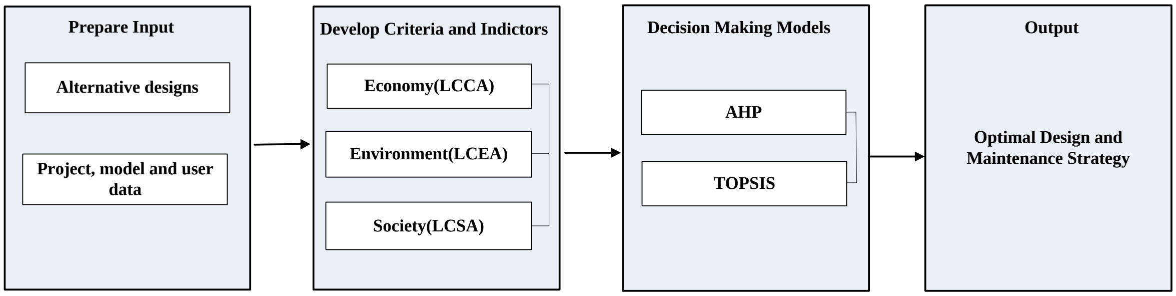

Figure1. Proposed extended framework for sustainable pavement management at project-level

3.1 Preparing input

The tasks of "Prepare Input" module in the proposed framework are to develop alternative designs and collect data related to the project, model, and user. The first step is to develop alternative pavement options for SPM at project-level, which provide equivalent function and performance. Beside traditional pavement type comparison, transportation agencies currently are inclined to develop environment-friendly pavement designs to achieve the goal of sustainability for pavement project. New technologies are developed to make materials and construction processes less energy consumption and lower emissions. These practices include:

- Warm mix asphalt and half-warm mix asphalt are developed as material-related technology that allows asphalt mixtures to be produced at lower temperatures. The benefit of these new materials is to reduce energy consumption and emission, improve workability and compaction efficiency (Gianiet al. 2015).
- Reclaimed asphalt pavement (RAP) is another material-related technology that reduce the amount of asphalt and aggregate for pavement project and save natural resources. Several studies stated that hot mix asphalt containing RAP has the same qualities as asphalt produced from virgin material if the reclaimed asphalt is implemented properly (Gianiet al. 2015).
- Industrial by-products used as material alternatives fora pavement project is an environment-friendly practice that can contribute to reduce wastes and preserve natural resources (Anastasiou et al. 2015).
- Applying in cold-in-place recycling during maintenance strategies is a new construction technology that generated less environmental burden compared with other rehabilitation strategies (Gianiet al. 2015).

Another part of "Prepare Input" module is to collect enormous data varied from different disciplines, include project data, model parameters and user data. In general, the data used in SPM are available online or database, for example, pavement management database from transportation sectors, various database for LCEA. However, there have been some changes for not up-to-date data in environmental impacts due to methodology development, new materials and construction techniques applied in pavement project in the last decade. In addition, the required data for LCSA is incomplete and ambiguous due to early stage of its application. Therefore, questionnaire survey, interview, databases, and national statistics are used to collect data for LCSA in previous works (Dong and Thomas 2015). Input data is a significant challenge for SPM due to data scarcity and reliability issues.

3.2 Developing Criteria and Indicators

3.2.1 Life-cycle cost analysis

Life-cycle cost analysis has been accepted as a popular approach to evaluate economic factor for alternative designs. LCCA can be classified into deterministic and probabilistic approach. All the costs are calculated into a determined value with deterministic approach. Considering some level of uncertainty on pavement projects, input variables and risk assessment method is conducted by probabilistic approach. If all inputs are analyzed probabilistically, LCCA system is deemed much more valid and powerful (Babashamsi 2016). However, according to a survey among US State highway agencies for pavement LCCA, deterministic approach have more application in real practices (Sundeep 2016). The probabilistic approach is not in practice due to the complexity of input. Several organizations have designed computer software for their LCCA approaches in order to assist with the decision-making process. For example, FHWA has developed a LCCA software product namedRealCost2.5 to perform the numerical calculations. Many highway agencies in the US have adopted LCCA to analyze alternative designs by using RealCost2.5.

In this study, a combination of deterministic, sensitive analysis and risk assessment approach was used for conducting LCCA using Real Cost 2.5. Two components are considered in LCCA module, including agency cost and user cost. The agency cost is the investment from transportation agencies to perform initial construction cost and future maintenance cost in constant dollars during the service life. The user cost is an incorporation of vehicle operation cost and user delay cost.

3.2.2 Life-cycle environmental assessment

ISO (2006) divided LCEA into four steps: the definition of goal and scope, life-cycle environmental inventory analysis (LCEI),life-cycle environmental impact assessment(LCEAI), and interpretation. In this paper, the proposed LCEA criteria is developed based on ISO (2006) and previous reviews. The details are discussed as follows:

Goal and Scope
The scope for pavement LCEA is displayed in Fig 2. Use phase which include rolling resistance, albedo, and lighting is integrated into this study, but no well-established models can be assessed the emissions mainly due to diversity of traffic condition and pavement surface type in this phase. Although a unique environment burden is posed on EOL phase for pavement projects, there is no clear solution whether the pavement would be recycled or landfilled, and thus it is not considered in this study.

Life-cycle environmental inventory analysis
The pavement LCEI covers data collection associated with all life-cycle phases within the system boundaries. A number of models are being used in pavement LCEA, such as GREET, Motor Vehicle Emission Simulator (MOVES), NONROAD2008 model. In practice, a complete pavement LCEA needs various models and databases due to the complexity and diversity of components in various phases for pavement project. So far, FHWA has not reviewed and endorsed any LCEI database currently available for a pavement LCEA. In this paper, the proposed LCEI models are shown in Fig.2, but rolling resistance, albedo, and lighting models in use phase are need to be studied in detail.

Life-cycle environmental impact Assessment
LCEIA is defined as "aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts, includes two mandatory elements: classification and characterization" (ISO 2006). Most current pavement LCEIA maintained at classification and characterization stage (Sundeep 2016).In this paper, another optional steps which include normalization and weighting are taken into consideration to assist with decision making. Normalization aims at converting various impact categories into a common unit with a reference system to facilitate comparison among alternative designs. But normalization is considered as high risk subjectivity due to the uncertainty on selection of a reference system.

Interpretation
During interpretation step, uncertainty analysis is performed with final results. There are several uncertain sources should be considered in pavement LCEA process, such as omitted phases and components, diversity of LCEI models and database, the limitation of characterization and normalization models that contribute to lack of accuracy and reliability in life-cycle assessment for pavement project (Santeroa et al. 2011a). Uncertainty analysis is conducted using Monte-Carlo simulation in this paper.

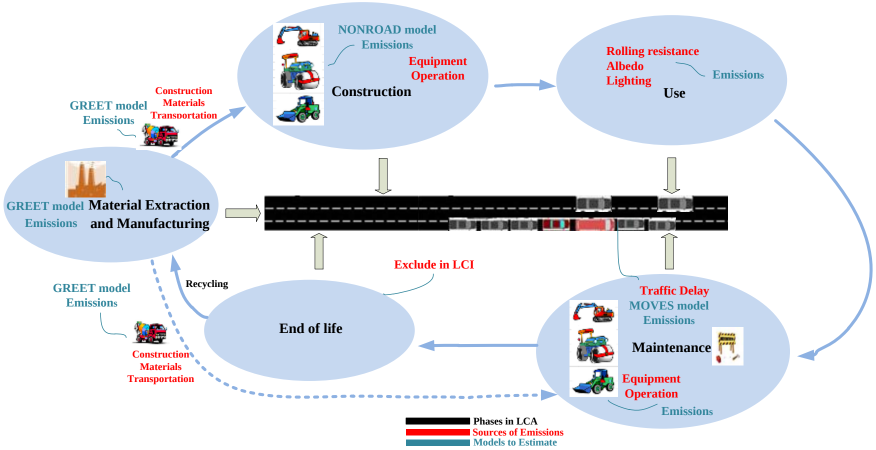

Figure2. Study scopes and used LCI models for pavement LCEA

3.3.3 Life-cycle social assessment

Some published studies on social perspectives in sustainable construction activities indicated that identifying a significant theme, defining associated stakeholder groups, selecting applicable indicators and developing the assessment methodology are important for social assessment (Zhao et al. 2012). In this paper, the proposed pavement LCSA is developed based on ISO 14040 guidelines and UNEP Guidelines. According to ISO 14044 guidelines, LCSA include four-step structure as LCEA: (1) goal and scope, (2) life-cycle social inventory analysis (LCSI), (3) life-cycle social impact assessment (LCSIA), and (4) interpretation (ISO 2006). In this paper, the first step is to identify several critical issues of pavement LCSA, include study goal, system boundary, key stockholders, impact indictors etc. The second LCSI step is to collect data, establish reasonable LCSA model to calculate social impacts. In LCSIA step, the inventory results are converted to impact subcategories and the weights of subcategories are determined by AHP method. Then, a scoring system based characterization and normalization model is developed to assess the social impact. The last step is to interpret the results of SLCIA and identify hotspots.

Based on the literature review, the proposed methodology of pavement LCSA is as follows.

Selecting stakeholders, subcategories and indictors:
In most LCSA, the subcategories are classified both by stakeholder categories and impact categories. Social impact indictors are determined according to relevant subcategories. In this study, 3 stakeholders, 12 subcategories and 16 social impact indictors are identified based on UNEP/SETAC Guidelines (2009).

Developing scores of indicators and normalize the results into comparable scales:
The LCSI methodology is to collect inventory data for social impact indictors and then aggregate the results of qualitative and semi-qualitative indicators using positive and negative sign or a scoring system (Hewage and Sadiq 2015).This study adopts national statistics and questionnaire survey to collect data and normalize the results into comparable scales[-1, 1] based on relevant models.

Determining the weights of subcategories:
Considering the importance of subcategories and indicator, this study adopts the AHP method to determine the relative weights of the subcategories. Experts who cover several different sectors, including government, consultant, contractor, supplier/manufacturer, academic researchers were invited to compare the importance of subcategories. The detail process to determine the weights by AHP is explained in the Section 3.3.

Developing a formula for calculating social impact scores:
Based on the scales of the social impact indictor and weights calculated by AHP, a new SLCIA method is proposed. In this study, social impact is assessed based on both quantitative and semi-quantitative indicators. The results of the indicators are normalized into comparable scales. The comparable score is subsequently multiplied by the weight of each subcategory from the AHP method, and a final social impact

score (SIS) is obtained for pavement LCSA. The formula for calculating social impact score is shown in Eq. (1).

[1] Social Impact Score= $\sum_{i=1}^{n} S_i \times W_i$

where S_i and W_i are the score and weight of indicator *i*, respectively.

Finally, the scores obtained for each subcategory are combined into a single score to facilitate a comparison among different pavement alternatives.

3.3 Decision-making models

TOPSIS is considered as an important and effective tool to optimize and select alternatives. However, there is a gap in TOPSIS method that it cannot decide the weight of different criteria in the process and need to input predetermined weights. Meanwhile, the significant advantage of AHP method is that it can provide a powerful procedure to determine the relative importance of different criteria related to the objective. Hence, to take advantage of both the methods, a combined AHP-TOPSIS approach is adopted to optimize the alternative pavement designs and maintenance strategies in this study.

The combined AHP-TOPSIS method consist two basic stages: (1) AHP is used to determine the weights of criteria. (2)TOPSIS method is adopted to obtain final ranking of alternative pavement designs and M＆R strategies that uses input weights calculated by AHP. The process is illustrated as follows (Steps 1-3 are related to AHP, while Steps 4-8 are related to TOPSIS):

Step 1: The task of conducting AHP is to construct a hierarchical structure of alternative solutions. In the framework, the three criteria are developed based on economy (LCCA), environment (LCEA), and Society (LCSA).
Step 2: The experts are given the task of forming individual pairwise comparison matrix by using the scale from 1 to 9 for each pairwise comparison and the weights are calculated for each criteria.
Step 3: Consistency test is performed to check the logicality of the pairwise comparison matrix which is required by less than 0.1.
Step 4: Establish a normalized decision matrix.
Step 5: Prepare a weighted normalized decision matrix based on the weights calculated by AHP and the normalized decision matrix which is established in step 4.
Step 6: Determine negative and positive solution, which are not required to be existed in practice.
Step 7: Calculate the distance to negative and positive ideal solution for each alternative.
Step 8: Calculate the relative closeness to the ideal solution for each alternative.
Step 9: Rank the preference order for each alternative according to the relative closeness.

In the combined AHP-TOPSIS method, the weight of criteria is a critical factor that affects the decision-making process. The weight of criteria in the decision-making models is calculated by AHP which are based on the experts' comparison of different criteria. The experts in SPM are from various fields that have different preference on the economy, environment and social factors and different experience and confidence. Therefore, a sensitivity analysis is necessary to be conducted in the combined AHP-TOPSIS methodology. The weights obtained from AHP are changed for different alternatives, and then TOPSIS is performed to obtain the new results. This helps the decision-maker to determine priorities and select optimal strategies.

4. CONCLUSIONS

This paper has proposed a decision-making framework for sustainable pavement management at the project-level that integrates LCCA, LCEA, and LCSA. In this framework, an enhanced pavement LCEA module is proposed by incorporating three components in the use phase which are rolling resistance, albedo, and lighting models. In the LCSA module, stakeholders, subcategories and social impact indicators related to pavement project are identified and an approach is proposed for performing LCSA with a final

SIS which is calculated by the score of quantitative and semi-quantitative social impact indicators and the weights of subcategories. An MCDA model that combined AHP-TOPSIS is proposed for evaluating and selecting the optimal pavement design. To validate the proposed methodology for selection of pavement projects, a sensitivity analysis is conducted by changing the weights that calculated by AHP. There are some limitations in this paper and need to be work further in the future, such as addressing the network level in SPM and incorporating more elements of the use phase.

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