SUSTAINABILITY EVALUATION OF PAVEMENT TECHNOLOGIES THROUGH MULTICRITERIA DECISION TECHNIQUES

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ABSTRACT

This paper presents findings of a recent study that was conducted in Canada on the quantification of pavement sustainability. The ultimate goal of this study was to develop a framework and explore the use of multicriteria decision-making techniques to formally assess the sustainability of pavement engineering alternatives. While sustainability is of increasing concern in pavement engineering, environmental performance is rarely used by pavement managers to select maintenance practices. There is therefore a need to develop a framework for the practical consideration of environmental effects in pavement management. This paper is aimed to provide a better understanding on the use of multicriteria decision-making techniques based on Hierarchy Process (AHP) and Choosing by Advantages (CBA) for the integration of sustainable aspects in the decision-

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making process of pavement management. A case study comparing pavement maintenance technologies using cold-in-place recycling and traditional solutions based on mill and overlay is analyzed for illustrative purposes. Results obtained using both multicriteria techniques are compared, including a sensitivity analysis on the importance of sustainability criteria in the evaluation of maintenance alternatives. Results obtained from this case study show that AHP and CBA provide consistent recommendations in which cold-in-place technologies are preferred over traditional alternatives. However, CBA presents the advantage of separating cost from the analysis, letting the agency to decide whether they are willing to pay more to use more sustainable alternatives. This finding has significant implications for engineering practice, given that AHP is widely used not only in the pavement field but in infrastructure management. Further research is needed to incorporate social aspects and existing barriers for the implementation of sustainable technologies in the proposed sustainability evaluation.

Key words: sustainability, recycling, life cycle assessment, multicriteria decision-making, analytic hierarchy process, choosing by advantages.

INTRODUCTION

In order to maintain quality, comfort, and safety of existing infrastructure, pavement managers have traditionally selected maintenance treatments based on economic and technical criteria (Torres-Machi et al. 2014, 2015). The importance of these criteria is unquestionable: they allow for the selection of appropriate maintenance treatments and for the reduction of life cycle costs. However, considering the definition of sustainable development provided in the Brundtland Report as "*development that meets the needs of* *the present without compromising the ability of future generations to meet their own needs*" (WCED 1987), the consideration of technical and economic criteria alone cannot provide a sustainable pavement management system. Environmental efforts have traditionally been focused on reducing the effects generated by vehicle operation. However, the environmental impact of the stages of road construction, use, and maintenance is not negligible. Indeed, it is estimated to increase the environmental effects caused by vehicle operation by 10% (Chester and Horvath 2009). There is therefore a need to incorporate environmental criteria alongside technical and economic in pavement management (Torres-Machi et al. 2017a, 2018).

Existing literature is rich with information on sustainable practices applied to pavement design, construction, and material selection (AzariJafari et al. 2016). Previous studies have explored the environmental impact of initiatives such as: the implementation of new construction techniques on pavement construction (Celauro et al. 2015); the use of recycled materials (Santos et al. 2015a; Kodippily et al. 2016); and the selection of materials (Kucukvar et al. 2014), among others. This valuable information has enabled the development of environmental certification systems initially inspired by Leadership in Energy and Environmental Design (LEED) (USGBC 2017) and adapted to road infrastructure, such as GreenRoads (Muench et al. 2010), GreenPave (MTO 2010), and GreenLITES (NYSDOT 2013). These systems promote the design and construction of more sustainable pavements by assigning a series of points to environmentally friendly practices. However, they do not attempt to provide any decision-making methods nor incorporate other criteria (such as technical and/or economic) in the evaluation of alternatives (Arroyo et al. 2016). Although these systems and previous studies have provided a valuable foundation for the assessment of environmental impacts in the design and construction of pavements, little attention has been paid to maintenance (Tighe and Gransberg 2011).

Some studies have tried to overcome this limitation by quantifying the environmental impact of maintenance treatments. In this regard, several initiatives are worth mentioning, including the Pavement Life Cycle Assessment Tool for Environmental and Economic Effects (PaLATE) (Horvath 2007), an Excel worksheet that quantifies the environmental impact in pavement design, construction, and maintenance stages; and the environmental evaluation included in the pavement management system (PMS) developed by the World Bank HDM-4 (Bennett and Greenwood 2004). More recently, Santos et al. (2015b) proposed a complete model that considers the entire pavement life cycle and includes maintenance and rehabilitation activities. Such approaches, however, focus on the analysis of a specific road segment, making them difficult to apply at the network level (Harvey et al. 2014) and therefore to incorporate a sustainable approach in the planning of maintenance programs and PMSs (Giustozzi et al. 2012; Gosse et al. 2013; Bryce et al. 2014; Torres-Machi et al. 2014, 2017b).

Many transportation agencies are recognizing, promoting and encouraging the use of sustainable pavement technologies in their pavement network and terms such as green, sustainable development, environmental impact, energy efficiency, global warming, greenhouse gases (GHG), and eco-efficiency are becoming more widely recognized (Tighe and Gransberg 2011; AzariJafari et al. 2016). In Canada, the United States, and other developed countries, transportation agencies have taken steps to develop specifications and guidelines for the use of various sustainable or green pavement technologies including innovative pavement materials as well as pavement maintenance techniques for construction and rehabilitation of road networks. However, this does not translate to direct measures within their management process. Indeed, a study developed by Tighe and Gransberg (2011) found that only 4% of transportation agencies in the USA and Canada were using environmental performance to select maintenance practices.

Multicriteria Decision Making (MCDM) methods have already been used in the pavement field to integrate different criteria in the decision-making process (Wu et al. 2012; Torres-Machi et al. 2015). Previous studies have used approaches such as the Multi-attribute approach (Giustozzi et al. 2012; Bryce et al. 2014) and the Analytic Hierarchy Process (AHP) (Smith and Tighe 2006; Farhan and Fwa 2011; Gurganus and Gharaibeh 2012; Oswald and Treat 2015; Inti and Tandon 2017). Given the broad use of MCDMs in the pavement field, one approach to developing a sustainable framework would be to integrate economic, technical, and environmental criteria in the sustainable evaluation of alternative designs. Some previous attempts have been made to incorporate such criteria into a single pavement management framework (Chan 2010). However, different multicriteria approaches have yet to be compared within a sustainable pavement management framework. Specifically, this study analyzes and compares the results obtained using two MCDM techniques: AHP and Choosing by Advantages (CBA). Whereas the AHP has been widely used in the infrastructure management and specifically in the pavement field (Smith and Tighe 2006; Gurganus and Gharaibeh 2012; Kabir et al. 2014; Inti and Tandon 2017), CBA is mostly known only in the lean construction community (Arroyo et al. 2016). One of the main differences between AHP and CBA is how the cost criterion is considered in the evaluation. Meanwhile AHP traditionally considers cost as one of the criterion in the decision-making process, CBA separates value from cost. That is, CBA considers costs after the attributes of alternatives have been evaluated based on factors and criteria (Arroyo et al. 2016). The basis of this approach is that CBA aims to select the alternative that yields the best project outcomes within the existing financial constraints. Recent studies developed by Arroyo et al (2015, 2016) have drawn promising results on the use of CBA for choosing sustainable materials in building construction. The case study developed by Arroyo et al. (2016) demonstrated that CBA is better than AHP in terms of providing transparency, supporting consensus, and allowing for continuous improvement. Based on these promising results and the lack of application of this method on the pavement field, the present study explores the application of CBA for the selection of sustainable alternatives for pavement maintenance.

The pavement management field has already accepted and adopted other indicators aimed to integrate different aspects in the evaluation of maintenance alternatives. This is the case of Cost-Effectiveness, which integrates the economic cost and the benefits derived from a good pavement performance. Cost-Effectiveness is now extensively used to evaluate maintenance alternatives (Khurshid et al. 2009, 2011; Dong and Huang 2012; Dong Qiao et al. 2013; Torres-Machi et al. 2014; Mousa et al. 2018). However, there is not a generally accepted approach to integrate technical, environmental, and economic aspects in the evaluation of maintenance alternatives.

Objectives and Scope of the Study

The ultimate goal of this research is to develop a framework and explore the use of multicriteria decision-making techniques to formally incorporate sustainability into pavement management. In order to do so, this paper presents findings of recent projects that were conducted in Canada to incorporate sustainability in pavement engineering. The framework considered in this study ranks traditional and sustainable practices using a MCDM approach. In order to illustrate the capabilities of different MCDM techniques, a case study comparing pavement maintenance technologies using cold-in-place recycling and traditional solutions based on mill and overlay is analyzed. Particularly, two sustainable practices based on cold-in-place recycling are explored: Cold-In-Place Recycling using both Bitumen Emulsion (CIR) and Expanded Asphalt Mix (CIREAM). These technologies are compared with traditional mill and overlay (M&O) and mill and overlay using 20% of reclaimed asphalt pavement (M&O 20% RAP). In order to compare these technologies under a sustainable approach, three set of criteria are considered in the evaluation: environmental, technical and economic. While sustainability evaluations consist of environmental, economic, and social criteria, the umbrella of technical criteria was chosen in this study to reflect the priorities of transportation agencies conducting such evaluations. Although our technical criteria are not directly equivalent to social impacts, they do encompass certain social impacts such as curing time, which leads to user delays. While comprehensive social impacts of pavement management are excluded in this analysis, sustainability assessment requires the selection of appropriate measurable indicators that are relevant to stakeholders (Sala et al. 2015). These criteria are included in the decision-making process by the use of two MCDM techniques: Analytic Hierarchy Process (AHP) and Choosing by Advantages (CBA). The aim of this study is to better understand how to incorporate sustainability criteria in pavement management.

Methodology

To achieve the proposed objective, this study considered a four-step research methodology:

- Define the factors to consider in sustainable pavement management.
- Explore two different MCDM techniques (AHP and CBA) for the integration of sustainable criteria.
- Evaluate different sustainable technologies (based on cold-in-place recycling) and compared them with traditional practices based on: (a) mill and overlay and (b) mill and overlay using recycled aggregates.
- Perform a comparative analysis of the results obtained using AHP and CBA and recommend the most suitable MCDM technique for future implementation in sustainable pavement management.

Pavement Rehabilitation Technologies Evaluated

Mill and Overlay (M&O) is the simplest rehabilitation technology. It involves milling the existing surface and replacing it with a hot-mix overlay (TAC 2013). This study considers traditional M&O as well as mill and overlay with 20% of reclaimed asphalt pavement (RAP), in which 20% of the hot-mix overlay comprises of recycled materials (M&O 20% RAP). In both M&O and M&O 20% RAP, it was assumed that 100 mm of the existing surface is milled and a 100 mm hot-mix overlay is added.

Cold-In-Place Recycling using Bitumen Emulsion (CIR) involves cold-milling of the pavement surface and adding emulsified asphalt to mix with the RAP. Cold-In-Place Recycling with Expanded Asphalt Mix (CIREAM) is similar to CIR but uses expanded asphalt to mix with the RAP. CIR and CIREAM have low energy consumption because they do not require asphalt heating (Chan 2010). For this study, it was assumed that 50 mm of the surface is cold-milled and a 50 mm new overlay is added.

PROPOSED FRAMEWORK FOR THE SUSTAINABILITY EVALUATION OF PAVEMENT TECHNOLOGIES

This study proposes a sustainable evaluation considering, in an integrated manner, environmental, technical, and economic aspects. As depicted in Figure 1, different subcriteria are considered for each of these evaluations.

FIGURE 1

Although the proposed framework is applied to a case study comparing cold-in-place and traditional technologies based on mill and overlay, it is important to note that the method proposed for the sustainable evaluation could be similarly applied to other maintenance alternatives. The main goal of this study is not to derive general recommendations on the use of cold-in-place or traditional technologies, but to use the proposed framework for the analysis of different MCDM techniques aimed to enhance the sustainable management of pavements. A detailed description of each of these criteria and subcriteria is included in this section.

Environmental Evaluation

The purpose of the environmental evaluation is to determine a set of measurable and significant environmental impacts of each practice which allow for direct comparison in decision-making. The environmental effects were measured through the release of harmful atmospheric emissions by these practices as well as through the consumption of virgin materials. These impacts were selected for this study for their significant and measurable implications for human health, climate change, and waste generation.

Emissions

Pavement maintenance releases emissions of greenhouse gases and air pollutants through the production and processing of materials, transportation, and use of heavy equipment. These emissions contribute to climate change, form smog and acid rain, and have adverse effects on human health (Shindell 2015). Emissions were calculated for carbon dioxide (CO_2), a greenhouse gas, and four air pollutants: sulphur dioxide (SO_2), nitrogen oxides (NOx), particulate matter smaller than 10 microns (PM_{10}), and carbon monoxide (CO). Each of these four pollutants is classified as a criteria air contaminant by Environment Canada (2017).

PaLATE was used to determine emissions for these practices. PaLATE is a life cycle assessment (LCA) tool developed in the United States by the Consortium on Green Design and Manufacturing for decision-making in pavement management (Horvath 2007).

PaLATE users input data on the design, component costs, maintenance, and equipment usage of a proposed road. The tool uses this information to output environmental impacts and economic costs for the proposed design. Emissions in PaLATE are calculated using an emission factor which describes the average rate at which a particular activity or source releases a greenhouse gas or pollutant. For this study, these emissions factors were adapted to better reflect present conditions in Ontario, Canada. Details of these updates are provided as Supplemental Data. PaLATE users input data on a road design which is combined with the background data in the tool to calculate overall emissions for a proposed design.

Emissions were calculated for a hypothetical two-lane, one-kilometer highway located in Ontario, Canada. Table 1 provides the estimated emissions for rehabilitation of this highway for each of the practices considered in this paper.

As each of the pollutants considered has different effects on health and the environment, they cannot be directly compared with each other. *The Social Cost of Atmospheric Releases*, a study which quantified the effects of several greenhouse gases and pollutants, was used as the basis for developing a scale for the pollutants based on their relative social and environmental effects (Shindell 2015).

TABLE 1

Virgin material consumption

Material consumption is an important environmental consideration as it reduces waste and energy consumption. Moreover, the production of new materials is the largest source of emissions for pavement maintenance practices. For this study, the consumption of virgin materials for each practice was determined based on the thickness of the virgin asphalt overlay on the milled surface. Values of each of the alternatives under consideration are shown in Table 1.

Technical Evaluation

The technical evaluation of maintenance techniques is important for pavement managers and decision makers. For the technical evaluation, three factors are considered: performance, contractor experience, and curing time.

Performance

Different indicators can be used to assess the long and short term performance of maintenance alternatives, such as expected service life, roughness, rutting, and cracking. For the technologies considered in this study (M&O, M&O 20% RAP, CIR and CIREAM), previous studies have found similar performance both in the short and long-term (Lane and Kazmierowski 2005; Chan et al. 2009; TAC 2013; Lane and Lee 2014). Therefore, performance evaluation is not included in this study; however, it can be incorporated into this framework for comparing technologies with more distinct performance levels.

Contractor Experience

Lack of experience presents a significant barrier to the introduction of new technologies in the construction industry. Contractors are often reluctant to change construction practices as it requires the acquisition of new skills and adoption of new equipment to guarantee overall construction quality. Previous studies in the construction industry have identified resistance to change as one of the most important barriers for the introduction of new technologies or processes (Chan et al. 2017; Lines et al. 2017). Given this, one of the subcriteria considered in the technical evaluation of alternatives is contractor experience.

In order to compare alternatives, contractors' experience is assessed in terms of the years since the technology was first introduced in Canada. M&O has been widely used in Canada for paving asphalt roads since 1888 (Hudson et al. 1997; TAC 2013), so contractors have considerable experience with this technology. Canadian contractors also have relatively significant experience in the use of recycled aggregates (M&O 20% RAP). This technology was first introduced in Canada in 1978 and it is now common practice in Ontario (Sanchez 2014). Canadian contractors have some experience with CIR, as the technology was first introduced in Ontario in 1990, and the Ontario Ministry of Transportation has since successfully carried out over 75 CIR contracts (Lane and Lee 2014). On the other hand, CIREAM is a relatively new technology, as it was first introduced in Ontario in 2003 (Lane and Lee 2014).

Curing Time

Construction time varies widely from project to project, considering its dependence on many factors and is not directly linked to the performance of a technology. A relatively recent survey of transportation agencies' pavement preservation practices reported that the majority of the agencies used single-shift or overnight lane closures for treatment application (Smith and Peshkin 2011). To avoid unacceptable delays in weekday peak travel during daytime closures, highway maintenance projects in North America have typically used nighttime closures (Lee and Ibbs 2005). Society can benefit from accelerated road maintenance techniques that foster reduced traffic disruption and traffic delay, which translate into reduced user costs and fewer work zone accidents (Babashamsia et al. 2015; Smith and Peshkin 2011).

Unlike construction time, curing time can be directly linked to performance of technologies since inadequate moisture loss through improper curing may lead to premature failure of pavement structure. Their effects on tensile strength, dynamic modulus, stiffness, and rutting resistance of innovative technologies has been widely studied (Bhavsar 2015; Kim and Im 2011; Varamini 2016). The traditional M&O technique is the top choice based on this criteria, as it requires little to no time for curing. Thus, a roadway treated with M&O can be open to traffic almost immediately (Cuelho et al. 2006). For this study, 1 day for curing M&O with 20% RAP was selected. In the case of cold recycling technologies, the optimal curing period is usually up to 3 days and 14 days for CIREAM and CIR, respectively (Bhavsar 2015; Chan et al. 2009).

Economic Evaluation

The purpose of the economic evaluation was to determine the costs associated with each maintenance practice using a life cycle cost analysis (LCCA). LCCA is commonly used in pavement management systems by transportation agencies to determine the costs of a proposed design over a longer period which could range from 20 to 50 years (TAC 2013). LCCA accounts for the varying service life of different rehabilitation practices.

The costs for each maintenance practice were sourced from the 2010 MTO Highway Costing System (Chan 2010). The service life of all maintenance practices is considered to range from 12 to 15 years (TAC 2013). As the expected service life of all practices considered is the same, only the cost for one rehabilitation treatment was considered in the analysis.

Summary of Alternatives Evaluation

Based on the criteria proposed in this study, Table 1 summarizes the characteristics of each of the alternatives under evaluation. Although the proposed framework could be generally applied to different situations, it is important to note that the actual values of some of the criteria/subcriteria considered in this study (e.g. contractor experience) are specific to Canada and should not be generalized.

MULTICRITERIA DECISION MAKING (MCDM) TECHNIQUES

The selection of a feasible maintenance technique involves the consideration of multiple factors which are often conflicting and cannot be directly compared. For pavement engineers and agencies, choosing maintenance techniques based on cost, performance, and environmental criteria is a complex decision. Transportation agencies often approach this problem using the subjective judgement of engineers, through the use of a decision tree or performance modelling, but often forego considering the sustainability of the alternatives (Smith and Peshkin 2011; Varamini and Tighe 2015). To evaluate the sustainability factors of the four maintenance technologies considered in this study, two multi-criteria decision making methods (MCDMs) are used to compare and rank each maintenance alternative based on factors addressing economic, technical, and environmental implications.

Analytic Hierarchy Process (AHP)

The analytic hierarchy process (AHP) is a structured analytical method developed in the 1970s by Saaty (2008). It is an established prioritizing tool used for solving the choosing problem, comparing alternatives, ranking best practices, and making multi-criteria decisions when both qualitative and quantitative factors must be considered. AHP helps decision makers select the alternative that best suits their goal. It is a rational framework designed for structuring a decision problem into a comprehensive one-on-one comparison of alternative solutions by quantifying the attributes of the alternatives and relating those attributes to an overall goal (Farhan and Fwa 2011; Smith and Tighe 2006). AHP helps the decision maker to intuitively solve a complex choosing problem that may involve environmental, social, economic, and technical factors.

AHP shows strengths (such as the calculation of consistency ratio to assure decision-makers and its ability to incorporate both qualitative and quantitative criteria) and limitations (such as the complex and time-consuming implementation and computation when increasing the number of criteria considered in the evaluation) (Whitaker 2007; Saaty et al. 2009; Kabir et al. 2014; Torres-Machi et al. 2015). AHP has been selected in this study not because of the strengths of the method, but because it is extensively used in infrastructure management. A comprehensive literature review developed by Kabir et al. (2014) on the use of MCDM techniques in infrastructure management showed that, other than the combined methods, the most commonly applied method was AHP. Kabir et al. (2014) found AHP is especially applied in the management of transportation infrastructure (53.9% of the times, followed by ELECTRE, which is applied in 8.9% of the reviewed papers). Given the importance of AHP in MCDM applied to transportation management, authors believe AHP is representative of current efforts in incorporating multiple criteria in pavement management and is therefore the technique considered in this study to be compared with CBA.

AHP uses a ratio scale to evaluate and rank the alternatives for the decision to be made. It involves the following phases:

(a) Identify the goal and model the decision to be made by creating a hierarchy consisting of the overall goal at the top, a set of criteria, and a set of alternatives at the bottom. The criteria may be further broken into many other levels of sub-criteria. Figure 1 depicts the hierarchy structure for this study.

(b) Construct a pairwise comparison matrix (PCM) for alternatives and for criteria. The PCM was developed from the one-to-one comparisons made for all possible pairs of alternatives with respect to the importance or preference level of all pairs to each criterion. PCM of alternatives were calculated for all factors in Table 1. Table 2 provides the value scale used for comparison of all pairs of alternatives.

(c) Normalize the PCM and compute priority weights for the alternatives by averaging the row elements.

(d) Construct PCM for factors (criteria and sub-criteria) similar to the procedure in phase (b) and (c). Compare all pairs of criteria with respect to the AHP value scale, determine factors PCM, and calculate priority weights for each criteria and sub-criteria. The PCM for emission factors was created using an importance value scale based on Shindell (2015)'s social cost estimates for each factor. Equal importance values for the main criteria (environmental, technical and economic) were considered in the base case. Different scenarios of importance level awarded to the main criteria were analyzed in 6 cases to test the sensitivity and the effects of criteria importance level on the overall weights and ranking of alternatives.

(e) Finally, calculate the overall alternative priority weights and ranking by summing up and multiplying alternative priority weights with respect to each criterion by the corresponding criterion's priority weights.

TABLE 2

AHP Process Example

This section provides an example of the process followed in this study to calculate the pairwise comparison matrix (Step b of the AHP process) and normalization (Step c of the AHP process) under economic cost criteria. A similar procedure was followed for all the other criteria/subcriteria considered in this study.

In order to build the pairwise comparison matrix, we first need to calculate the difference between the alternatives' criteria scores (Table 1). Pairwise comparisons are then assigned based on this difference and the value scale of criteria defined in Table 2. For the economic cost criteria, the values of the first column of the pairwise comparison matrix will be determined as follows:

- Compare M&O to M&O, equal cost. Based on Table 2, assigned value = 1;
- Compare M&O 20% RAP to M&O, reduces cost (∆) of $35,460/km. Based on Table 2 and because 0 > ∆ > -3.8k, then assigned value = 3;
- Compare CIR to M&O, reduces cost (∆) of $75,813/km. Based on Table 2 and because ∆< -66k, then assigned value = 7;
- Compare CIREAM to M&O, reduces cost (∆) of $44,193/km. Based on Table 2 and because -3.8k>∆> -66k, then assigned value = 5.

This process is repeated for Columns 2 and 3 of the matrix to obtain the pairwise comparison matrix (Table 3).

TABLE 3

Priority weights for the alternatives are obtained by normalizing the matrix and calculating row averages. First, the pairwise values in each column are totaled, as shown in Table 3. Second, the individual values in each column are divided by the total (Table 4). Third, the values are averaged along each row to form the priority weight for the alternatives, as shown in Table 4.

TABLE 4

Step (d) follow a similar procedure to the one shown for steps (b) and (c). Finally, the alternative with the largest priority weight is ranked first and the alternative with the smallest weight is ranked last.

Choosing by Advantages (CBA)

CBA, introduced by Shur (2009), is a decision-making technique based on comparing the advantages of alternatives. In CBA, decisions are solely based on the advantages. An advantage is a beneficial difference between the attributes of two alternatives. The process followed by CBA is: (1) identify alternatives; (2) define factors, that is, the differentiating aspects that will be considered in decision-making; (3) for each factor, summarize the attributes (characteristics) of each alternative; (4) identify the least preferred attributes for each criterion and then determine the advantage of each alternative relative to that least-preferred one; and (5) assess the importance of each advantage (IoA) (Arroyo et al. 2013).

Considering the factors proposed in this study, Table 5 shows the sustainability evaluation of maintenance alternatives. The importance of each advantage (IoA) was assessed based on the advantages of each alternative considering equal importance to technical and environmental aspects. Economic evaluation is not included in Table 5 because CBA considers costs in a second stage, when the agency has to decide whether it is willing (or not) to pay more for an alternative having higher advantages.

TABLE 5

CBA Process Example

This section provides an example of how the importance of alternatives (IoA) were calculated. A specific example from the PM_{10} subcriteria is provided below.

First, the attributes (characteristics) of the alternatives are summarized. As a result of this process, values shown in Table 1 are expressed as the attributes of each of the alternatives in Table 5. Then, the least and most preferred attributes for each criterion are defined. These values are highlighted in Table 5 by using italic font for the least preferred alternative and bold font for the most preferred attribute. Considering the evaluation of PM_{10}, the criteria for this attribute is “the lower, the better”. Therefore, the most preferred alternative is CIREAM, as it produces the lowest PM_{10}. Meanwhile, the least preferred alternative in terms of PM_{10} production is M&O. For each of the attributes, the advantage of each alternative is calculated as the difference in attribute values between the alternative under evaluation and the least preferred alternative. For instance, the advantage of CIR in terms of PM_{10} is the difference between the PM_{10} of CIR and the PM_{10} of M&O (which is the least preferred alternative for this attribute). As shown in Table 5, the advantage of CIR in terms of PM_{10} is 288.2 – 145.6 = 142.6 kg.

As a final step, the importance of each advantage (IoA) is determined based on the value of the advantages and the importance given to the different criteria. At this point, it is worth mentioning that the IoA was assessed on a 0-100 scale with a final score rounded to the nearest 25. In the case of PM_{10}, the advantages produced by CIR and CIREAM are similar (61 and 68% reduction compared to M&O, respectively). Therefore, the IoA of this attribute is considered to be the same for both options and equal to 75. As M&O reduces PM10 emissions only by 21%, the assigned IoA in this case was 25.

RESULTS AND DISCUSSION

Multicriteria Approach to Sustainability Evaluation

Figure 2 shows the different rankings obtained from the sustainability evaluation of maintenance alternatives using the two MCDM techniques explored in this study: AHP and CBA. Based on AHP, the most preferred alternative would be CIR, followed by CIREAM, M&O 20% RAP and M&O. As stated before, AHP and CBA differ in the way cost is considered in the evaluation. Whereas cost is usually considered as one of the criteria in AHP, CBA considers financial implications after attributes of alternatives have been evaluated. This is the reason why CBA results are shown in three stages in Figure

2: “CBA” shows the results of the total importance of advantages obtained in Table 5, while “CBA + cost” shows the effect of including cost in the evaluation considering two scenarios reflecting the agency budgetary capacity: the scenario analyzing “low budgetary capacity” simulates an agency who is not able or willing to pay more to use more sustainable solutions; whereas “high budgetary capacity” simulates an agency able or willing to spend more resources in more sustainable solutions.

FIGURE 2

What stands out in Figure 2 is that cost data is only significant when choosing between cold-in-place alternatives (that is, between CIR and CIREAM). Because in this example CIR costs less but also has lower advantages than CIREAM, the choice is not obvious. The decision is whether the transportation agency is willing to pay more money on an alternative (CIREAM) that provides more advantages (mainly based on the reduced curing time) than the CIR alternative. This decision will mainly depend on the agency budgetary capacity. What is evident from this example is that choosing M&O or M&O 20% RAP does not make sense because CIR or CIREAM cost less and have advantages that are more important.

As can be seen from Figure 2, the sustainability evaluation obtained using AHP and CBA is similar when cost is included in CBA analysis and the budgetary capacity of the agency is low (cases labelled as “AHP” and “CBA + cost with low budgetary capacity” in Figure 2). The advantage of CBA is that it allows for distinguishing cost from the analysis and deciding whether the agency is willing to pay more to use CIREAM over CIR. This approach is probably more similar to actual engineering decisions, where stakeholders look for the best solution within their budgetary capacity.

Importance of Sustainability Criteria

This section illustrates the results of sensitivity analysis conducted to highlight the effect of the importance value allocated to each criteria and discrepancies in importance judgement on ranking the pavement alternatives using the two different MCDMs techniques. This analysis will complement the results shown in the previous section, where technical, environmental and economic evaluation were assigned equal importance. Three importance categories – high (10 points), medium (5 points) and low (1 point) were considered for all criteria in the six importance judgement scenarios shown in Figure 3. For the cases (1&2), cases (3&4), and cases (5&6) the criteria environmental, economic and technical respectively had low importance. In cases 1 and 4, medium importance was given to technical criteria, while the economic criteria in cases 1 and 5 had high importance.

FIGURE 3

The importance of each of the criteria were compared using a pair-wise comparison matrix and normalized (following a similar procedure to the one explained in the example application of AHP). As a result of this process, the relative weight of the criteria in the sensitivity analysis are 72%, 20%, and 8% when the importance of the criteria is high, medium, and low, respectively. In the base case, where all the criteria are given the same importance, all criteria have a relative weight of 33%. Considering these weights of relative importance between criteria, the AHP and CBA process described before were computed for each of the six cases.

The results of the AHP and CBA sensitivity analysis of all six cases are presented in Figure 4. AHP and CBA show identical ranking for each technology in all case scenarios except in case 6, where CIR and CIREAM change ranks, CIREAM is ranked first with AHP while CIR is ranked first with CBA.

The level of importance awarded to environmental, technical, and economic criteria and the different rankings obtained reflects the importance of environmental considerations in selecting most sustainable maintenance practice. Cases 4 and 6, where environmental criteria were given higher importance, show the potential effects of considering environmental implication of the alternatives. In these cases (4 and 6), solutions with lower environmental burdens (CIR and CIREAM) were preferred to traditional technologies (M&O and M&O 20% RAP).

FIGURE 4

The two scenarios where environmental criteria were given low importance (cases 1 and 2) show very different results. Although the decision in case 1 depends on less than 10% for environmental criteria, CIR and CIREAM ranked high in case 1 where 72% of the decision was dependent on the economic criteria. Both technologies have higher environmental performance and are less expensive than M&O alternatives. CIR and

CIREAM are relatively new technologies and have longer curing periods, thus the effects of giving higher importance to these factors is reflected in the decision of case 2, which depended largely on the technical criteria. The decision in case 2 may change when more factors are considered under the technical criteria.

Similar contrasting effects are show in cases 3 and 5, both considering medium priority to environmental criteria. The result in case 5 is like case 6 as both cases consider technical criteria has a low importance in their decision. The ranking of alternatives in case 3 is similar to case 2. Given that 72% of the decision in both cases depended on technical performance, and the contractor's experience in M&O is very high and the curing time of M&O is usually a day or less, M&O is ranked first in both cases.

CONCLUSIONS

This study analyzed different approaches to assess the sustainability of pavement management decisions. In order to do so, new technologies using cold-in-place recycling (CIR and CIREAM) were analyzed and compared to traditional solutions based on mill and overlay (M&O and M&O 20%RAP). Two multicriteria decision making (MCDM) techniques were explored to integrate technical, environmental, and economic evaluation: AHP and CBA. Results obtained using both techniques are compared, including a sensitivity analysis on the importance of criteria weights in the sustainability evaluation of maintenance alternatives.

This study shows AHP and CBA provide consistent recommendations. That is, the sustainability evaluation obtained using both techniques are very similar. However, CBA presents the advantage of separating cost from the analysis, allowing the agency to decide whether they are willing to pay more to use more sustainable alternatives. This is a significant research finding, as this approach is probably more similar to actual engineering decisions, where stakeholders look for the best solutions within their budgetary capacity. Given the wide spread use of AHP not only in pavement management but in infrastructure management in general, this finding has significant implications for engineering practice, which may benefit from the application of CBA in MCDM problems.

The results from this study analyzing different pavement technologies in Canada show that CIR and CIREAM are equivalent to M&O in performance and cost less due to lower virgin material consumption. However, the Transportation Association of Canada Guide lists M&O as the more commonly used practice (TAC 2013). As discussed, contractor experience may be one factor which contributes to this. Future research should focus on existing use of sustainable rehabilitation practices and identifying barriers to further implementation of these practices.

In this study, three criteria (technical, environmental, and economic) were included for evaluating the sustainability of alternatives. Each of these criteria was assessed in terms of a set of subcriteria including emissions, virgin material consumption, curing time, and contractor experience, among others. Although our technical criteria encompass certain social impacts such as curing time, which leads to user delays, more research is needed to account for social aspects and therefore fully acknowledge the three pillars of sustainability (economic, social, and environmental). Further work is also needed to incorporate existing barriers for the implementation of sustainable technologies in the proposed sustainability evaluation.

SUPPLEMENTAL DATA

This paper includes an appendix with supplemental data comprising the updated emissions considered in PaLATE. Appendix S1 and Tables S1–S4 are available online in the ASCE Library (www.ascelibrary.org).

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