APPROACHES TO WEIGHTING WITHIN TRANSPORTATION INFRASTRUCTURE SUSTAINABILITY ASSESSMENT

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ABSTRACT

Sustainability assessment systems are increasingly being used as tools to encourage more sustainable practices in the provision of civil infrastructure. In several cases, agencies have developed unique sustainability assessment systems, or adopted modified versions of sustainability assessment systems currently available for a wider market. In any case, the nature of sustainability as a multi-criteria problem requires that preferences must be expressed in order to determine optimal outcomes for more sustainable decision making. These preferences are typically expressed in terms of weights applied to the various criteria in sustainability assessment systems, and the techniques used to derive these weights, as well as how the weights are applied, varies across the many different systems. In this paper, the authors review how weighting is typically included in sustainability assessment systems and make recommendations about how some of the incongruities between the various systems can be understood. Furthermore, the authors present the results from a pilot study which was conducted using an online survey system, and then use the results to make recommendations regarding future surveys designed to elicit weights from such a group.

INTRODUCTION

The sustainable provision of transportation infrastructure requires a paradigm shift from traditional decision-making techniques based mainly on economics to methods which account for the resulting impacts on environmental and social systems *(1)*. This also includes modifying organizational policies to reflect sustainability in the strategic objectives of the various transportation agencies. The European Conference of Ministers of Transport (ECMT) described the paradigm shift more broadly as treating the transportation sector as a means of promoting political objectives (e.g., promoting sustainable development), as opposed to treating it as a self-contained sector within an agency *(2)*. This shift requires active cooperation from both the political sectors and the transportation agencies in charge of managing the infrastructure. Holden *(3)* discussed the relationship between the technical sector, public sector and the political sector, and how the implementation of sustainable management should include indicators to act as intermediary communication tools between the sectors.

Several approaches exist for use by transportation agencies when developing and implementing plans for sustainability. For example, the US Federal Highway Administration (FHWA) released the Transportation Planning for Sustainability Guidebook in 2011 *(4)*. The FHWA report also presents the results of a survey designed to gauge the level of implementation of sustainable practices at each US state Department of Transportation (DOT), and several case studies related to the development and implementation of methods and tools to support sustainability. Another method to guide development and implementation of sustainable practices is presented in Barrella et al. *(5)*. An important aspect that is addressed in Barrella et al. *(5)* is the concept of organizational design, and how the structure of an organization can influence the outcomes of implementing sustainable practices. Furthermore, Mansfield and Hartell *(1)* evaluated sustainability plans from several transportation agencies in the United States, and found that the majority of the implementations that were studied have had positive impact related to sustainable outcomes when compared to the alternative of no plan being implemented.

One method which transportation agencies are employing to shift focus towards more sustainable practices is by developing and implementing sustainability assessment systems. These sustainability assessment systems have been developed both by industry, or agencies which manage transportation networks. For example, the IllinoisDOT's Livable and Sustainable Transportation system (I-LAST) was developed in an effort to, "…incorporate a broader range of issues into the development and completion of state highways" *(6, pg 4)*. The New York DOT's Green Leadership in Transportation and Environmental Sustainability system (GreenLITES) was developed in an effort to improve the quality of transportation infrastructure in ways that minimize environmental impacts, including the depletion of irreplaceable resources *(7)*. Given that the use of sustainability assessment systems has been shown to influence decisions made about projects, such as influencing design and material procurement *(8)*, it is expected that the development and implentation of similar sustainability assessment systems will continue to grow as additional agencies seek to develop more sustainable practices.

An important property of sustainability is that it is a multi-objective problem in which multiple criteria are defined based on the objectives, and then parameters are used to define the system with regard to each criterion. Given that the optimality of solutions to functions with multiple objectives is generally not unique, some preferences must be expressed by decision makers in order for a final solution to be reached *(9)*. The most common form of expressing preferences within infrastructure sustainability assessment is through assigning relative weights to each parameter in the assessment. However, these weights are not unique within a group of decision makers, and the variability within the preferences expressed by many decision makers has the potential to significantly impact the decisions made. In an effort to better understand how weights are applied and interpreted in sustainable transportation infrastructure assessment; this paper examines weighting techniques used in current infrastructure sustainability assessment systems. Additionally, this paper presents a pilot study which analyses weighting preferences obtained from a large group of transportation professionals with regards to the cost, condition and energy consumption resulting from the construction and use of road pavements.

Objective

The objective of this paper is to review weighting techniques used in determining the relative importance of sustainability criteria for transportation infrastructure, and examine variability within relative weights assigned to parameters related to road pavement management decisions. Parameters are defined as qualitative (indicators) or quantitative (metrics) factors which define the state of a sustainable system, and criteria are defined as areas in which objectives are defined in order to judge progress towards more sustainable systems. Furthermore, this paper presents a pilot study on gathering data to determine the weights of sustainability criteria. Results were obtained from a survey designed to collect relative weights of each criteria from transportation professionals, which represent the relative importance of parameters between the various criteria.

BACKGROUND

Given the significant investments made each year to maintain and expand public transportation infrastructure, the public has a vested interest in future goals and decisions made about infrastructure beyond such attributes as capacity expansion or condition. One important role that the public, in the form of elected or appointed representatives, plays in the sustainability of transportation networks is advocating for policy implementations that drive agencies towards more sustainable outcomes. Ideally, these policies are then reflected in decisions that are made regarding the transportation network, and the policies influence the relative importance of outcomes. From a decision making perspective, the relative importance of outcomes are translated into weights which are applied to each criteria under consideration. Given that decision making within sustainable transportation infrastructure is a multi criteria problem *(10)*, the weights which represent the relative importance of the criteria are used to choose the maintenance or development option which results in the most ideal outcomes.

One example of including the input of various stakeholders into policy decisions is discussed in Ananda and Herath *(11)*, which presented a method for assessing stakeholder risk preferences when evaluating land use alternatives for forest management. A benefit cited by the researchers was that the preferences of the many stakeholders could lead to a better understanding of conflicts in preferences as management decisions are being considered. Many more papers relating to transportation infrastructure have proposed techniques to combine stakeholder preferences in terms of maximizing overall utility *(12, 13)* or by using weighting and preference rank aggregation *(14, 15)*.

The need to involve input from many stakeholders in environmental decision-making and resulting benefits from doing so has been demonstrated through several undertakings *(15, 16, 17)*. However, some challenges have been recognized when involving some stakeholders in technical decisions, such as clearly conveying the problem and transparently stating the uncertainties to a general audience. In order to address the varying challenges to public involvement in environmental policy and decision-making, the US National Academies of Science sponsored a study conducted through the National Research Council

(NRC) that culminated in a report with several recommendations *(16)*. The first recommendation from the NRC report is that public involement should be fully incorporated within environmental assessment and decision-making. This paper takes a step in the direction of including more broad public involvement in sustainable transportation decision making by discussing how preferences can influence decision making, and using the results from a pilot to make recommendations about obtaining preferences from a group of stakeholders.

Weighting Methods Used in Current Assessment Systems

Sustainability assessment systems contribute an important element towards informing more sustainable practices within an agency. However, weighting methods within current road sustainability assessment systems are not standardised. Weighting is performed in order to indicate the relative importance of performing a certain action or set of actions such as Greenroads *(18)*, or to indicate the relative importance of outcomes such as BE^{2}ST-in-Highways *(19)*. The method for weight elicitation also varies between each sustainability assessment system. A subset of road and road pavement sustainability assessment systems are described below along with the method by which they elicit relative weights within each sustainability criterion.

Greenroads™

Greenroads is a point based rating system that is designed to quantify sustainable practices within the design and construction of roadways *(18)*. In this context, roadway refers to not only the pavement structure, but the entire road system (e.g., road signs and lighting, etc.). Greenroads evaluation includes a set of eleven project requirements with no point assignments which must be met in order to be considered for assessment, as well as 37 voluntary credits which are assigned scores from one to five. The one-to-five scale is cited as a way to avoid placing too much emphasis on any one category by limiting the possible range of values. After completion of the eleven requirements is verified, the summation of the scores (i.e. credits received) over each category is taken as a project score, and then a certification level is assigned to the project *(20)*.

The development of the assigned number of credits for each voluntary category is outlined in Muench and Anderson *(21)*. In this case, the scores are treated as weights which reflect the relative importance of each category towards more sustainable outcomes. For example, because the construction phase is relatively short, and the environmental impacts of the construction phase are relatively small related to other phases in the roads' lifecycle, the sum of credits for all construction activities are lower than credits for other categories such as Access and Equity. To determine the weights, the developers of Greenroads started by assigning the least impactful activities a value of one, and then the remaining categories were weighted accordingly based on their impacts found in literature.

CEEQUAL

CEEQUAL (Civil Engineering Environmental Quality), which was developed in the UK, is a credit based evaluation framework designed for use within all infrastructure projects. CEEQUAL is designed to assess the sustainability of a project based on nine categories focused on the social and environmental aspects of sustainability *(22)*. Unlike Greenroads, the CEEQUAL assessment is typically performed at the end of the project. The assessment is typically conducted through a two-step process; (1) an assessor employed by the project team determines which questions are applicable to the particular project and develops a score, and (2) an independent verifier then reviews the points, along with the supporting documentation, and awards the final certification *(23)*. Additional details regarding the history and development of CEEQUAL can be found in CEEQUAL *(22)*. A review of CEEQUAL rated projects can be found in Johansson *(8)*.

Similar to Greenroads, the points within CEEQUAL act like weights which reflect the relative importance of particular categories. However, the weights derived in CEEQUAL are based on input from large groups of stakeholders in the country where the assessment is conducted. These weights are updated when the version of CEEQUAL is updated. The weighting is conducted by first assigning a value of ten to all criteria. Then the criteria are compared using ten as a mean value, twenty as a value representing maximum importance, and one as the minimum value for relative importance. An average is then taken over all responses for each category to obtain the final weights.

BE²ST-in-Highways™

BE²ST-in-Highways (Building Environmentally and Economically Sustainable Transportation-Infrastructure-Highways) was developed by the Recycled Materials Research Institute *(24)*. The main objective of BE²ST-in-Highways was to quantify the impact of using recycled materials in construction. BE²ST-in-Highways is composed of two layers, a mandatory screening layer which is used to ensure that the project conforms to all regulatory standards, and a judgment layer which includes the calculation of nine metrics related to environmental and economic assessments *(19)*. The BE²ST-in-Highways assessment measures relative sustainability, which means that the design alternatives must be compared to a conventional pavement design. The results of the environmental and economic calculations are then compared to a certain set of goals to determine the degree of compliance on a scale of zero to one.

Unlike the previous sustainability assessment systems described in this paper, weighting between the parameters is optional. Each of the parameters are scaled between one and zero based on their degree of achievement to a particular goal (derived from policy objectives or literature), and, if weighting is not performed, it is assumed that all parameters are equally preferred. If weighting is chosen, then it is performed using the analytical hierarchy process (AHP, *(25)*) by conducting a set of pairwise comparisons. Scoring is performed, and the results are shown in a plot in order to visualize the compliance towards a set of goals.

Greenpave

Greenpave is a pavement sustainability rating system which was developed by the Ontario Ministry of Transportation, and outlines very specific actions in order to obtain points towards a sustainability score *(26)*. Similar to Greenroads and CEEQUAL, Greenpave is a point based system, and the amount of obtainable points represents the degree of importance for a specific objective relative to the other objectives, essentially reflecting its weight. Each objective is accompanied by clearly defined action steps which need to be completed to obtain the points, or a subset of the points, associated with a particular objective. The strategies and goals were based on other sustainability assessment systems, as well as a sustainable pavement workshop which brought together many stakeholders to discuss techniques and policies which can contribute to pavement sustainability *(27)*. Points (representing relative weights) were developed based on literature and feedback from various stakeholders.

Critique of Weights in Sustainability Assessment Systems

Although the review presented within this section is not exhaustive of all infrastructure sustainability assessment systems, it is representative of how weights are applied within similar systems. In general, there are two types of weights employed by current sustainability assessment systems; (1) weights which express preferences of certain objectives relative to other objectives (e.g., CEEQUAL), and (2) weights which express the contribution of certain activities towards meeting certain goals (e.g., Greenpave). Although these two weighting methodologies are treated as exclusive in modern sustainability assessment systems, it can be argued that both types of weights should be employed at different stages within the same sustainability assessment. To demonstrate this, the structure of a sustainability assessment as a decision problem is shown in Figure 1.

Many of the sustainability assessment systems used in transportation infrastructure do not directly follow the structure shown in Figure 1, but instead link some sub-processes to higher level objectives directly. For example, in systems such as Greenroads and Greenpave weights are placed directly on the responses or activities, and it is assumed that the degree of implementation of a response or activity is directly correlated to the degree of improvement towards particular means objectives. This is analogous to improving individual components of a system and assuming that the entire system as a whole is improved. Thus, the calculation of specific indicators is not part of the assessment.

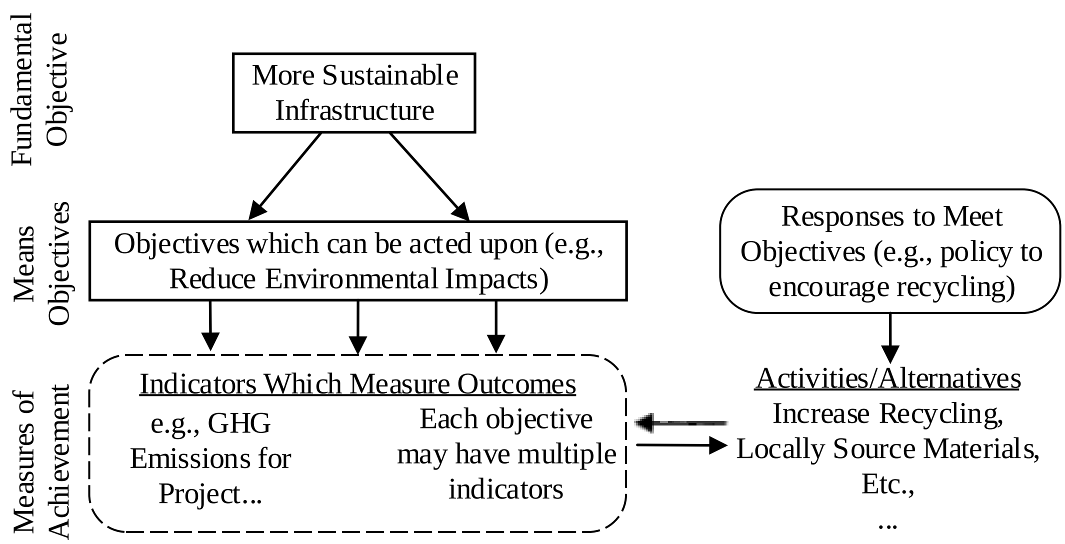

FIGURE 1 Structure of a Sustainable Objective Hierarchy for Decisions

Each means objective, as shown in Figure 1, may have multiple indicators for which a level of achievement of the objective may be measured, and each of these indicators can be weighted to define their relative contribution to these objectives. These weights are more synonymous with the weights employed in the Greenroads systems in that Greenroads weights activities relative to their contributions towards specified goals or objectives. For example, if a means objective is stated as maintaining healthy water resources, then the indicators which describe this may be any combination of eutrophication, water use and acidification (among other potential indicators). Each of these indicators can be weighted in order to signify their relative impact on healthy water resources.

Additionally, the importance of each means objective towards the fundamental objective must also be established, which requires some level of preferences to be expressed, which is typically in the form of relative weights. This is more synonymous with the weights employed in the CEEQUAL method. For example, if ‘maintain healthy water resources’, ‘maintain a healthy climate’, and ‘maintain healthy people’ are used as more generalized means objectives, their relative importance to the overall objective of sustainability would need to be assessed in order to quantify the impacts of decisions on sustainability. The application of the two types of weights to a sustainable decision problem is demonstrated in Figure 2.

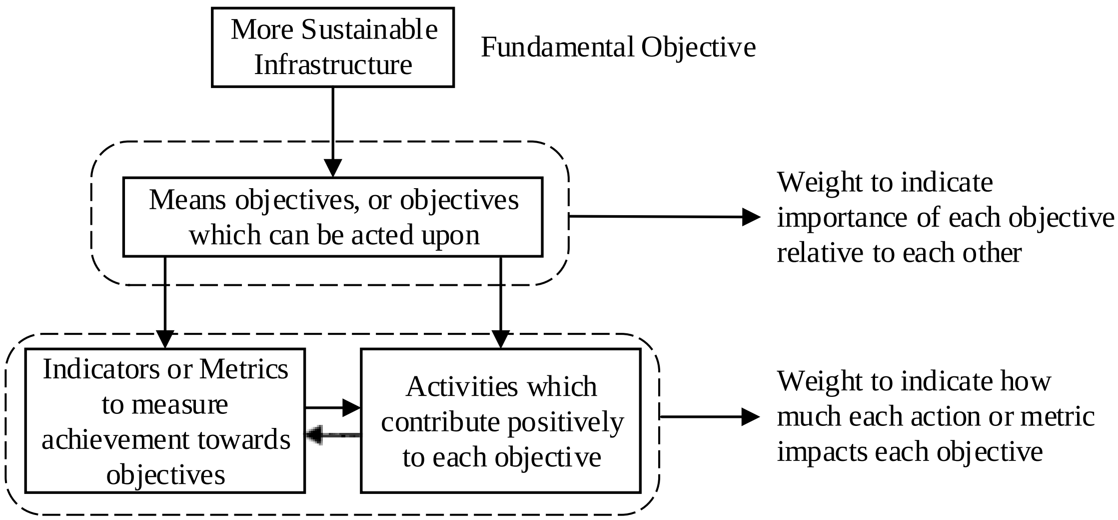

FIGURE 2 Applying Weights in a Sustainable Decision Problem

The development of the two types of weights discussed previously requires different approaches. Whereas the weights which link indicators (or responses) to means objectives may potentially be developed analytically (i.e. by determining how each indicator contributes to the objective relative to other indicators), the weights linking the means objectives to the fundamental objective must express human preferences. This is because the importance of each means objective relative to other means objectives, for example the importance of human health relative to economic prosperity, must reflect human values and judgment. Furthermore, the preferences expressed by different stakeholders are expected to be different, which may lead to different responses being considered more or less important. In order to further explore the linkages between these objectives, a survey was designed which asked transportation professionals to express their preferences between three objectives. The next sections of this paper describe the survey and survey results.

PILOT STUDY ON WEIGHTING MEANS OBJECTIVES

In an effort to explore the potential challenges of obtaining weights for means objectives (the second level of objectives in Figure 1 and Figure 2), a survey was designed and distributed to transportation professionals throughout the US. Sustainability includes considerations for economic systems, social systems and environmental or ecological systems, and improving the quality of each of these systems constitutes what is typically referred to as the triple bottom line of sustainability. The survey results presented in this paper represent two aspects of the triple bottom line of sustainability, economic and environmental impacts. The third aspect of the triple bottom line, social impacts, is not explicitly discussed in this paper, but it is recognized that transportation facilities are directly related to the quality of life within countries *(28)*. The results are expected to provide insights into how future preference elicitations regarding sustainable objectives should be performed.

Assessment Methodology

A survey was designed and distributed among transportation professionals that work within the field of infrastructure management in order to capture their preferences. The survey was built using an online based platform so that the survey could be distributed via email using a link to a particular website which contained the survey questions. The answers were recorded anonymously and stored in a database. Three parameters were used in the assessment; costs, pavement condition and energy consumption. Condition has economic implications, as well as consequences related to user satisfaction and user costs. Energy consumption was used as a proxy variable for environmental impacts.

The survey was designed in four sections. The first section was one question to determine the approximate length of time the respondent has worked in the field of infrastructure management. The second section included two questions related to obtaining weights for each of the three parameters. The first question of section two simply asked the respondent to rank the three parameters in order from most important to least important. The second question (Figure 3) was designed to gauge the relative weights of each parameter using the AHP. The third section consisted of four questions to obtain certainty equivalents for each of the parameter. The questions in the third section were more time intensive, and discussed scenarios in which the respondent was asked to choose a certain value that would make them indifferent between their choice, and a risky choice. The results from the third section are not discussed in this paper, but can be found in Bryce *(29)*. The final section included one question which asked the respondent to indicate their level of confidence in their responses, as well as a comment box for further input from the respondent.

Please compare your preferences about the costs of maintenance related to condition and energy consumption (used to determine global climate change impacts).

Choose the option that best fills in the blank for the corresponding statement

	Extremely less important	Very Strongly less important	Strongly less important	Moderately less important	As Important	Moderately More Important	Strongly more important	Very Strongly more important	Extremely more important
I consider costs (blank) related to energy consumption.	○	○	○	○	○	○	○	○	○
I consider condition (blank) related to costs.	○	○	○	○	○	○	○	○	○
I consider energy consumption (blank) related to condition	○	○	○	○	○	○	○	○	○

FIGURE 3 Question to Weight Using the AHP

A number of methods are available that can be used to evaluate the weights applied to various criteria or parameters, and an overview of many of the techniques can be found in Choo et al. *(30)*. The weighting technique associated with the AHP developed by Saaty *(25)* was used to determine the relative weights for this work. The AHP has proven to be a powerful and thorough method when comparing multiple criteria across multiple people in business and economic decisions, particularly when little prior information is known regarding some criteria (e.g. environmental sustainability) *(31)*. The basis for AHP is the pairwise comparisons made through the various criteria and parameters, and consistency within the responses can then be demonstrated mathematically. Consistency can be seen in terms of the following example; if I prefer a 2 times more than b, and I prefer b two times more than c, it goes to follow that I should prefer a four times more than c. Thus, saying I prefer a three time more than c would be considered inconsistent. However, because not every decision maker can be expected to follow perfectly rational preference values, some level of inconsistency is allowable.

Results

The survey was distributed to approximately 60 DOT personnel from agencies throughout the US that work within pavement and infrastructure management, with at least one person in each state DOT contacted. The survey was also distributed to approximately 20 researchers and consultants in the field of infrastructure management. Of the potential respondents, only 38 responded to the survey. Upon review of the results, only 30 of the respondents completed the first two sections to a level where the weighting preferences can be evaluated. The average respondent recorded between five and ten years' experience in pavement management, with the minimum being 5 years and the maximum being greater than 15 years.

The results for the ranking and weighting of the parameters are shown in Figure 4 and Figure 5. In general, condition was ranked and weighted the highest. An interesting result is that cost was ranked the second most important by a significant margin, but the mean of the weights of cost and energy consumption are very similar (0.37 and 0.33, respectively). This demonstrates the fact that ranking relative parameters does not necessarily preserve the range of preferences in the outcomes (i.e., preferring one objective more than the other does not provide a degree of preference between the two). In other words, using ordinal results to derive the weights will not provide adequate data to make the best decision.

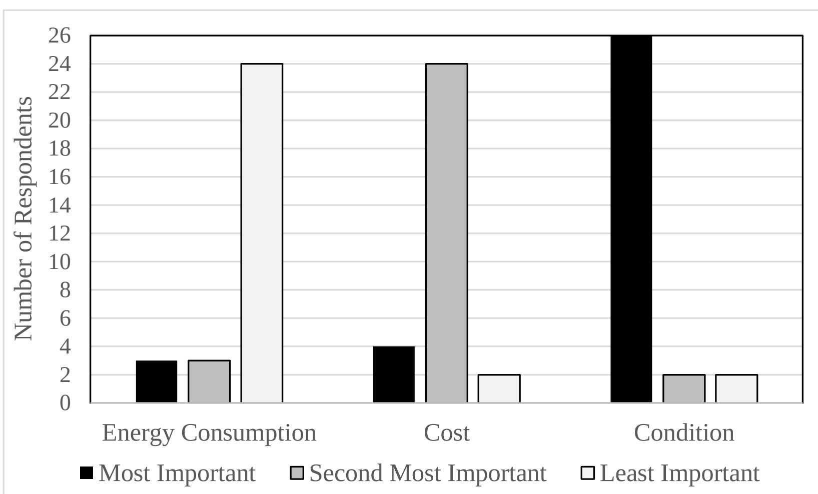

FIGURE 4 Results of Directly Ranking the Parameters

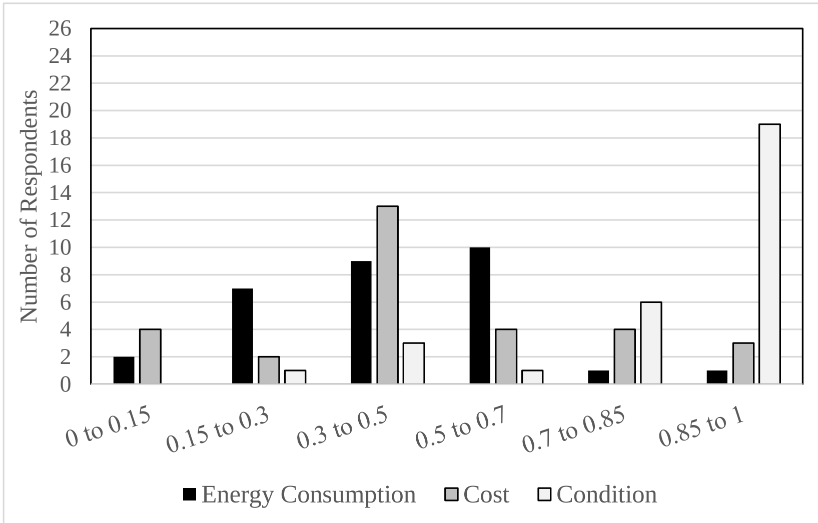

FIGURE 5 Results of Weighting the Parameters Using the AHP

The consistency of the responses was checked in two ways. First, the direct ranking of the importance of the three parameters was compared to the relative weighting (i.e. the results of the weighting using the AHP) to make sure that the rankings matched the weighting. Secondly, the consistency ratio was calculated using the method prescribed within the AHP to ensure the relative weightings were consistent. It is worth noting that many of the respondents indicated having trouble understanding the questions regarding the weighting, particularly given the relatively large number (9) of options to choose from, and the confidence expressed in the answers was generally low. This could be a factor that contributes to relatively high levels of inconsistency. One way to counteract this in future studies would be to use a dynamic platform that presents real time feedback to the respondents regarding the consistency and implications of their responses. The benefits of providing real time feedback to respondents has been described as a way to increase participation, as well as increase information gained by the respondent *(32)*.

When comparing the ranking of the three parameters to the weighting, an interesting pattern emerged. Twenty three of the 30 respondents (77 percent) ranked condition as the most important parameter, followed by cost, and then energy consumption. However, when determining the weights based on the scale for the AHP, the final values indicated that the 11 of the 23 respondents who ranked cost higher than energy consumption had final weights that indicated the opposite. For example, one respondent ranked the parameters in the following order: condition as the most important, cost as the second most important, energy consumption is the least important. When the same respondent answered the question related to the weighting they responded as follows: energy consumption is strongly more important when compared to cost, condition is extremely more important related to costs, and condition is strongly more important when compared to energy consumption. This equates to weights for cost, condition and energy consumption as 0.08, 1 and 0.28, respectively. The principal eigenvalue for the comparison matrix is 3.117, which equates to a consistency ratio of 0.1 (generally seen as acceptable). This, along with the general low level of confidence reported by the respondents (average of 5 on a 1 to 10 scale), lends credence to the conclusion that the AHP may not be the best method for determining the relative importance of the criteria in an online survey system.

The consistency ratio for each respondent was calculated, and the majority of the consistency ratio's had values greater than 0.1, which is generally defined as unacceptable. Therefore, it was decided to investigate the reasons why each consistency ratio was greater than 0.1 before determining whether the responses were too inconsistent to be considered usable. For example, one respondent labeled cost as extremely more important that energy consumption and condition as extremely more important than costs. Based on these two, the highest level of consistency achievable would be 0.18, and would be the case that they considered energy consumption extremely less important than condition. However, the respondent indicated that energy consumption is very strongly less important that condition, which resulted in a consistency ratio of 0.61. Thus, it was decided that the inconsistencies in this particular respondents weights were acceptable given that the overall trend in the preferences was maintained.

Discussion

The results of the pilot study are expected to provide valuable information regarding the design of future surveys to elicit weights. For example, the methods for obtaining weights and certainty equivalents are generally performed in an interview setting (e.g., *(11)*) so that feedback can be given to the respondents about the implications and consistencies of their selections. The lack of feedback in the survey reported in this paper potentially led to a considerable amount of the inconsistencies seen in the answers (e.g., the case where the rankings and weightings of the parameters were reversed for respondents). Therefore, any future work on collecting certainty equivalents and weights at a large scale should be done using a platform which enables immediate feedback to the users about the consistency of their responses.

Although there was variability in the responses regarding the relative weights of each parameter, general trends could be seen when the responses were compiled. It is expected that these trends can be used to develop a consensus about the weights which can be applied to means objectives. For example, by interpreting the results from Figure 5 it can be seen that condition should be weighted approximately two times more than costs or energy consumption, which should be weighted similarly relative to each other. Furthermore, the results showed that the high weight for condition was fairly dominant, whereas there is much higher deviation in the cost and energy consumption results. This indicates that results from the sustainability assessment should be represented with some level of uncertainty (e.g., by presenting the final score as a potential range of values as opposed to a single deterministic value).

The AHP is only one of many potential methods for deriving relative weights, and the results presented in the previous section indicate that it may not be the most appropriate method for deriving weights without some level of feedback given to the respondents regarding their level of consistency. Another method, which was not described in this paper, but is similar to the approach taken by CEEQUAL, is the Simple Multi-Attribute Rating Technique (SMART). The SMART method does not require pairwise comparisons, which simplifies the problem, but also assumes that the stakeholder can accurately quantify their degrees of preference. Other alternative methods for weighting can be found in many resources, including Choo et al. *(30)*.

The results are representative of one stakeholder group that is familiar with pavement management, and this could explain the considerably high weights associated with condition. The condition of pavements is directly related to maintenance costs, and it is well known that the relationship is non-linear (i.e., a small drop in condition could lead to a relatively large increase in future costs). Therefore, by placing such a high importance on condition, this stakeholder group may have considered that maintenance costs would decrease. By providing feedback, it would be important to see whether their preferences changed or stayed consistent.

CONCLUSIONS

Within infrastructure sustainability assessment systems, weights are used to ascribe preferences to particular goals in order to define their relative importance. The authors have shown that, although multiple sustainability assessment systems apply weights in different contexts, each of the weighting systems is applicable to different stages within sustainability assessment. Weights which describe the impact that criteria have on specific goals are needed in order to link indicators (or responses) to means objectives. Weights which ascribe relative importance between many goals are needed in order to link the means objectives to the overall goal of sustainability. The authors also demonstrated the interaction of these two sets of weights by structuring sustainability assessment as a decision analysis problem.

Sustainable infrastructure management is a multi-criteria problem that involves the input from many different stakeholders. Thus, sustainable decision making within infrastructure management requires tradeoffs to be made between the many objectives *(10)*. This paper expanded on previous research that used various decision analysis techniques to measure the preferences of decision makers on a more broad scale *(12, 13, 14, 15)*. It was determined that a platform that provides real time feedback to respondents would be a more appropriate approach over the static platform used in this work. However, some insightful findings could be made from this work. For example, people who work within infrastructure management tend to be much more concerned with condition than costs and energy consumption. Secondly, energy consumption and costs were weighted similarly, although this could be due to inconsistencies in the responses given that the majority of respondents ranked costs second most important (although ranking does not preserve the scale of preferences, only the order).

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REFERENCES

(1) Mansfield, T. J., and A. M. Hartell. Institutionalizing Sustainability at the Level of State Departments of Transportation. *Transportation Research Record: Journal of the Transportation Research Board No. 2271*, Transportation Research Board of the National Academies, Washington, D.C., 2012, pp. 9-18.

(2) European Conference of Ministers of Transportation. *Assessment and Decision Making for Sustainable Transport*. Paris: OECD Publications Service, 2004.

(3) Holden, M. Sustainability indicator systems within urban governance: Usability analysis of sustainability indicator systems as boundary objects. *Ecological Indicators*, Vol. 32, 2013, pp. 89– 96.

(4) Amekudzi, A., Michael Meyer, Catherine Ross, and Elise Barrella. *Transportation Planning for Sustainability Guidebook*. FHWA, US Department of Transportation, 2011.

(5) Barrella, E. M., A. A. Amekudzi, and M. D. Meyer. Evaluating Sustainability Approaches of Transportation Agencies Through a Strengths, Weaknesses, Opportunities, and Threats Framework. *Transportation Research Record: Journal of the Transportation Research Board No. 2357,* Transportation Research Board of the National Academies, Washington, D.C., 2013, pp. 41-49.

(6) *Illinois Department of Transportation. Illinois - Livable and Sustainable Transportation*. Illinois Department of Transportation, 2012. www.eastsidehighway.com/wp-content/uploads/2014/05/I-LAST-Version-2-DRAFT.pdf. Accessed December 5, 2014.

(7) NYDOT. *New York Department of Transportation: GreenLITES*. 2014. https://www.dot.ny.gov/programs/greenlites. Accessed October 08, 2014.

(8) Johansson, Rebecca. *Evaluation of experiences from using CEEQUAL in infrastructure projects*. Thesis, Uppsala University, Sweden, 2011.

(9) Keeney, R., and H. Raiffa. *Decisions With Multiple Objectives: Preferences and Value Tradeoffs*. Cambridge University Press, Cambridge, UK, 1993.

(10) Bryce, James M, Gerardo Flintsch, and Ralph P Hall. A multi criteria decision analysis technique for including environmental impacts in sustainable infrastructure management business practices. *Transportation Research Part D: Transport and Environment* Vol. 32, 2014, pp. 435-445.

(11) Ananda, Jayanath, and Gamini Herath. Evaluating public risk preferences in forest land-use choices using multi-attribute utility theory. *Ecological Economics* Vol. 55(3), 2005, pp. 408-419.

(12) Li, Z., and K. C. Sinha. *Methodology for the Development of a Highway Asset Management System for Indiana*. Publication FHWA/IN/JTRP-2003/21. West Lafayette, Indiana: Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, 2004.

(13) Zietsman, J., Rilett, L. and Kim, S.-J. Transportation Corridor Decision Making with Multi Attribute Utility Theory. *International Journal of Management and Decision Making*, Vol. 7 No. 2/3, pp. 254-266, 2006.

(14) Smith, J., and Susan Tighe. The Analytical Hierarchy Process as a Tool for Infrastructure Management. *Transportation Research Record: Journal of the Transportation Research Board No. 1974,* Transportation Research Board of the National Academies, Washington, D.C., 2006, pp. 3-9.

(15) Stich, B., J. H. Holland, R. A. Noberga, and C. G. O'Hara. Using multi-criteria decision making to highlight stakeholders' values in the corridor planning process. *The Journal of Transport and Land Use,* Vol. 4(3), 2011, pp. 105-118.

(16) Committee on Sustainability Linkages in the Federal Government. *Sustainability for the Nation: Resource Connection and Governance Linkages*. National Research Council, Washington, 2013.

(17) Dietz, Thomas, and Paul C. Stern. *Public Participation in Environmental Assessment and Decision Making*. National Research Council, Washington, 2008.

(18) Muench, S.T., and J.L. Anderson. *Final Technical Report on Greenroads: A sustainability performance metric for roadway design and construction*. Report No. TNW 2009-13/WA-RD 725.1. Seattle, University of Washington, 2009.

(19) Lee, Jin Cheol, Tuncer B. Edil, Craig H. Benson, and James M. Tinjum. Evaluation of Variables Affecting Sustainable Highway Design With BE2ST-in-Highways. *Transportation Research*

Record: Journal of the Transportation Research Board No. 2233, Transportation Research Board of the National Academies, Washington, D.C., 2011, pp. 178-186.

(20) Muench, Stephen T., Jeralee Anderson, and Tim Bevan. Greenroads: A Sustainability Rating System for Roadways. *International Journal of Pavement Research and Technology*, Vol 3 (5), 2010, pp. 270-279.

(21) Muench, S.T., J.L. Anderson, J.P. Hatfield, J.R. Koester, and M. et al. Söderlund. *Greenroads Manual v1.5*. Seattle: University of Washington, 2011.

(22) *Ceequal Version 5.1 Assessment Manual for Projects*. Ceequal Ltd., London, 2013.

(23) Campbell-Lendrum, E., and J. Feris. Trialling Ceequal on a London Railway Embankment. Proceedings of the Institution of Civil Engineers, *Engineering Sustainability*, Vol. 161(1), 2008, pp. 71-76.

(24) Lee, Jincheol, Tuncer B. Edil, Craig H. Benson, and James M. Tinjum. Building Environmentally and Economically Sustainable Transportation Infrastructure: Green Highway Rating System. *Journal of Construction Engineering and Management*, Vol. 139(12), 2013, DOI:A4013006.

(25) Saaty, T.L. *The Analytic Hierarchy Process*. McGraw-Hill International, New York, 1980.

(26) Lane, Becca, Stephen Lee, Betty Bennett, and Susanne Chan. *GreenPave Reference Guide: Version 2.0*. Ontario Ministry of Transportation's Materials Engineering and Research Office, Toronto, 2014.

(27) Chan, Peter Cheuk Pan. *Quantifying Pavement Sustainability for Ontario Highways*, MS Thesis, Waterloo, Ontario: University of Waterloo, 2010.

(28) Bryceson, Deborah Fahy, Annabel Bradbury, and Trevor Bradbury. Roads to Poverty Reduction? Exploring Rural Roads' Impact on Mobility in Africa and Asia. *Development Policy Review*, Vol. 26 (4), 2008, pp. 459-482.

(29) Bryce, James. *Applying Pavement Life Cycle Assessment Results to Enhance Sustainable Pavement Management Decision Making*. PhD Thesis, Blacksburg, VA, USA: Virginia Tech, 2014.

(30) Choo, Eng U., Bertram Schoner, and William Wedley. Interpretation of criteria weights in multicriteria decision making. *Computers & Industrial Engineering*, Vol. 37(3), 1999, pp. 527-541.

(31) Handfield, R., S. V. Walton, R. Sroufe, and S. A. Melnyk. Applying environmental criteria to supplier assessment: A study in the application of the Analytical Hierarchy Process. *European Journal of Operational Research*, Vol. 141, 2002, pp. 70-87.

(32) Robbins, M., B. Simonsen, and B. Feldman. Citizens and Resource Allocation: Improving Decision Making with Interactive Web-Based Citizen Participation. *Public Administration Review*, 2008, pp. 564-575.