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EVALUATING THE SUSTAINABLE PERFORMANCE OF PUBLIC INFRASTRUCTURE PROJECTS

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Abstract: It is more common than ever to hear practitioners, academics, and decision makers discuss the topic of sustainability in public infrastructure. Not only has the Canadian Society for Civil Engineering (CSCE) embraced sustainable infrastructure as a key strategic goal (CSCE 2015), but municipalities and provinces themselves have begun to include sustainability in their decision making. Despite the concern and attention to this topic area, decision makers still have questions; “What exactly constitutes sustainability?” and more importantly “How can I measure my infrastructure’s sustainable performance?” This paper introduces the Sustainable Efficiency Model (SEM), a stochastic decision support system which combines cost-benefit and multi-criteria methodologies into a single quantitative indicator to demonstrate a public infrastructure project’s sustainable performance. The SEM includes a total of 18 sustainability criteria as defined by the ISO 21929-2 “Framework for the development of sustainability indicators for civil engineering works” (ISO 2015). In addition to detailing the SEM methodology, a single case study is used to demonstrate the model’s application as a project prioritization tool. A second potential application, as a design alternative evaluation tool, is briefly discussed.

1 INTRODUCTION

Sustainability, or sustainable development, is a broad idea which can be interpreted in a variety of ways. The most cited definition of sustainable development stems from the 1987 Brundlandt Report “Our Common Future.” Sustainable development is defined as “development which meets the needs of the present without compromising the ability of future generations to meet their own needs” (Brundtland 1987). Significant emphasis is placed on intergenerational equity, yet the specifics are ill-defined. More recently, it is common to see sustainability characterized as three main objectives: economic development, environmental protection, and social development. This is alternatively referred to as the “triple bottom line” approach – a term coined by John Elkington in the mid-1990s (Slaper and Hall 2011).

As it concerns infrastructure, building with sustainability in mind has become the main area of concern for many organizations and jurisdictions. The Canadian Society for Civil Engineering (CSCE) has embraced sustainable infrastructure as a key strategic goal (CSCE 2015) and has recently begun a formal process to facilitate the adoption of a Canadian infrastructure sustainability rating system. At the municipal level, the Federation of Canadian Municipalities (FCM) has brought sustainability to the forefront of infrastructure with both their Green Municipal Fund (GMF) and the Leadership in Asset Management Program (LAMP), whereby sustainability goals are being integrated into asset management (FCM 2016).

As effective decision-makers, civil engineers and asset managers require the tools to help them determine how sustainable a project is. This idea of “measuring” the sustainability or sustainable performance of public infrastructure has existed for some time. Generally viewed as a multi-objective optimization problem, the ability to objectively measure the sustainability of infrastructure has proved difficult (Sahely, Kennedy, and Adams 2005), but is recognized as an important goal towards realizing sustainable development. Recent attention has been brought to sustainability rating systems such as Envision. While these tools are a great guide to building a single piece of sustainable infrastructure, they often are not well suited when used as a decision-making tool to compare multiple infrastructure projects. This paper aims to review existing methods to evaluate the sustainable performance of public infrastructure and introduce a new method to measure infrastructure projects of dissimilar typologies within a universal framework to assist in decision-making.

2 REVIEW OF EXISTING METHODS

Existing methods to evaluate the sustainable performance of infrastructure projects have been categorized by the authors into two distinct categories: i) monetary, and ii) non-monetary. Monetary methods identify criteria which can be monetized using economic valuation methods such as the derived demand functions, hedonic price, contingent valuation, or damage costs avoided. Non-monetary methods typically assign “points”-based values to criteria and impacts.

2.1 Monetary Methods

The most common monetary method for evaluating the sustainable performance of infrastructure is the social cost-benefit analysis (CBA). Given an investment or policy decision, all known impacts over the life-cycle of this decision are identified, measured, assigned dollar values based on economic valuation methods and discounted back to the present using time value of money principles. The results of a CBA are typically reported as the benefit-cost ratio (BCR), net-present value (NPV), or internal rate of return (IRR). The BCR is of significant interest in decision-making since it represents how efficiently a project generates benefits when compared to costs. In short, the BCR puts all infrastructure projects, large and small, on an even playing field. The BCR and NPV are governed by Equation 1 and 2 respectively.

$$[1]\ BCR = \frac{PVB}{PVC}$$

$$[2]\ NPV = PVB - PVC$$

Where PVB is the present-value of all benefits, and PVC is the present-value of all costs.

Despite the objective rigor that can be applied to a social cost-benefit analysis, not all criteria and impacts relevant to sustainability can be included in the analysis. While criteria such as carbon emissions and health and safety are well understood amongst economists, many of the remaining sustainability criteria are not. Criteria such as aesthetic value or cultural heritage have little to no valuation evidence. The UK Department of Transport’s (UKDofT) “New Approach to Appraisal (NATA)” methodology highlights this discrepancy (UKDofT 2009).

In their basic form, CBAs are calculated with deterministic values which rely on a single value. It is widely recognized that a complete assessment will include a degree of uncertainty with the use of Monte Carlo simulations or sensitivity analysis (Williams, Larocque, and Berger 2012; Environmental Assessment Institute 2006).

2.2 Non-Monetary Methods

Contrary to monetary methods, non-monetary method assigns “points” to criteria based on project performance. The most popular method identified is the multi-criteria analysis (MCA). While there are many variations of a MCA available (see DfCLG 2009), the authors will focus on their most basic form. This is identified as a three-step process: i) indicator identification and development, ii) indicator evaluation and measurement, and iii) weighting and ranking. At its core, the MCA is governed by Equation 3 (Pohekar and Ramachandran 2004) which is used to determine the design alternative which achieves the highest score.

$$[3]\ A^* = Max \sum_{i=1}^{I} a_{ij}\, w_j$$

Where A* is the score of the best alternative, a_{ij} is the value of alternative i in terms of criterion j, and w_j is the weighting factor applied to criterion j.

Significant contributions to indicator identification and development are made in Ugwu et al. (2006) whereby four distinct characteristics of indicators are defined. These characteristics are that indicators should be: i) quantifiable and effective, ii) relevant, iii) understandable, and iv) usable. ISO 21929-2 “Framework for the development of sustainability indicators for civil engineering works” supports these characteristics but adds that indicators can also be qualitative or descriptive (ISO 2015). The ability to include criteria which do not have inherent quantitative results (e.g. aesthetic value) is recognized as a significant benefit and overcomes the major disadvantage of a CBA.

When evaluating or measuring indicators, criteria are typically scored along a pre-determined linear scale. This linear scale can be determined from a variety of methods. One of the more popular methods is a normalization technique identified in Dasgupta and Tam (2005). This method of normalization is effective when evaluating project design alternatives, but is unable to compare projects of dissimilar typology (e.g. comparing a transportation project against a wastewater treatment project). In such cases, universal scales which generalize sustainability impacts are typically employed.

The final step in a MCA is the development and use of weighting factors. An objective pairwise comparison method to determine weighting factors is the Analytical Hierarchy Process (AHP) developed by Saaty (1980). While not the only method available, the authors recognize the AHP as a rigorous and objective method to determine weighting factors. One significant benefit of the AHP is the ability to check for consistency from an evaluator or group of evaluators.

3 SUSTAINABLE EFFICIENCY MODEL (SEM)

To overcome the shortcomings identified in monetary and non-monetary methods, the authors have developed the Sustainable Efficiency Model (SEM) to measure the sustainable performance of public infrastructure projects. The SEM is defined as a stochastic decision-making tool which integrates economic, environmental, and social criteria into a single quantitative indicator using multi-criteria and cost-benefit analysis methodologies. The model is unique in that it integrates monetary and non-monetary results using efficiency indicators. Additionally, consideration is given for a stochastic analysis at all levels, to allow decision makers to make objective decisions given uncertain results and information. The model works very similarly to a MCA, whereby criteria and indicators are determined and then combined with relevant weighting factors to determine sustainable efficiency “points.” The SEM is defined by Equation 4.

$$[4]\ SES_a = \sum_{i=1}^{I} w_i\, mBCR_{ia} + \sum_{j=1}^{J} w_j\, QTEI_{ja} + \sum_{k=1}^{K} w_k\, QLEI_{ka}$$

Where SES_a is the sustainable efficiency score of project a, w_i, w_j, and w_k are the weighting factors for criteria i, j, and k respectively, $mBCR_{ia}$ is the “modified” benefit-cost ratio for monetary criteria i, $QTEI_{ja}$ is the efficiency indicator for non-monetary quantitative criteria j, and $QLEI_{ka}$ is the efficiency indicator for non-monetary qualitative criteria k.

As is evident in Equation 4, the SEM has categorized criteria into three distinct categories: i) monetary, ii) non-monetary quantitative, and iii) non-monetary qualitative. This categorization is further detailed in Section 3.2. The SEM’s primary purpose is to be a decision-making tool to aid decision makers in prioritizing the sustainable performance of infrastructure projects of dissimilar typology. Additional application as a design alternative evaluation has been explored but is not included in this paper.

3.1 Sustainability Criteria Identified

Before any sustainability assessment can begin, a consistent and holistic set of criteria which compromise "sustainable infrastructure" must be established. This first step is often one of the most difficult. Regional differences and personal biases can all influence what an individual or evaluator deems as to be inclusive in the breadth of sustainability. The ISO (2015) 21929-2 "Framework for the development of sustainability indicators for civil engineering works" is used to generate a set of criteria through which an evaluation can be based on to avoid personal biases. Additionally, to better serve the SEM, these criteria have been slightly modified to result in the criteria list shown in Table 3.1.

Table 3.1 - Criteria Included in the SEM

Economic	Environmental	Social
Life-Cycle Costs	GHG Emissions	Health and Safety
Other External Costs	Material Use	Job Creation
	Water Use	Cultural Heritage
	Energy Use	Access to Nature
	Waste Production	Urban Sprawl
	Eutrophication Potential	Public Acceptability
	Acidification Potential	Aesthetic Value
	Ozone Depletion Potential	
	Land Use Changes	

3.2 Efficiency Indicators

To evaluate each of the criteria listed in Table 3.1, efficiency indicators are developed. The purpose of an efficiency indicator is to quantify how *efficiently* a project has met the goals and objectives defined by the criteria. This is contrasted against determining the volume or absolute size of an impact which is typically found. Like a benefit-cost ratio result, the SEM attempts to determine high-quality projects, regardless of the scope or size.

As is evident and previously discussed, there are varying methods to evaluate the criteria that are included in the breadth of sustainability. As such, the authors have categorized these criteria into three distinct categories: i) monetary, ii) non-monetary quantitative, and iii) non-monetary qualitative. These categorizations enable an evaluator to determine an efficiency indicator for all 18 criteria. The criteria in Table 3.1 have been categorizing by the authors and are shown in Table 3.2.

Table 3.2 - Efficiency Indicator Categorization of 18 Criteria for the SEM

Monetary	Non-Monetary Quantitative	Non-Monetary Qualitative
Life-Cycle Costs	Material Use	Cultural Heritage
Other External Costs	Water Use	Access to Nature
GHG Emissions	Energy Use	Urban Sprawl
Health and Safety	Waste Production	Public Acceptability
	Eutrophication Potential	Aesthetic Value
	Acidification Potential	
	Ozone Depletion Potential	
	Land Use Changes	
	Job Creation	

Whenever possible, the most objective method for efficiency indicator evaluation should be used. The authors believe that a cost-benefit analysis (monetary) method is the most objective method available due to the supporting research and referencing available for impact valuations. Secondly, a non-monetary quantitative methodology is naturally more objective than a qualitative and subjective opinion to evaluate indicators.

3.2.1 Monetary

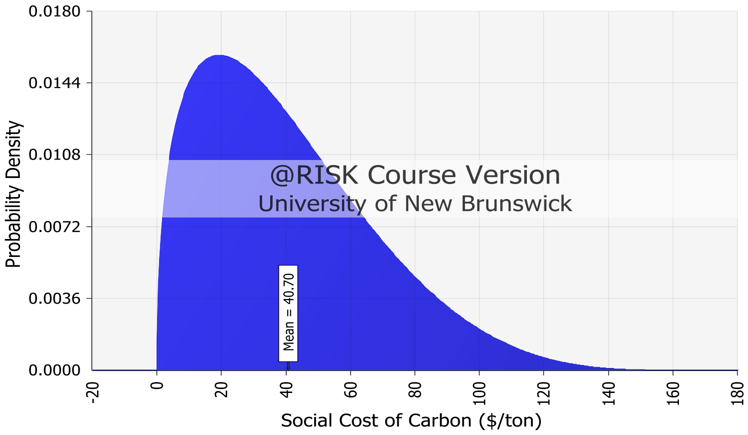
For monetary criteria, a modified benefit-cost-ratio is used as an efficiency indicator. Each criterion's impacts are isolated individually, and their respective benefits are valued. The modified benefit-cost ratio (mBCR) differs from a traditional BCR in that the numerator is the present-value benefit (both positive and negative) of the criterion in question, and the denominator is the initial construction or investment cost of the project. The mBCR is governed by Equation 5.

$$[5]\ mBCR_{ia} = \frac{PVB_i}{C_a}$$

Where PVB_i is the present-value benefit of criterion i and C_a is the initial construction or investment cost of project a.

To include uncertainty in a monetary efficiency indicator, an evaluator can use probability distributions to define variable inputs. For example, the social cost of carbon has been estimated to be $40.7 per ton but can be as large as $167.0 per ton. Rather than including this value as $40.7 per ton exclusively, a three-point estimation technique can be used to capture the uncertainty that the social cost of carbon could range between $0.0 and $167.0 per ton. This technique is shown in Figure 3.1

Figure 3.1 - Probability Density of the Social Cost of Carbon



3.2.2 Non-Monetary Quantitative

Non-monetary efficiency indicators have been split into two distinct categories: i) quantitative and ii) qualitative. Quantitative indicators can rely on actual and estimated results from infrastructure projects. The efficiency indicators determined must reflect how efficiently a project has achieved a certain goal or objective, with a result of 1 indicating 100% or complete efficiency. These indicators can vary depending on the criterion in question, and as such, there is no standardized formula available. Including uncertainty in a non-monetary quantitative indicator is done similarly as a monetary indicator using probability distributions.

3.2.3 Non-Monetary Qualitative

A non-monetary qualitative efficiency indicator cannot be determined with actual or estimated project results and will, therefore, rely on subject matter experts to evaluate the given criteria. As a subjective result, qualitative and descriptive terms are required. A standardized subjective linear scale has been developed for non-monetary qualitative efficiency indicators shown in Table 3.3.

Table 3.3 - Non-Monetary Qualitative Indicator Evaluation Scale

Negative	Neutral	Positive

Significant	Major	Moderate	Minor		Minor	Moderate	Major	Significant
-1.0	-0.75	-0.50	-0.25	0.00	0.25	0.50	0.75	1.00

To include uncertainty, guidance is sought from Rosén et al.'s (2015) SCORE methodology. In this method, subject matter experts are given an opportunity to indicate both a result and an uncertainty category to each criterion. It is then assumed that a qualitative result will follow a normal distribution and each uncertainty would, therefore, have an appropriate standard deviation assigned to it. The SCORE methodology prescribes the uncertainty categories and standard deviations shown in Table 3.4.

Table 3.4 - Uncertainty Categories for Non-Monetary Qualitative Efficiency Indicators

Uncertainty Category	Range	Standard Deviation
Low	-1.0 to +1.0	0.091
	-1.0 to 0.0; 0.0 to +1.0	0.046
Medium	-1.0 to +1.0	0.137
	-1.0 to 0.0; 0.0 to +1.0	0.068
High	-1.0 to +1.0	0.182
	-1.0 to 0.0; 0.0 to +1.0	0.091

3.3 Weighting Factors

The authors recommend implementing the Analytical Hierarchy Process to determine appropriate weighting factors, however, acknowledges that other methods are available. The SEM does not attempt to justify or validate one method over another but encourages that a robust and objective-based method be used. It is common to see evaluators or decision makers subjectively determine weighting factors to determine a set of results which are heavily influenced by personal biases.

4 CASE STUDY

To demonstrate the Sustainable Efficiency Model’s application as a project prioritization tool, a case study has been completed to evaluate the Sustainable Efficiency Score of a major traffic intersection upgrade project in Fredericton, NB.

4.1 Project Description

The Regent and Prospect Street Intersection currently functions under fully-actuated control, with two thru lanes and an exclusive left turn lane on each approach. The intersection is Fredericton’s busiest, with roughly 65,000 vehicles entering vehicles per day (Lewis 2014). The proposed intersection upgrades include the following scope of work: i) Implementation of protected left-turn phasing, ii) Construction of new right-turn island design, iii) Construction of dual left turn lanes on Regent Street and Vanier Highway, iv) Reconstruction of an existing concrete roadway intersection, v) Replacement of various underground services (sewer, storm, and water), and vi) Increased lighting and visibility.

4.2 Results

After evaluating all 18 criteria (Table 3.2) in the SEM, it was determined that the Regent and Prospect Street Intersection Upgrades project earned a Sustainable Efficiency Score (SES) of +31 (please refer to Table 4.1). Additionally, the results of a Monte Carlo simulation indicate a 90% confidence that the project had a SES between +25.3 and +36.2. The relative frequency curve for the range of SESs is shown in Figure 4.1. Additionally, a summary of the individual criteria, their efficiency indicators, the results obtained, and weighting factors applies are shown in Table 4.1.

As is evident in Table 4.1, a significant portion of the benefits realized by the project are from the health and safety criterion. This is due to a strong $mBCR_{H\&S}$ score of 0.69, combined with a significant 35% weighting factor as prescribed by City of Fredericton decision makers through the AHP (Table 4.1). Other benefits such as reduced life-cycle costs from infrastructure asset upgrades, reduced congestion and travel time for users, and reduced quantity of freshwater lost due to water main leaks and bursts are realized with the SEM, as shown in Table 4.1. To help better demonstrate the calculation of efficiency indicators, a brief example for each category from each efficiency indicator category (monetary, non-monetary quantitative, and non-monetary qualitative) are determined in Section 4.3.

Figure 4.1 - Range of Potential SESs for the Regent and Prospect Street Intersection Upgrades

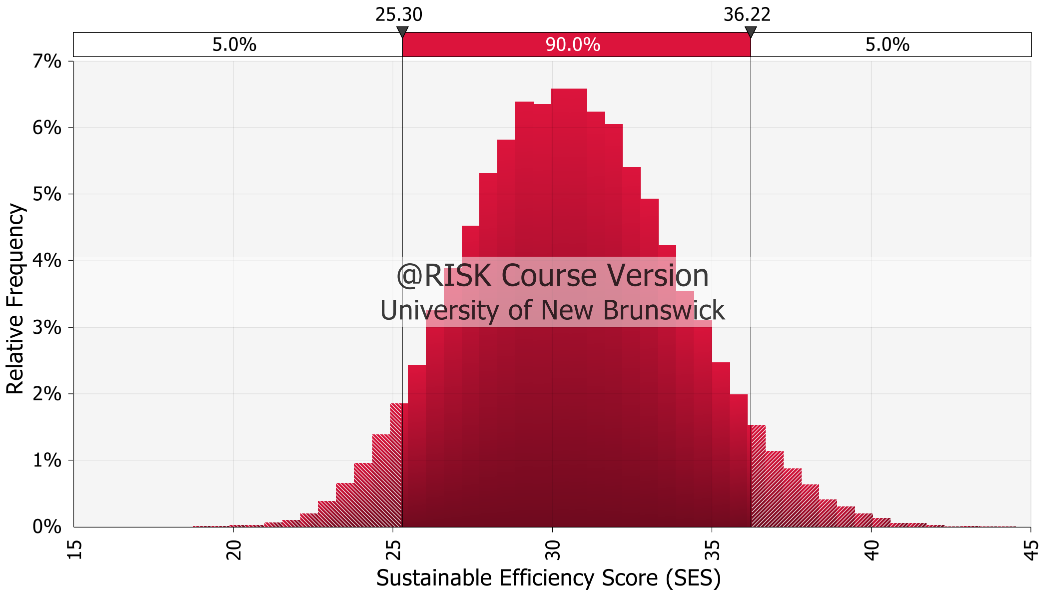


Table 4.1 - Summary of Results for the Regent and Prospect Street Intersection Upgrades

Category	Criteria	Sustainable Efficiency Indicator	Result	W_i	SES_i
Economic (18.9%)	Life-Cycle Costs	$= PVB_{LCC}/C_a$	0.14	11%	1.47
	Travel Time	$= PVB_{TT}/C_a$	0.15	7%	1.05
Environmental (29%)	GHG Emissions	$= PVB_{GHG}/C_a$	0.00	6%	0.03
	Land Use Changes	None	0.00	4%	0.00
	Material Use	$= RM_i/RM_{max}$	0.03	3%	0.07
	Energy Use	$= \Delta EU/EU_o$	0.59	2%	1.01
	Water Use	$= \Delta WU/WUo$	0.91	4%	3.35
	Waste Reduction	= WR/WG	0.00	4%	0.00
	Eutrophication Potential	None	0.00	3%	0.00
	Acidification Potential	None	0.00	2%	0.00
	Ozone Depletion Potential	None	0.00	2%	0.00
Social (53.1%)	Health and Safety	$= PVB_{H\&S}/C_a$	0.69	35%	24.22
	Access to Nature	Contribution to Nature Access	0.20	2%	0.42
	Urban Sprawl	Contribution to Urban Sprawl	-0.20	3%	-0.54
	Public Acceptance	Degree of Public Acceptance	0.40	2%	0.72
	Aesthetic Value	Contribution to Aesthetic Value	0.40	2%	0.84
	Job Creation	$= LR_i/LR_l$	-0.43	5%	-1.98
	Cultural Heritage	None	0.00	5%	0.00
			Total	100%	31

4.3 Efficiency Indicator Calculation Examples

Note: The data inputs presented in these examples do not include the uncertainty data that is used in the final analysis.

4.3.1 Monetary – Other External Costs (Travel Time)

From a traffic study conducted by Lewis (2014), it has been estimated that the two additional left turning lanes will reduce the amount of congestion experienced at the intersection during peak traffic volumes (denoted as AM and PM). From this study, the authors have determined that the intersection upgrades will reduce traffic delays by 3,873 hours annually in the first year, decreasing down to 3,522 hours annually in year 10, and climb back to 4,561 hours annually in 20 years. Given these results, the total delay hours reduced per year over a 20-year period can be linearly interpolated.

To determine the social cost of congestion or travel time, guidance is sought from Litman (2009). The social cost of personal travel time has been estimated to be 35% of the average local wages. Assuming an average wage of roughly $21.15 per hour (Statistics Canada 2015), the social cost of travel time is estimated to be $10.04 per hour. Given the total travel time delay hours reduced by the intersection upgrades, a total present-value benefit of $614,101 is determined (assuming a 3% discount rate). Additionally, the project’s initial construction cost was estimated to be $4.2 million. Therefore the modified benefit-cost ratio can be determined by Equation 5.

$$mBCR_{TT} = \frac{PVB_{TT}}{C_{R\&P}} = \frac{\$614{,}101}{\$4{,}200{,}000} = 0.15$$

4.3.2 Non-Monetary Quantitative – Material Use (Recycled Material)

For the Material Use criterion, a non-monetary quantitative efficiency indicator was developed. The authors determined that the efficiency indicator used should reflect how efficiently the project has used recycled material in the design of asphalt pavement. To do this, it was determined that Equation 6 would be the most appropriate.

$$[6]\ QTEI_{MU} = \frac{\%RAP_{R\&P}}{\%RAP_{max}}$$

Where $\%RAP_{R\&P}$ is the percentage of reclaimed asphalt pavement used in the project, and $\%RAP_{max}$ is the maximum functional percentage of reclaimed asphalt pavement.

It is possible to use recycled material in asphalt through reclaimed asphalt pavements (RAP). However, there is a functional limit to its use. The US Federal Highway Administration (US FWHA) widely considers 50 percent RAP to be the maximum limit (US FHWA 2008). This value forms the basis for the maximum allowable quantity of recycled material used ($\%RAP_{max}$). There is not the exact quantity of RAP used in the intersection upgrades, but it is assumed to be 0% after consultations with the owner. There is a limit to the quantity of RAP in the City of Fredericton specifications of 15%. Using these assumptions and a PERT distribution, the expected quantity of RAP used in the project is 2.5%. Therefore, the efficiency indicator for the Material Use criterion can be determined by Equation 6.

$$QTEI_{MU} = \frac{\%RAP_{R\&P}}{\%RAP_{max}} = \frac{2.5\%}{50\%} = 0.05$$

4.3.3 Non-Monetary Qualitative – Public Acceptance

For the public acceptance criterion, a subjective scale is to be rated by a subject matter expert. The linear scale in Table 3.3 is used to determine the degree to which the project has the public acceptance. A traffic engineer who had consulted with local businesses and key stakeholders in the construction area was asked to rate the project. From the consultation period, the traffic engineer ranked the project as -0.8 in the short-term and a +0.8 in the long-term, therefore giving the project a total ranking of +0.4. Additionally, the result is given a “High” uncertainty rating and a standard deviation of 0.182.

5 DISCUSSION

It is important to note what the Sustainable Efficiency Model is not. It does not prescribe the perfect or ideal set of criteria to represent sustainability. As is evident from previous work, there is still little consensus on what truly compromises sustainability, and is an area of research which should continue. The SEM does not prescribe specific indicators to be used for each criterion. Every project will be unique and may have varying degrees of functional limits. This is exemplified with the maximum allowable quantity of RAP to be used in pavements for the case study. While specific indicators are not prescribed, the SEM does the define the purpose of an indicator – to determine how efficiently a project has met the stated goals or objectives. This notion of determining efficiency ratios is key to integrating monetary and non-monetary criteria into a single quantitative indicator.

The main purpose of the SEM is to evaluate public infrastructure projects of dissimilar typology and size. This is believed to be one of the main advantages identified. The case study project is shown above, with an earned Sustainable Efficiency Score (SES) of +31, can then be compared to another potential infrastructure investment such as a wastewater treatment plant upgrade. The goal of the SEM is to put all potential investments on an even playing field, where regardless of size or scope, projects are evaluated within a universal framework. This will allow decision-makers and asset managers the ability to compare “apples” to “apples.” Additionally, the inclusion of flexible weighting factors can allow the SEM to be adjusted depending on regional or jurisdictional priorities and is not constrained by limits set by a governing body.

6 CONCLUSIONS

This paper aimed to complete two specific goals. The first is to introduce existing methods to evaluate the sustainable performance of infrastructure. The authors have categorized these methods as monetary and non-monetary. The significant difference between the two is the unit of measurement for the criteria and impacts. Monetary methods naturally monetize specific impacts but are limited in the breadth of criteria to include. Non-monetary methods are much more flexible, where any criteria can be included if an indicator is developed. A significant limitation of non-monetary methods is the subjectivity and biases which can influence the results.

Secondly, the SEM is introduced as a unique method to evaluate the sustainable performance of infrastructure. The SEM is a hybrid method which combines monetary and non-monetary methodologies into a single quantitative indicator. To do so, efficiency indicators are developed for all criteria, both monetary and non-monetary. Combined with flexible weighting factors, the use of efficiency indicators allows for monetary and non-monetary criteria to be combined in a way that is consistent and allows from of dissimilar typology and size to be prioritized and compared amongst each other. Additionally, the SEM emphasizes the use of uncertainty in both variable inputs and results.

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