Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 00 (2018) 000–000

Transportation Research Procedia

www.elsevier.com/locate/procedia

World Conference on Transport Research - WCTR 2019 Mumbai 26-31 May 2019

Scaling functions for aligning evaluation criteria in transportation appraisal and decision making – a synthesis and case study

Samuel Labi[a]*, Arun Shirole[b], Adjo Amekudzi-Kennedy[c], Zongzhi Li[d], Qiang Bai[e], Pranamesh Chakraborty[f]

a. Purdue University, 550 Stadium Mall Drive, W. Lafayette IN, 47907, USA
b. S&A Shirole, Inc., Minneapolis, MN, USA
c. Georgia Institute of Technology, 790 Atlantic Drive, Atlanta, GA 30332-0355 USA
d. Illinois Institute of Technology, 3201 South Dearborn Street, Chicago, IL 60616
e. Chang'an University, School of Highway, Xi'an, Shaanxi Province, 710064, China
f. Iowa State University, Ames, Iowa, 50011, USA

Abstract

The increasing use of multiple criteria techniques in transportation decision making is fostered by the growing number of evaluation criteria that need to be included in project and program appraisals. Most multiple criteria techniques require a scaling process that converts the different units of the individual evaluation criteria into a common metric or unit. This facilitates the conversion of all the different performance outcomes of any specific decision as a single value or utility, the comparison of the outcomes of alternative decisions, and the analysis of tradeoffs between conflicting evaluation criteria and also between competing transportation projects, policies, or programs. This paper reviews existing methods for scaling the evaluation criteria, thereby showing how some of these methods can be used to develop value functions or utility functions for the different evaluation criteria in the management of bridges and transportation assets in general.

Peer-review under responsibility of WORLD CONFERENCE ON TRANSPORT RESEARCH SOCIETY.

Keywords: Decision-making, Project evaluation, Scaling, Utility function, Multiple criteria

1. Introduction

1.1 Background

The transportation environment is currently characterized by evolving trends that are gradually reshaping the landscape of transportation policy and practice (TRB, 2013). The later decades of the last millennium, as well as the early years of the current millennium, have seen an increased number of stakeholders in transportation decision making

* Corresponding author. Tel.: +1-765-637-6038; fax: +1-765-494-0395.
E-mail address: labi@purdue.edu

Peer-review under responsibility of WORLD CONFERENCE ON TRANSPORT RESEARCH SOCIETY

and investment, increased need for including their concerns, and increased user awareness as well as their expectations of facility's levels of service (McNeil et al, 1992; USDOT, 2007; Sinha and Labi, 2007). The stakeholders include the owning or operating agency, the facility users, persons affected by the facility (often adversely) such as workers, residents, pedestrians, and parties affected by the facility, pressure groups, chambers of commerce, community groups, environmental groups, and so on. The multiplicity of stakeholders is not the only challenge: the concerns and interests of the different stakeholders often are not only parochial but also conflict with each other. For this reason, transportation agencies seek decision-making processes that are based on a broad array of evaluation criteria that adequately reflect the perspectives of such stakeholders. This way, it is expected that transportation decisions can be made more balanced, rational, defensible, and cost-effective. Other motivations for multiple criteria decision making (MCDM) in transportation include funding limitations, aging infrastructure, and the often controversial nature of transportation investment decisions (Speicher et al. 2005) and the drive towards transportation sustainability (Oswald and McNeil, 2009; Amekudzi et al., 2009; Zheng et al., 2013). With MCDM, the investment decisions of agencies could become more accountable and transparent.

Studies in various areas of transportation management have yielded a set of evaluation criteria that could be used in evaluation and decision making in those areas (Pickrell, 2000; OECD, 2001; The World Bank, 2003; Sinha and Labi, 2007; Patidar et al., 2007a; Dolan et al., 2016; Carhart et al., 2016; Srinivasan et al., 2017; Sinha et al., 2017). In bridge management, the multiple evaluation criteria can be grouped under the broad goals of agency and user cost, traffic safety, vulnerability to man-made or natural disasters, facility longevity and condition, and social and community values (Sivakumar et al., 2003) and these were applied in a fairly recent NCHRP study by Patidar et al. (2007b) and other studies (Bai et al., 2013; Alinizzi et al., 2018). With regard to overall highway asset management, a 2004 study identified broad performance goals for asset management at a state highway agency (Li and Sinha, 2004) as follows: facility state-of-good-repair, agency costs, direct and indirect user costs including mobility and safety, and the environment. Saaty (2005) discussed transport planning based on multiple criteria. Zak (2011) discussed the use of MCDM in public transportation projects, and Macharis et al. (2009) presented a multi-criteria, multi-actor analysis methodology for transport project evaluation. Shi (1995) proposed a model for evaluating transportation investments using multiple criteria and multiple constraint levels. In the area of pavement management, the use of multiple criteria has been implicit through the consideration of agency costs (monetary) and user benefits (often surrogated by pavement condition) in various decision-making contexts including the identification of cost-effective preservation treatments and schedules (Khurshid et al., 2014). Multiple criteria techniques have also been applied, at least implicitly, in the areas of safety management (Murillo Hoyos et al., 2015) and safety policy evaluation (Labi et al., 2017), congestion management (Bai et al., 2017), highway asset valuation (Dojutrek et al., 2015), transport infrastructure security (Dojutrek et al., 2016) and sustainability assessment. In their discussion of the continuing issues, and emerging opportunities and challenges in infrastructure management in the current era, Sinha et al. (2017) identified the incorporation of multiple criteria as one of the key considerations in decision making.

1.2 The Scaling Process

A key issue is decision-making involving multiple evaluation criteria is associated with the criteria units or metrics. Where all the criteria have the same units (such as dollars), the analysis is relatively straightforward. However, in most cases, the criteria are expressed in different units and therefore are non-commensurate. While some multi-criteria decision-making (MCDM) techniques such as cost-effectiveness analysis (or other ratio-based techniques) can proceed notwithstanding differences in the evaluation criteria units, most other MCDM techniques require that the units should all be converted into a single, common unit or metric. If this is done, then it will be possible to: measure the different impacts of an intervention in terms of the different evaluation criteria, on the same scale; establish the combined impact of all evaluation criteria; analyze the trade-offs between conflicting evaluation criteria is facilitated.

In effect, scaling or metricizing involves the establishment of an ordered reference standard that reflects the DM's preference of each level of a given evaluation criterion relative to other levels of the same evaluation criterion. In other words, each evaluation criterion should have its own preference structure that indicates the relative desirability (or undesirability) of the various levels of that evaluation criterion. The decision-maker's stated or revealed preference, which may reflect the combined perspectives of the various stakeholders (including the agency, user, and community), can be established using questionnaire surveys of individuals representing the various stakeholders. In operations research jargon, these individuals are also referred to as decision makers. Decision making methodologies that involve the establishment of such preferences are rooted in utility theory. In other words, it is assumed that the preferences of the DM can be captured using a value function or utility function (Keeney and Raiffa, 1976). Considering that the evaluation criteria have different units, the scaling process establishes multiple single-criterion utility functions for each evaluation criterion, thereby yielding a scale of measurement that is uniform across the evaluation criteria.

Scaling is different from weighting in that the former involves the establishment of decision-makers perceptions of the relative value between different levels of the same evaluation criterion, while weighting involves establishment of perceptions of relative importance between several different evaluation criteria. As implied in a previous paragraph, the application of scaling techniques in multiple criteria evaluation problems depend on whether the multiple evaluation criteria have commensurate units. Where the units are commensurate, there is no need for scaling. Therefore, not all multi-criteria evaluation problems involve scaling. The most common scaling mechanism is monetization (thus the monetary value such as euros or dollars is the most common commensurate unit of evaluation criteria). Monetization is only possible where there are established and accepted monetary values for a unit of each evaluation criterion. For instance, air pollution value in dollars/ton of pollutant; safety value in Euros /fatality; facility condition in dollars/unit increase in condition; system durability in Euros/year of extended life, etc. Monetization of evaluation criteria is probably the best scaling mechanism to express the desirability (or undesirability) of multiple stakeholders for any level of each indicator. Unfortunately, not all evaluation criteria can be converted to monetary value due to practical or sometimes, presumably, ethical reasons. As such, stakeholders, for purposes of multiple criteria evaluation, are required to express their desirability of a given level of any evaluation criterion in terms of the utility or value they attach to that level of the criterion.

1.3 Role of Scaling in the Overall MCDM Framework and the Issue of Uncertainty

In most classes of solution methods for multi-criteria analysis, scaling of the evaluation criteria is the second of three steps. The first step is weighting (which assigns relative weights to each evaluation criterion based on their relative importance, and the third step is amalgamation (which combines the weighted and scaled utility values into a single combined utility function). Using the combined utility function, the overall value or utility of each transportation alternative can be determined. The mathematical structure of the combined utility function is governed by the assumptions associated with the preference structure of the decision maker.

In developing the overall utility function, a critical issue that needs to be considered is that of the variability of the outputs. The multiplicity of variables in MCDM and their inherent uncertainties (due to natural and man-made conditions) render variability in the impacts of any alternative and hence the choice of the optimal alternative decision. As such, scaling of evaluation criteria may be carried out not only under the certainty case (where the outcomes of each intervention, in terms of each criterion, can be predicted with certainty) but more realistically under the risk case (where the exact consequences of any intervention are unknown). For the certainty case, value functions are used and for the uncertainty case, utility functions are used. With regard to the uncertainty case, uncertainty ranged from 0% uncertainty to 100% uncertainty. As such, certainty may be considered a special case of uncertainty. For this reason, the utility and value functions share some similarity regarding their outputs and usefulness. Nevertheless, the former is a more general form of the latter, incorporates the risk propensity of the decision maker, and has a somewhat different assessment methodology.

1.4 Past Transportation Studies that Involved Scaling

Previous transportation studies in multiple criteria evaluation that implicitly or explicitly involved scaling of transportation evaluation criteria include Lambert et al. (2005) whose framework was used to coordinate and prioritize transportation projects in Virginia. Their criteria included system preservation, economic development, security and safety, efficiency of passenger and freight movement, and quality of life. The researchers requested experts to indicate the desirability of each level of a given criterion for the evaluation, and thereby established the overall desirability of each transportation alternative. Speicher et al. (2000) discussed a collaborative process where workshop participants constructed a preference order or desirability scale for each evaluation criterion and used the developed scales to screen projects as part of Sacramento’s Northeast Area Transportation Study. Tsamboulas et al. (1999) used input from an expert panel of transportation policy makers, academia, and industry in Greece to establish multi-attribute utility functions for three criteria: economic efficiency, the environment, and user and community safety. Younger (1994) described a multimodal evaluation study for Metropolitan Transportation Commission of San Francisco where 35 participants (representing various transportation and environmental concerns) developed weights across several evaluation criteria and developed a scale for each criterion by assigned scores representing their desirability for each level of the criterion. The criteria included system efficiency, system physical condition, mobility, safety, system expansion, air quality, energy conservation, and land use. The authors used the established weights and scales to determine the overall scores for each transportation alternative under consideration. Scaling functions for the different evaluation criteria continue to play a key role in the evaluation of transportation actions (projects, programs, or policies). Using scaling functions, the impacts of any alternative transportation action in terms of the multiple evaluation criteria can be measured and compared. In addition, scaling functions facilitate the conduction of trade-off analysis between the evaluation criteria and also between competing transportation actions.

2. Existing Methods For Scaling

As stated in the preceding section, scaling methods can be categorized by the level of certainty regarding the outcomes of the transportation actions (Figure 1): for the certainty case, value functions are used. The methods used to establish these functions include direct rating, statistical regression, and the mid-value splitting technique. For the risk case, utility functions are used, and methods used to establish utility functions can be further categorized by the type of risk involved. For subjective risk, direct questioning approach, the gamble method, or the certainty equivalent approach can be used, while for objective risk, probability distribution functions are commonly used.

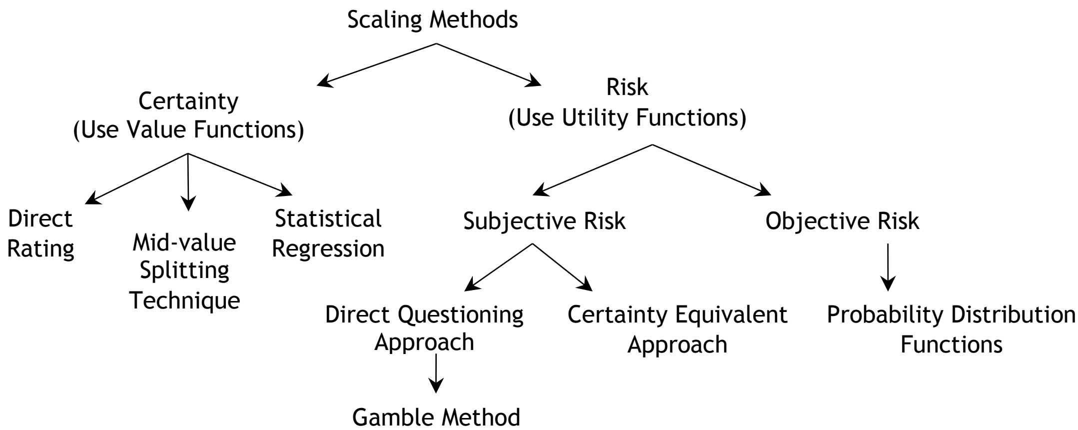

Figure 1 Some Existing Scaling Methods (Sinha and Labi, 2007)

2.1 Case of Decision-making under the Certainty

This case refers to the case where the consequences of each alternative intervention, in terms of each criterion, is known with absolute certainty. With regard to this case, the methods that capture, construct, or quantify the DM's preferences of the levels of each evaluation criterion, are described below.

A fundamental assumption in the application of utility theory is that the DM is fully aware of the outcomes of the alternatives, is capable of evaluating them in a rational manner, and can make a rational choice among the available alternatives in order to maximize the DM's satisfaction. It is assumed that all the information regarding the outcomes associated with each level of the criterion can be adequately represented in the *value function* of the DM. This function, unique for each criterion, is a scale of preference (or the intrinsic value) for that criterion level from the DM's perspective). In other words, the DM's value function is a formal, mathematical representation of their preference structure.

The multivariate value function for each individual DM can be expressed as follows:

$$v(\boldsymbol{z}) = v(z_1, z_2, \ldots\ldots, z_p) \quad (1)$$

where: $\boldsymbol{z}$ represents the set of anticipated outcomes associated with a transportation alternative in terms of p evaluation criteria. The value function has the following property (Keeney and Raiffa 1976):

$v(\boldsymbol{z}') > v(\boldsymbol{z}'')$ if and only if $\boldsymbol{z}'$ is preferred to $\boldsymbol{z}''$.

With this property, the value function can be used to quantify the trade-offs between each pair of evaluation criteria. Multivariate value functions help establish the DM's preferences under various combinations of the evaluation criteria levels, but may be difficult to develop. Also, the analytical complexity increases with the number of dimensions (which in turn increases with an increased number of evaluation criteria). Due to the multidimensional nature of the problem, developing these multivariate value functions can be a rather difficult undertaking. This difficulty can be overcome by reducing the dimensionality where possible. Specifically, the multivariate value function can be decomposed into single-criterion value functions for its constituent evaluation criteria (Keeney and Raiffa 1976). Next, we discuss the decomposed functional form for value functions and its underlying assumptions.

Methods for Developing Single-criterion Value Functions

A value function is a scalar index of the DM'S preference structure or the value they attach to each level of a given evaluation criterion. This section of the paper describes the mid-value splitting technique and the direct rating scaling techniques that were used for constructing single-criterion value functions in the bridge and asset management case studies.

The Mid-value Splitting Technique (MST)

The MST method, which is implemented using a questionnaire survey of the decision-maker, proceeds in the form of an interactive dialogue between the survey administrator and the survey respondent (that is, the decision-maker). The DM, through a survey, assigns a number to reflect how indifferent they are regarding a specified level of an evaluation criterion compared to another. Their indifference between any two levels is reflected by the "equal delight" or "zero relative desirability' between the two levels. A generalized procedure for evaluation criterion W (whose domain of possible values ranges from W_L to W_U units), is presented below:

Step 0: Set $v(W = W_L) = 0$ and $v(W = W_U) = 100$

Step 1: Establish W_{50} for which $v(W_{50}) = 50$

Establish W_{50} such that the survey respondent is equally delighted with

(i) an enhancement of W from 0 to W_{50} and (ii) an enhancement of W from W_{50} to W_U

Step2: Establish W_{25} for which $v(W_{25}) = 25$

Establish W_{25} such that the survey respondent is equally delighted with

(i) an enhancement of W from 0 to W_{25} and (ii) an enhancement of W from W_{25} to W_{50}

Step 3: Establish W_{75} for which $v(W_{75}) = 75$

Establish W_{75} such that the survey respondent is equally delighted with

(i) an enhancement of W from W_{50} to W_{75} and (ii) an enhancement of W from W_{75} to W_U

Step 4: Consistency Check

Is the survey respondent equally delighted with

(i) an enhancement of W from W_{25} to W_{50} and (ii) an enhancement of W from W_{50} to W_{75} ?

If the answer to the last question is affirmative, then the values are consistent. If not, the DMs are asked to individually revise their previous 3 responses (steps 1-3). Using these values, the value function for the evaluation criterion can be constructed. The mid-value splitting technique is rather easy to implement.

The Direct Rating Method

This is relatively straightforward technique for assessing decision-makers preferences for the different levels of a evaluation criterion, is useful where the evaluation criteria have only few (and discrete) levels. The DMs, through a survey instrument, directly assign their preference value for each possible level of the evaluation criterion.

2.2 The Case of Decision Making under Risk

This case, which accounts for uncertainty in the consequences of the transportation decision, is pertinent in transportation management practice because agencies are typically unable to predict exact outcome levels of their decisions, be it a physical intervention or a policy change. As such, it is useful, probably even necessary, for agencies to incorporate uncertainty and risk in their evaluation criteria scaling processes. In the case of decision making under risk, the probability distribution of potential outcomes of each evaluation criterion, are known. Risk can be objective or subjective. Objective risk is based on theory, experiment, or observation of past events, whereas subjective risk is based on personal perceptions. In the case of decision making under uncertainty, the probability distribution of the potential outcomes in terms of each evaluation criterion, are unknown.

Utility functions are used for scaling evaluation criteria where the problem has considerable uncertainty or risk. The decision-maker specifies a certain level of “desirability” (or “utility”) to each evaluation criterion, and the expected overall utility of each transportation alternative decision is determined. The best intervention is that which yields maximum expected utility (Keeney and Raiffa, 1976). A utility function implicitly captures the DM’s risk preferences for a criterion by providing a scale of the DM’s preferences for different levels of the criterion. The utility function’s shape (examples shown in Figure 2) can be used to establish the risk propensity of the DM. A risk-averse DM has a concave utility function, a risk-prone DM has a convex utility function, and a risk-neutral DM has a linear utility function. The risk-taking behaviour of the decision-maker, in turn, reflects the DM’s risk premium (Winston, 1993).

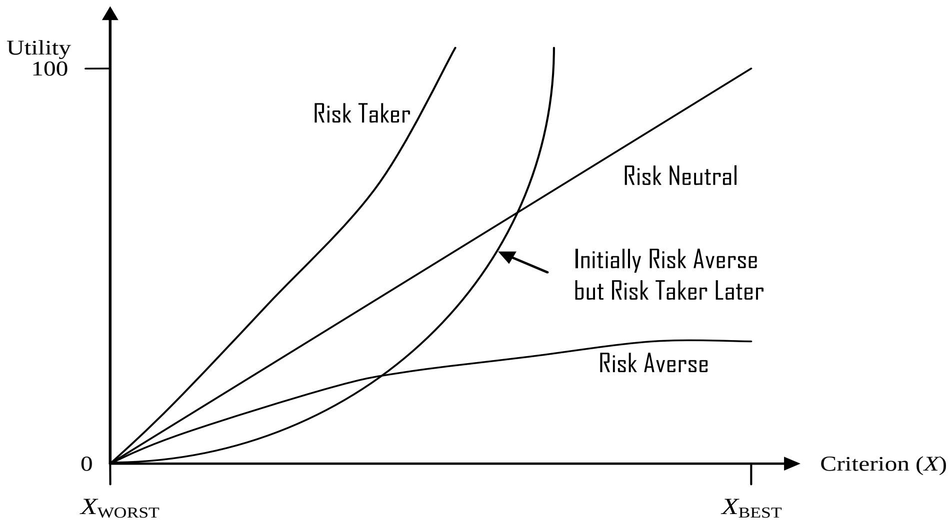

Figure 2. Different Risk Behaviors of Decision Makers

The Multi-Attribute Utility Theory

When the DM assigns a utility to each possible level of each evaluation criterion, the expected overall utility of each decision for all evaluation criteria combined, can be calculated, and the best decision can be identified as that having the highest expected overall utility. This is the underlying principle of multi-attribute utility theory (Keeney and Raiffa 1976). The utility of an alternative is a random variable and the expected utility can be estimated as the first moment or mean of the random variable. Goicoechea et al. (1982) established the following steps for applying the multi-attribute theory:

1. Postulate appropriate assumptions about the DM’s preferences
2. Derive an appropriate functional form on the basis of the assumptions
3. Verify the appropriateness of the assumption using the perceptions of the DM
4. Construct preference orders (utility functions) for each evaluation criterion.
5. Synthesize single-criterion utility functions using the derived functional form and the relative weights between the evaluation criteria.
6. Construct a preference order for the transportation alternative using the expected utilities of their performance outcomes.

This paper focuses on the development of scaling functions. As such, only Steps 1-4 are relevant for the context of this paper. A utility function is a general form of a value function. In other words, a value function is a specific form of a utility function where the degree of uncertainty is 0%. Also, a utility function incorporates the risk attitudes of the DM. Thus, the development of utility functions for an evaluation criterion can be facilitated after the value function for that criterion has been developed for the certainty case. This is rather convenient because it is relatively easier to develop value functions. To develop a utility function from a value function, the following theorem (Keeney and Raiffa, 1976) provides a mathematical basis: For a given a set of evaluation criteria M_1, M_2,….., M_p, that are mutually independent (in the case of certainty), the utility function u adopts one of three functional forms:

$$u(m) \sim -EXP(-c.v(m))$$

$$u(m) \sim v(m)$$

$$u(m) \sim EXP(c.v(m))$$

Where: $v(m)$ is value function for evaluation criterion m, $u(m)$ is the utility function for criterion m, c is a positive non-zero constant.

This theorem is useful because it facilitates the development of a multi-attribute utility function for an evaluation criterion whose value function is known. Furthermore, using this theory, the utility and value functions can be assessed independently.

3. Examples In Bridge Management

A project funded by the NCHRP established a multiple-criteria decision making methodology by which transportation agencies can optimize their investments in bridges (Patidar et al., 2007b). Evaluation criteria considered in the study include bridge physical condition (in terms of health index, NBI condition ratings, and sufficiency rating), highway safety (in terms of inventory/operating rating and geometric rating), and protection from disasters (in terms of bridge vulnerability ratings for scour, earthquake, fatigue/fracture, and man-made threats including collision and overload) (Sivakumar et al., 2003; Patidar et al., 2007b). These criteria, which are measured in different units, were scaled using questionnaire surveys of the NCHRP Panel, a collection of eminent bridge experts in the United States. The sections below discuss the value and utility functions developed for individual evaluation criteria.

3.1 The Certainty Case – Value Functions Developed for each Evaluation Criterion

The study developed value functions for each evaluation criterion using the Direct Rating and the Mid-value Splitting techniques. The Direct Rating method was found to be more appropriate for bridge evaluation criteria that have relatively few possible levels such as bridge vulnerability ratings. For other evaluation criteria, the Mid-value Splitting technique is found to be more appropriate. For each evaluation criterion, various functional forms were investigated and the functional form that best fits the survey data, was identified based on the goodness of fit and engineering intuitiveness of the model. The developed value functions are shown in Table 1. In the table, w represents the level of the evaluation criterion in question.

Table 1. Calibrated Value Functions for Individual Evaluation criteria

Performance Goal	Evaluation criterion (*M*)	Value Function	R^2	Units of *x*
Bridge physical condition	Deck condition	$v(DCR) = 122.75(1-e^{-0.19w})$	0.93	0–9 rating
	Superstructure condition	$v(SCR) = 119.13(1-e^{-0.203w})$	0.93	0–9 rating
	Substructure condition	$v(SBCR) = 119.49(1-e^{-0.202w})$	0.94	0–9 rating
	Culvert condition	$v(CC) = 140.51(1-e^{-0.14w})$	0.93	0–9 rating
	Health index	$v(HI) = 0.092([1397.9/(1+e^{0.0852(85-HI)})]-1)$	0.93	0–100 index
Bridge safety	Sufficiency rating	$v(SR) = 37.96([5.54/(1+e^{0.0216(70-SR)})]-1)$	0.89	0–100 rating
	Geometric rating	$v(GR) = 332.15(1-e^{-0.04w})$	0.88	0–9 rating
	Inventory rating	$v(IR) = 115.33(1-e^{-0.02w})$	0.85	Tons
	Operating rating	$v(OR) = 134.13(1-e^{-0.014w})$	0.83	Tons
Protecting bridge from extreme events	Scour vulnerability	$v(SVR) = 121.76(1-e^{-0.43(w-1)})$	0.95	0–9 index
	Other disaster vulnerability	$v(OVR) = 129.5(1-e^{-0.37(w-1)})$	0.94	0–9 index
	Fatigue – concrete	$v(CFVR) = 137.03(1-e^{-0.33(w-1)})$	0.93	0–9 index
	Fatigue – steel	$v(SFVR) = 125.35(1-e^{-0.40(w-1)})$	0.93	0–9 index
	Earthquake vulnerability	$v(EVR) = 130.57(1-e^{-0.36(w-1)})$	0.95	0–9 index

DCR – Deck condition; SCR – Superstructure condition; SBCR – Substructure condition; CC – Culvert condition; HI – Health index; SR – Sufficiency rating; GR – Geometric rating; IR – Inventory rating; OR – Operating rating; SVR – Scour vulnerability; OVR – Other disaster vulnerability; CFVR – Fatigue – concrete; SFVR – Fatigue – steel; EVR – Earthquake vulnerability.

3.2 The Risk Case – Single-criterion Utility Functions

Using the Certainty Equivalent Method, utility functions were developed for each evaluation criterion. For each criterion, the developed utility function indicated the survey participants' preferences for each level of the criterion and provided insight into their risk propensities regarding that criterion. The certainty equivalent *value* for each evaluation criterion and each survey respondent is first calculated using the developed value functions, and the values are averaged across all survey respondents. This is compared to the expected value of the gamble (which is 50 in our case since it consists of 50% chance of best and worst levels). The functional forms of individual utility functions are then established based on Keeney and Raiffa (1976)'s theorem discussed in a previous section of this paper. Therefore, the average value of the certainty equivalents, δ, were determined as follows:

$\delta > 50$: $u(w) = e^{c.v(w)}$, $c > 0$

$\delta = 50$: $u(w) = v(w)$

$\delta < 50$: $u(w) = -e^{-c.v(w)}$, $c > 0$

where: $u(w)$ is utility function and $v(w)$ is value function for a given evaluation criterion.

For each evaluation criterion, a hypothesis test was carried out to test if the average of *values* of certainty equivalent was statistically different from 50.

H_0: the average certainty equivalent is not statistically different from 50

H_1: the average of certainty equivalent is statistically different from 50

Table 2 presents the results of the hypothesis tests. A rejection of the null hypothesis implies that there is no evidence that the average certainty equivalent is statistically different from 50 (that is, there is no evidence that the utility function is the same as the value function).

The results of the analysis suggest that for the following evaluation criteria, the utility functions are the *same* as their respective value functions: Health index, Geometric rating, Sufficiency rating, Operating rating, Inventory rating, Fatigue (Steel) vulnerability rating and Earthquake vulnerability rating. To ascertain the value of the constant *c*, the utility of certainty equivalent is equated to the expected utility of the gamble using the functional form given in the Keeney and Raiffa (1976) theorem and solved numerically for *c*. The utility function is then scaled from the least utility (0) to the highest utility (100). For some evaluation criteria such as bridge health index, the utility function is S-shaped because since changes in condition near the network average are more valuable to the decision-maker compared to changes that are closer to both extremes (farther away from the network average in positive or negative direction). The results for the utility function development shows that the values of the constant *c* for the various evaluation criteria are as follows: Deck Condition – 0.017; Substructure Condition – 0.012; Superstructure Condition – 0.014; Culvert Condition – 0.012; Fatigue (Concrete) Vulnerability – 0.014; Scour Vulnerability – 0.011, Other Vulnerability – 0.011. For these evaluation criteria, the results (in terms of the curvature of the utility functions), indicate that the developed utility functions and the developed value functions are significantly different.

Table 2. Appropriateness of Functional Forms for the Utility Functions Developed

Evaluation criterion	**CEV_{avg}**	**Stdev**	**t-stat**	**Conclusion**	**Inference (Functional Form)**
Deck condition	69.31	7.75	8.26	Reject H_0	$u(w)$ = e^(c.$v(w)$)
Superstructure condition	66.62	8.28	6.65	Reject H_0	$u(w)$ = e^(c.(w))
Substructure condition	64.27	9.69	4.88	Reject H_0	$u(w)$ = e^(c.$v(w)$)
Culvert condition	64.16	8.59	5.47	Reject H_0	$u(w)$ = e^(c.$v(w)$)
Health index	38.85	20.55	-1.80	Do not Reject H_0	$u(w) = v(w)$
Sufficiency rating	50.60	15.11	0.13	Do not Reject H_0	$u(w) = v(w)$
Geometric rating	54.16	14.04	0.98	Do not Reject H_0	$u(w) = v(w)$
Inventory rating	54.48	16.02	0.93	Do not Reject H_0	$u(w) = v(w)$
Operating rating	52.03	16.48	0.41	Do not Reject H_0	$u(w) = v(w)$
Scour vulnerability	63.50	17.91	2.50	Reject H_0	$u(w)$ = e^(c.$v(w)$)
Fatigue – concrete	66.21	16.46	3.27	Reject H_0	$u(w)$ = e^(c.$v(w)$)
Fatigue – steel	60.61	16.24	2.17	Do not Reject H_0	$u(w) = v(w)$
Earthquake vulnerability	59.07	16.36	1.84	Do not Reject H_0	$u(w) = v(w)$
Other vulnerability	63.62	16.88	2.68	Reject H_0	$u(w)$ = e^(c.$v(w)$)

CEV_{avg} = Average Certainty Equivalent Value. Critical value of the t-statistic = $t_{90\%,10df}$ = 2.23

4. Concluding Remarks

This paper discusses the scaling techniques by which the different dimensions (units) of the different evaluation criteria typically used in transportation decision making can be converted into commensurate units; that way, the respective prospective outcomes and consequences of the transportation alternative, in terms of that criterion, can easily be compared or amalgamated with other alternatives. This paper also presents some scaling functions that were developed. For scaling the evaluation criteria, two different cases were considered: first, where the consequences of decision are known with certainty and second, here the consequences and outcomes are known with uncertainty. For each case, the paper discussed at least one scaling process. The examples provided by the paper include value and utility functions; these can be used in multiple criteria evaluation and decision making in the respective areas of transportation asset management. Furthermore, the methodologies discussed in the paper can be replicated by facility managers and engineers at other agencies who seek to develop utility and value functions for their individual evaluation criteria. The explicit use of multiple criteria techniques for transportation decision making, spawned by current and evolving trends in the transportation environment, is poised to have a significant impact on the landscape of transportation decision making policy and practice. The anticipated benefits of this practice include greater transparency, and therefore greater accountability transportation investment and polices.

Acknowledgements

The contents of this paper reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Indiana Department of Transportation or the National Cooperative Highway Research Program, nor do the contents constitute a standard, specification, or regulation. We herein acknowledge the contributions of Professor Kumares Sinha, Dr. Vandana Patidar, Paul Thompson, and William Hyman.

References

Alinizzi, N., Chen, S., Labi, S., Kandil, A. (2018). A Methodology to Account for One-way Infrastructure Interdependency in Preservation Activity Scheduling, Computer-Aided Civil and Infrastructure Engineering, DOI: 10.1111/mice.12380.

Bai, Q., Labi, S., Sinha, K.C., Thompson, P. 2013. Multi-Objective Optimization for Project Selection in Network-Level Bridge Management Incorporating Decision-Maker's Preference Using the Concept of Holism , ASCE Journal of Bridge Engineering 18(9), 879–889.

Bai, Q., Ahmed, A., Li, Z., Labi, S. 2014. A Hybrid Pareto Frontier Generation Method for Trade-off Analysis in Transportation Asset Management, Computer-Aided Civil and Infrastructure Engineering 30(3), 163–180.

Bai, Q., Labi, S., Sinha, K.C. 2017. Traffic Volume Benchmarks for Major Arterial Widening versus Expressway Construction - An Exploratory Approach, Journal of Transportation Engineering 13(8), 10.1061/JTEPBS.0000065.

Carhart, N.J., Bouch, C., Walsh, C.L., Dolan, T. (2016). Applying a new concept for strategic performance indicators, Infrastructure Asset Management 3(4), 143–153.

Dojutrek, M., Volovski, M., Labi, S. 2015. Elemental Decomposition and Multicriteria Method for Valuing Transportation Infrastructure , Transportation Research Record 2460, 137–145.

Dojutrek, M., Dietz, E., Labi, S. 2016. A Multi-Criteria Methodology for Measuring the Resilience of Transportation Assets, International Journal of Disaster Resilience in the Built Environment 7(3), 290–301.

Dolan, T., Walsh, C.L., Bouch, C., Carhart, N.J. (2016). A conceptual approach to strategic performance indicators, Infrastructure Asset Management 3(4), 132–142.

Goicoechea, A., Hansen, D.R., Duckstein, L., 1982. *Multiobjective Decision Analysis with Engineering and Business Applications*, Wiley & Sons, New York, NY.

Keeney, R. L., and Raiffa, H., 1976. *Decision with Multiple Objectives – Preferences and Value Tradeoffs*, Wiley & Sons, New York, NY.

Khurshid, M. B., Irfan, M., Ahmed, A., Labi, S. 2014. Multidimensional benefit-cost evaluation of asphaltic concrete overlays of rigid pavements, Structure & Infrastructure Engineering 10(6), 792–810.

Labi, S., Chen, S., Preckel, P., Qiao, Y., Woldemariam, W. 2017. Rural two-lane highway shoulder and lane width policy evaluation using multiobjective optimization , Transportmetrica Part A: Transport Science 13(7), 631-656.

Lambert, J.H., Peterson, K.D., Wadie, S.M., Farrington, M.W., 2005. Development of a Methodology to Coordinate and Prioritize Multimodal Investment Networks, *Tech. Rep. FHWA/VTRC 05-CR14, Virginia Transp. Res. Council, Charlottesville, VA.*

Li, Z., and Sinha, K.C., 2004. Multicriteria Highway Programming Incorporating Risk and Uncertainty: A Methodology for Highway Asset Management System, *Tech. Rep. FHWA/IN/JTRP-2003/21*, W. Lafayette, IN.

Macharis, C., DeWitte, A., Ampe, J. 2009. The multi-actor, multi-criteria analysis methodology (MAMCA) for the evaluation of transport projects: theory and practice, J. Adv. Transp. 43(2), 183–202.

McNeil, S., Markow, M., Neumann, L., Ordway, J., Uzarski, D. (1992). Emerging issues in transportation facilities management, Journal of

Transportation Engineering 118 (4), 477-495.
Murillo Hoyos, J., Athigakunagorn, N., Labi, S. 2015. Rural Two-Lane Highway Safety Improvement Programming Using Constrained Network-Level Optimization, Transportation Research Part C Emerging Technologies 50, 106–116.
OECD, 2001. *Performance measures for the Road Sector, Organization for Economic Cooperation and Development*, Paris, France.
Oswald, M.R., McNeil, S. (2009). Rating sustainability: Transportation investments in urban corridors as a case study, Journal of Urban Planning and Development 136(3), 177–185.
Pickrell, S., and Neumann, L., 2000. Linking Performance Measures with Decision-making, Presented at the 79th Annual Meeting of the Transportation Research Board, Washington, D.C.
Patidar, V., Labi, S., Sinha, K.C., Thompson, P.D., Hyman, W.A., Shirolé, A., 2007a. Performance Measures for Enhanced Bridge Management, *Transportation Research Record 1991*, 43–53.
Patidar, V., Labi, S., Sinha, K.C., Thompson, P.D., Shirole', A. 2007b. *Multi-objective Optimization for Bridge Management Systems, NCHRP Report 590*, Transportation Research Board, Washington, DC.
Saaty, T. 1995. Transport planning with multiple criteria: the analytic hierarchy process applications and progress review. J. Adv. Transp. 29(1), 81–126.
Sinha, K.C., and Labi, S., 2007. *Transportation Decision-Making: Principles of Project Evaluation and Programming*, Wiley, New York, N.Y.
Sinha, K.C., Labi, S. Agbelie, B. 2017. Transportation Infrastructure Asset Management in the New Millennium: Continuing Issues, and Emerging Challenges and Opportunities, Transportmetrica Part A: Transport Science 13(7), 591-606.
Sivakumar, B., Minervino, C, M., Edberg, W., 2003. New Bridge Performance Measures for Prioritizing Bridges, 9th International Bridge Management Conference, Orlando, FL, 2003.
Speicher, D., Schwartz, M., Mar, T., 2000. Prioritizing Major Transportation Improvement Projects – Comparison of Performance measures, *Transportation Research Record 1706*, 38–45.
Srinivasan, R., Parlikad, A.K. (2017). An approach to value-based infrastructure management, Infrastructure Asset Management 4(3), 87–95.
Tsamboulas, D., Yiotis, G.S., Panou, K.D. 1999. Use of multicriteria Methods for Assessment of Transport Projects, *Journal of Transp. Engineering 125(5),* 407 – 414.
The World Bank, 2007. *Social Analysis Sourcebook: Incorporating Social Dimensions into Bank-supported Projects,* Social Dev. Dept., Washington, D.C.
TRB (2013). Strategic Issues Facing the Transportation Industry, Volumes 1-5, NCHRP Report 750, Washington DC.
USDOT. 2007. Results of the Joint AASHTO/FHWA Context Sensitive Solutions Strategic Planning Process, Technical prepared by the *Centre for Transportation and the Environment, North Carolina State University, Raleigh, NC*.
Younger, K., 1994. Multimodal Project Evaluation: A Common Framework, Different Methods, *Transportation Research Record 1429*, 24–29.
Zak, J. 2011. The methodology of multiple criteria decision making/aiding in public transportation. J. Adv. Transp. 45(1), 1–20.
Zheng, J., Garrick, N.W., Atkinson-Palombo, C., McCahill, C., Marshall, W. (2013). Guidelines on developing performance metrics for evaluating transportation sustainability, Research in Transportation Business & Management 7, 4-13