INTRODUCTION

The highway transportation system is a major component of most civil infrastructure systems and can be considered one of modern society’s critical foundations. In particular, bridges are an important item of the transportation system; because of their distinct function of joining highways as the crucial nodes, they are the most vulnerable element. In addition, bridges are exposed to aggressive environmental conditions and increasing traffic volumes and truck loads.

Maintaining the existing bridge infrastructure has become a major social and economic concern since bridges must be kept within acceptable limits of safety and serviceability. At the same time, maintenance, repair and replacement (MR&R) of bridges are very expensive items that involve large investments which are not always available to the transportation agencies. These agencies are required to go through a complex decision making process for selecting and prioritizing projects to implement the necessary actions in order to maintain a bridge network.

RANKING AND PRIORITIZING PROCEDURES

Ranking and prioritizing projects provide the insight needed for the decision making process. Ranking and prioritizing procedures have been widely used by several
departments of transportation to evaluate and select bridge projects. Capital budgeting decisions at the network level are commonly based on ranking procedures. Bridge management systems are required to produce the ranking of various projects in a network. Pontis, the most widely used bridge management system in the United States, provides this functionality and can rank projects according to a benefit-to-cost ratio, the average health index or the sufficiency rating for each project (AASHTO 2005). The following is a discussion of these procedures, including an overview of their major drawbacks.

**Benefit-to-cost ratio analysis**

The benefit-to-cost ratio analysis evaluates all of the benefits and costs associated with a project, including both direct agency cost and indirect user cost using the dollar as the unit of measure. Priority is given to projects that provide more benefits and incur less cost.

The direct agency cost can be estimated from the available cost data. On the other hand, the indirect user costs or benefits are difficult to quantify and are usually estimated using certain parameters or simplifying assumptions. The length of detour that users must take as an alternative route during the bridge improvement project can reflect the user cost and the reduction in accidents can represent the user benefit.

Kulkarni et al. (2004) reported that concerns arise when the benefit concept is applied to evaluate a large number of diverse projects at many different locations, as opposed to a small number of projects. These concerns include fairness in selecting projects, since the approach may select a project with a lower need ahead of another project with a higher need because of the lower cost for the first project. Also, an excessive amount of effort is needed to apply the concept to a large number of projects.

**Health index (HI)**

The HI is a performance measure for bridges which has been developed for the California Department of Transportation (Roberts and Shepard 2000). The HI measures the structural condition of a single bridge or a network of bridges by using quantitative condition data collected as a part of the bridge inspection program. This index determines the remaining bridge asset value and is based on the assumption that the asset value decreases as the element deteriorates over time. The equations to compute the HI are as follows:

\[
HI = \left( \frac{\Sigma CEV}{\Sigma TEV} \right) \times 100
\]

(1)

where CEV is the current element value and TEV is the total element value.

\[
TEV = \text{total element quantity} \times \text{failure cost of element}
\]

\[
CEV = \Sigma (\text{quantity condition state} \times \text{weighing factor}) \times \text{failure cost}
\]

The weighting factors depend on the number of condition states under considerations. Table 1 presents these factors.

**Table 1: Condition state weighting factors**

<table>
<thead>
<tr>
<th>Number of condition states</th>
<th>State 1 (WF)</th>
<th>State 2 (WF)</th>
<th>State 3 (WF)</th>
<th>State 4 (WF)</th>
<th>State 5 (WF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 Condition states</td>
<td>1.00</td>
<td>0.50</td>
<td>0.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 Condition states</td>
<td>1.00</td>
<td>0.67</td>
<td>0.33</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>5 Condition states</td>
<td>1.00</td>
<td>0.75</td>
<td>0.50</td>
<td>0.25</td>
<td></td>
</tr>
</tbody>
</table>
The HI is an average of the conditions of the bridge elements. Abu Dabous et al. (2008) argued that the HI is an overall representation of a bridge or a network condition and might not accurately reflect the conditions of specific bridge elements.

**Sufficiency rating (SR)**

SR is a concept developed by the Federal Highway Administration (FHWA 1988) in the United States to rate and rank bridge inventory. The FHWA uses SR to provide an overall assessment of a bridge’s condition and to determine eligibility for receiving federal funds. SR can be used in combination with other factors to prioritize bridge projects.

The SR scale ranges between 0 and 100 with 0 representing a completely deficient bridge and 100 a completely sufficient bridge. SR categorizes bridges into three groups: Bridges with SR between 80 and 100 require no action; bridges with SR between 50 and 80 are eligible for rehabilitation and those with SR between 0 and 50 are eligible for replacement.

A fairly complex formula is used and is described in the FHWA’s Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation’s Bridges. In addition, SR has some limitations (Sianipar 1997): (1) It is not sensitive to certain important factors such as average daily traffic; (2) SR is determined on the basis of a single standard; and (3) the method provides no room for optimization.

**MULTI-ATTRIBUTE UTILITY THEORY (MAUT)**

Realizing the drawbacks of the available ranking methods, an alternative innovative method for bridge ranking and prioritizing is proposed in this paper. The proposed method is based on the MAUT which enables the decision makers to include multiple and conflicting criteria and to incorporate qualitative and quantitative measurements in the ranking process.

The basic principle of the MAUT is based on estimating performance using attributes that are concrete, measurable and representative to the degree of satisfaction with the various aspects of each alternative. The attributes of each alternative specify the characteristics of that particular alternative and can serve as scales against which the levels of achievement of the alternative are measured. The foundation of the MAUT is the use of utility functions, which are utilized to quantify the preference of the decision maker by depicting the degree of satisfaction, as the attribute under consideration takes values between the most and least desirable limits.

The purpose of the utility functions is to transform the measures of the different attributes into a common dimensionless scale ranging from zero to one. The utility functions can transform objective data such as the alternative measurable number of units or subjective knowledge such as expert judgment into a utility score. Having a representative set of utility functions, alternatives can be scored and ranked in a systematic way given that the value of the various attributes (objective and subjective) are readily available. To evaluate an alternative, the utility values of its attributes can be aggregated to estimate an overall utility or degree of satisfaction. The preferred alternative is normally the alternative with the highest overall utility score.
The most challenging step in implementing the MAUT is the development of the utility functions. Several procedures have been proposed to this end. Keeney and Raiffa (1993) discussed the most elaborate methods to develop these functions. The utility value is often defined on a normalized scale as the attribute changes between its lower and upper bounds and the function is usually evaluated by the certainty equivalence method developed by Keeney and Raifa (1993). However, it has been recognized that the convergence procedure in assessing a certainty equivalent is time-consuming and complicated (Pan and Rahman 1998).

Benefiting from the guidelines established by Keeney and Raiffa (1993) and from the intuitive Eigenvector approach embedded in the AHP (Saaty 1980), a novel procedure to develop the utility functions is developed and discussed in the next section.

**Procedure to develop utility functions**

To develop a utility function, the AHP can be used to extract the judgments regarding the relative importance between the different levels of an attribute, and the Eigenvector approach can be used to estimate the utility associated with each of these levels. The following is a detailed description of the procedure.

1. Define boundaries of the utility function:
   - Choose a value for the attribute under consideration that corresponds to the lowest utility and represents the least desirable scenario. This value represents the least preferred consequence L and has the lowest utility.
   - Assign a value of the attribute under consideration that corresponds to the highest utility and represents the most desirable scenario. This is the most preferred consequence M and has the highest utility. The M value can be found by finding the value of the attribute that has absolute importance over the least preferred consequence, L.
   - If $ L < M $, then the utility function is monotonically increasing and if $ L > M $, then the utility function is monotonically decreasing. A monotonically increasing function means that the attribute values selected in the following steps must be higher than L and are increasing in value each step, while the monotonically decreasing function means that the attribute values selected in the following steps must be lower than L and are decreasing in value with each step.

2. Within the defined boundaries (L and M), define a value of the attribute that has a slight importance over the least desirable scenario. This value is the attribute value that experience and judgment slightly favour over the value for the least desirable scenario. The intensity of the relative importance between this value and the least desirable scenario is 3 according to the scale of relative importance developed and validated by Saaty (1980).

3. Repeat step 2 to define a value of the attribute that has demonstrated importance when compared with the least desirable scenario. This value is the attribute value that experience and judgment strongly favour over the value for least desirable scenario and its dominance is demonstrated in practice. The intensity of the relative importance between this value and the least desirable scenario is 7 according to the scale of relative importance (Saaty 1980).

4. Develop a reciprocal and consistent matrix using the judgments from steps 2, 3 and 4. This matrix can be developed by applying the following three constraints to all elements in the matrix: $ a(ii) = 1 $, $ a(ji) = 1/a(ij) $, and $ a(ij) = ... $
a(ik) × a(kj). Where the elements in parenthesis are the row and column numbers respectively of any element a in the matrix.

Enforcing consistency is permissible in this case since the decision maker will review the developed utility function and can revise the judgments in the previous steps if the function does not represent the attribute under consideration. The eigenvector can be estimated for the developed matrix and then used to develop the utility points that correspond to the various levels of the attribute as shown in Figure 1. For convenience, the range is set from 0 to 100 instead of the 0 to 1 conventional range.

**Figure 1: Transforming the Eigenvector to utility points**

<table>
<thead>
<tr>
<th>Eigenvector</th>
<th>Ratios of Eigenvector</th>
<th>Utility Point (Ratio x 100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W_{max}</td>
<td>W_{max} / W_{max}</td>
<td>100</td>
</tr>
<tr>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>W_i</td>
<td>W_i / W_{max}</td>
<td>u_i</td>
</tr>
<tr>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>W_{min}</td>
<td>W_{min} / W_{max}</td>
<td>u_{min}</td>
</tr>
</tbody>
</table>

**Sample application of the utility function development**

The following is an example to demonstrate utility function development using the above procedure. A utility function for the bridge deck condition index is developed. The index ranges between 0 and 100 where 100 signifies the best possible condition. The utility function is required to represent the urgency for intervention based on the bridge deck condition.

First, the boundaries of the utility function are established. A bridge with a condition index higher than 90 is considered to be in excellent condition and does not require intervention. The 90 condition index is the least desirable value of the attribute and corresponds to the lowest utility value. On the other hand, the bridge index is not allowed to drop below 40 since a bridge with a condition index less than 40 becomes unsafe for the public. As a result, the most desirable value of the attribute is 40 which represents absolute importance over the lease desirable one and this value is given the maximum utility of 100. The utility function is monotonically decreasing.

Within the defined boundaries, the decision maker should specify the value of the bridge index that has weak importance, and the one that has demonstrated importance with respect to the least desirable scenario which is the condition index of 90. The decision maker realizes that a bridge with a condition index of 80 does not need intervention and as a result, it has a weak importance compared to 90. Meanwhile, a bridge with condition index 65 is due for intervention and has essential importance compared to 90. Based on these judgments, a consistent reciprocal matrix is developed and the utility points are estimated as shown in Figure 2.
The utility points are plotted against the different values of the bridge index, as shown in Figure 3. In this case, the condition index 40 is given the highest utility and it is more than double the utility given for condition index 80.

The decision maker(s) can inspect the developed utility function to ensure that it reflects the degree of satisfaction with the different levels of the attribute and can resubmit the judgments to adjust the function if necessary.

<table>
<thead>
<tr>
<th>Condition Index</th>
<th>90</th>
<th>80</th>
<th>65</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eigenvector</td>
<td>0.05</td>
<td>0.15</td>
<td>0.35</td>
<td>0.45</td>
</tr>
<tr>
<td>Utility Point</td>
<td>11.11</td>
<td>33.33</td>
<td>77.77</td>
<td>100</td>
</tr>
</tbody>
</table>

Figure 2: Pairwise comparison matrix, Eigenvector and utility points

DEVELOPMENT OF THE RANKING METHOD

The ranking method is based on the MAUT. The first step toward the development of the ranking method is breaking down the problem under consideration into a hierarchy structure. Eleven interviews with bridge engineers and decision makers from two ministries of transportation and two private companies were performed as a part of the research information collection. The objective of the interviews is to identify the main elements of the decision making process. These decision elements collected from the interviews are organized into a four-level hierarchy structure, which was found to be sufficient to capture the main elements of the problem under consideration. The natural top-down approach is used to develop the structure. This approach starts with identifying the overall goal and proceeding downward until all the measures of value are included.

The first level of the hierarchy is the overall goal of the ranking exercise. The second level contains the objectives necessary to achieve the overall goal. The third level of the hierarchy holds the criteria to be used for evaluating the objectives. The alternatives are added at the bottom level. Figure 4 presents the hierarchy structure developed in this research. Each objective or criterion has a specific weight reflecting its importance. The weights are defined based on the experts judgments extracted.
during the interviews. The hierarchy structure development and discussion of the various elements in the structure are presented in details in Abu Dabous (2008).

The utility functions measure the level of attainment of the various attributes of each bridge with respect to the evaluating criteria. These functions are developed using the procedure presented earlier. The utility functions for the different criteria under consideration are developed and provided also in Abu Dabous (2008).

Figure 4: Hierarchy structure for the ranking method
EXPECTED UTILITY VALUE

Upon constructing the decision hierarchy and selecting the appropriate utility functions, a utility model can be used to aggregate the utility values for the various attributes. Since the elements in each level of the hierarchy structure are considered to be independent, the additive utility model can be used as a simple and practical approach to aggregate utilities (Keeney and Raiffa 1993). In such a model, the overall relative utility is expressed as follows:

\[ U(x_1, x_2, \ldots, x_n) = \sum_{i=1}^{n} k_i u_i(x_i) \]  

(2)

where \( k_i \) is the weight for attribute \( i \), and \( u_i \) is utility value for attribute \( i \).

The utility scores obtained from the utility functions are aggregated using Equation 2 to estimate the utility associated with each objective. Then, the utilities of the various objectives are aggregated using the same equation to evaluate the overall utility of the bridge. All bridges in the network or sub-network can be ranked based on the overall utility values.

CASE STUDY

In order to demonstrate the application of the developed ranking method, a sample sub-network consisting of eleven bridge projects is considered. Data for these bridges is extracted from reports provided by the Ministry of Transportation of Ontario. Some data is not available in the provided reports, such as the load carrying capacity. This was compensated by requesting an expert from the industry to provide his assessments for the missing data. Sample data for three projects is shown in Table 2. The attributes values are transformed to utility values using the corresponding utility function of each criterion.

Table 2: List of attributes and the utility values of projects 10, 20, and 30

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Attribute</th>
<th>Utility</th>
<th>Attribute</th>
<th>Utility</th>
<th>Attribute</th>
<th>Utility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition rating</td>
<td>64</td>
<td>78.66</td>
<td>66.36</td>
<td>73.6</td>
<td>37.37</td>
<td>100</td>
</tr>
<tr>
<td>Load carrying capacity</td>
<td>1.6</td>
<td>28.89</td>
<td>2.2</td>
<td>8.88</td>
<td>1.3</td>
<td>51.11</td>
</tr>
<tr>
<td>Seismic risk</td>
<td>2.6</td>
<td>28.89</td>
<td>4.5</td>
<td>50</td>
<td>8.0</td>
<td>85.18</td>
</tr>
<tr>
<td>Average daily traffic</td>
<td>40,000</td>
<td>33.33</td>
<td>50,000</td>
<td>39.25</td>
<td>35,000</td>
<td>29.63</td>
</tr>
<tr>
<td>Supporting road type</td>
<td>Local</td>
<td>11.11</td>
<td>Regional</td>
<td>33.33</td>
<td>Local</td>
<td>11.11</td>
</tr>
<tr>
<td>Vertical clearance</td>
<td>0.25</td>
<td>24.44</td>
<td>0.20</td>
<td>28.89</td>
<td>0.12</td>
<td>46.66</td>
</tr>
<tr>
<td>Approach condition</td>
<td>Fair</td>
<td>77.77</td>
<td>Fair</td>
<td>77.77</td>
<td>Poor</td>
<td>100</td>
</tr>
<tr>
<td>Drainage system</td>
<td>0.60</td>
<td>62.95</td>
<td>0.60</td>
<td>62.95</td>
<td>0.70</td>
<td>77.77</td>
</tr>
<tr>
<td>Expected utility value</td>
<td>44.49</td>
<td>42.78</td>
<td>64.35</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The expected utility value for each project in the network is estimated using Equation 2. The utility values for the various attributes of each project are aggregated using the
weights of criteria and objectives. The weights for attributes and criteria are provided in Figure 4. For example, the expected utility value for bridge 10 is as follows:

\[
U = ((78.66 \times 0.4 + 28.89 \times 0.45 + 28.89 \times 0.15) \times 0.60) + ((33.33 \times 0.55 + 11.11 \times 0.45) \times 0.20 + ((24.44 \times 0.4 + 77.77 \times 0.35 + 62.95 \times 0.25) \times 0.20 = 44.49
\]

Projects in the sub-network can be ranked according to the overall expected utility, where bridges with higher overall expected utility must be prioritized for action. It is clear that Bridge 30 has the highest priority followed by Bridge 10 and then Bridge 20.

**CONCLUSION**

Ranking and prioritizing projects are essential steps in bridge management. The current methods for ranking and prioritizing bridge projects are associated with drawbacks. This paper proposes an innovative ranking method for bridge networks, based on the MAUT. The theory provides flexibility for the decision makers in expressing their degree of satisfaction with each bridge attribute. In addition, the theory enables the decision makers to include multiple and conflicting criteria and to incorporate qualitative and quantitative measurements in the ranking process. Also, the paper presents an innovative technique to develop the necessary utility functions. The proposed method is validated using a case study.

**REFERENCES**


