Multi-Criteria Comparison of Bridge Designs

András Farkas

Faculty of Economics, Óbuda University
Tavaszmező út 17, H-1084 Budapest, Hungary
e-mail: farkas.andras@kgk.uni-obuda.hu

Abstract: The selection of a bridge design from among a number of alternatives that meets desired conditions is a complex task. In such projects the stakeholders may have conflicting interests as they represent dissimilar perspectives. It is especially difficult to simultaneously satisfy the diverse engineering, economical, legal and environmental requirements implying both tangible and intangible data of multiple criteria. This paper discusses the methodology and the key activities of the project completion reports of bridge designs. The fundamentals of two well-known methods, a multiple-criteria decision making method, the analytic hierarchy process (AHP) and the Kane simulation technique (KSIM) are described. A realistic application of these methods to the evaluation and comparison of three bridges of different types is also presented.

Keywords: bridge design; analytic hierarchy process; Kane simulation

1 Introduction

In the planning of bridges, the close relationship between design and construction planning should be recognized. Broadly speaking, design is a process of creating the description of a new bridge, usually represented by detailed plans and specifications; construction planning is a process of identifying activities and resources required to make the design a physical reality. Hence, construction is the implementation of a design envisioned by architects and engineers. Several characteristics are unique to the planning of bridges and should be kept in mind even at the very early stage of the project life cycle. These include that nearly every bridge is custom-designed, it often requires a long time to complete, both the design and construction must satisfy several potentialities peculiar to a specific site and its execution is strongly influenced by natural, social, environmental and other local conditions.

The planning for a construction project begins with the generation of concepts which should meet the required engineering standards and the stakeholders' needs. Innovative concepts in design are highly valued for their contributions to reducing costs and to the improvement of aesthetics, comfort or convenience and environmental aspects. They must be tested for technological feasibility, safety and economic attractiveness. Since bridge construction is site specific, it is very important to investigate the subsurface conditions which often affect the design as well as its foundation. The uncertainty in the design is particularly acute in geotechnical engineering so that the assignment of risks in this area should be a major concern. Since the degree of uncertainty in a project is perceived differently by different parties involved in a given project, the assignment of risks arising from numerous unknowns to the owner, engineer and contractor is inherently difficult. For more detailed information about bridge projects, the interested reader may turn to the excellent books of [1] and [9].

An integral part of the planning process is to examine and evaluate various alternatives of the different bridge designs with respect to the desired system of criteria set up by the stakeholders. The analytic hierarchy process (AHP) is a multiple criteria scaling method proposed by T. Saaty [12]. It was designed to cope with both the rational (measurable characteristics) and the intuitive (qualitative attributes) in order to select the best from a number of alternatives evaluated with respect to several criteria. In this procedure the decision maker (stakeholder) carries out pairwise comparison judgments for every possible pair of alternatives according to each criterion. These are used to develop the overall priorities for ranking the alternatives.

The design process attempts to optimize a number of objectives in determining the suitability of a particular bridge for a defined geographic site and often involves a multitude of factors, sometime contradicting. Some of the important factors that add to the difficulty of the proper choice include the existence of possible options within a territory, intangible objectives, the diversity of interest groups, uncertainties regarding the objectives as well as their timing and magnitude, government and public influence on the design process through legislation, and uncertainties regarding possible delays of permitting and construction. In this paper the AHP method will be used to evaluate and compare bridge designs of different types (a cable-stayed suspension bridge, a truss bridge and a tied-arch bridge) planned to build at a given location as a flagship project of a given district in the USA. To relax some limitations of the AHP the use of a qualitative structural modeling technique called Kane simulation language (KSIM) [10] will also be discussed and applied to help the stakeholders in understanding the dynamic behavior of the system of evaluation criteria through the development of the interactions among the variables.

In Section 2, the methodology and the key activities related to the preparation of a bridge project completion report are discussed. In Section 3, a brief overview of the AHP method is presented. In Section 4, the KSIM procedure is shortly described together with its mathematical background. Finally, in Section 5, a real-world application of these methods to a bridge selection problem is reported.

2 The Methodology and Key Activities of Bridge Project Completion Reports

The preparation of a project completion report for a bridge design includes a series of multi-task professional activities (see e.g. in [16]). The major functional areas and the necessary content of a comprehensive preliminary analysis are described below.

2.1 Engineering and Project Management Analysis

The technical assistance experts (TA) appointed to a given project are responsible for reviewing the engineering aspects of the preliminary study and the design prepared by the feasibility study consultants. An engineering feasibility study is based on test work and subtle engineering analysis, which presents enough information to determine whether or not the project should be advanced to the final engineering and construction stage. The conceptual study is the first document that should be completed on a project. This is the preliminary evaluation of a project and is based on assumptions and factors. Conceptual studies typically identify technical issues that will require additional examination or test work. Generally, the end result of the study is a description of the general features and parameters of the project and an order of magnitude estimate of capital and operating costs. The TA consultants should ensure that the studies and plans are based on uniform design methodologies and design standards, with allowable variations on account of specific site conditions. Sites will be visited as necessary. Topographic surveys, hydrological risks of changing river morphology, design standards, traffic studies, proposed improvements and alignment, soil and material investigations, pavement options, toll plaza and wayside amenities, drainage and bridge structures, road safety measures, contract packaging, and cost estimates are reviewed. The TA will also carry out an institutional assessment of the project, focusing on the suitability of the current staff strength and expertise, authority for successful project management, and its current reporting arrangements. They will make recommendations on the institutional arrangements that need to be granted to ensure successful construction planning and implementation of the proposed bridge.

The assessment of institutional capability investigations for engineering and project management must comprise the following tasks:

(i) Review the existing traffic data, traffic counts, origin-destination, axle load surveys, and traffic forecasts for the project.

(ii) Review the engineering aspects (road, bridges, and river training works) in the feasibility study and preliminary design, and do surveys necessary to collect additional information and to verify the data and analysis, as well as the major engineering characteristics (geometric data, structural materials, bearing forces, mechanical stresses, vibration modes, etc.).

(iii) Review the cost estimates for the proposed improvements for the project components.

(iv) Establish criteria for selecting bidders, and assist in evaluating proposals and selecting successful bidders, as required.

(v) Carry out an institutional assessment necessary for successful project implementation.

(vi) Review the contracting practices of the authorities and the investors and recommend measures to ensure effective utilization of project funds in line with good governance principles.

2.2 Economic Analysis

Economic expert assistance should be provided to supplement efforts in ensuring that the economic analysis is in accordance with the state/regional *Guidelines for the Economic Analysis of Projects*. The TA reviews and improves as necessary

(a) the feasibility study, the consultants' economic analysis of the proposed bridge project; and

(b) the traffic forecasts, cost estimates, and benefits.

The economic internal rate of return (EIRR) will then be calculated. Sensitivity analyses are carried out with the project's risk assessment. The TA conducts additional surveys as necessary, and prepares the benefits distribution analysis. In addition, it is highly recommended that the TA look into the fiscal implications of the financing, sustainability, and eventually the foreign exchange components of the Government/ State taking loans for the implementation of the project and identify how the Government/State can raise the revenue necessary to finance its portion of the total cost. The TA may perform a comparative economic assessment of the project vis-a-vis other proposed bridge projects of similar size.

The assessment of the economic analysis should comprise the following tasks:

(i) Review the feasibility study, economic analysis, sensitivity analysis, and traffic diversion.

(ii) Prepare a socioeconomic profile of the area of influence, based on a review of existing studies and surveys of the representative road section.

(iii) Analyze the fiscal impacts of the project cost on the Government's/State's fiscal policies and sustainability, and the macroeconomic implications for the country.

(iv) Review the impacts of the investment in the bridge on other sectors.

(v) Analyze possible sources of revenue that the Government/State could use to finance its portion of the proposed construction cost.

(vi) Assess competitiveness in the road transport industry and the likelihood of vehicle cost savings being passed on to the general community.

(vii) Prepare a distribution analysis of the quantified benefits of the proposed project.

2.3 Financial Analysis

The TA should carry out a detailed financial analysis of the proposed project in accordance with the state/regional *Guidelines for the Financial Management and Governance of Investment Projects*. The TA reviews the project cost estimates and then will propose a financing plan. Also the TA prepares financial projections as well as the financial internal rate of return (FIRR) and compares it with the weighted average cost of capital (WACC). Sensitivity analysis will be carried out with the project's risk assessment. The minimum acceptable rate of return (MARR), also called the hurdle rate, is the minimum rate of return on a project the financial management is willing to accept before starting the project, given its risk and the opportunity cost of forgoing.

The key activities are to be undertaken in the financial analysis assessment component include the following tasks:

(i) Review project cost estimates and proposed drawdown schedules as provided by the engineers.

(ii) Review the proposed financing plan and assess the capacity of financiers to fulfill financing obligations to the project.

(iii) Assess and prepare financial projections for the proposed project.

(iv) Carry out a financial evaluation as well as a sensitivity analysis over the project construction and operation period by calculating the financial internal rate of return (FIRR) and comparing it with the weighted average cost of capital (WACC).

(v) Undertake a financial management assessment, which should include an assessment of the financial management control systems in place.

(vi) Collaborate with the project economist to ensure the consistency of the approach and the assumptions between financial and economic analyses.

2.4 Environmental Impact Study

The TA should collaborate with the appointed experts in complying with the environmental safeguard policies, by ensuring that environmental assessments are prepared in accordance with the Government's/State's environmental requirements, state/regional *Environmental Assessment Guidelines.* The consultants review, verify, and recommend any revision necessary to the environmental management plan prepared by the independent consultants and perform the environmental impact assessment (EIA) reports, including an environmental management and monitoring plan, in accordance with the approved environmental policy.

The work assignments that need to be carried out by the consultant for this component include, but are not limited to, these tasks:

(i) Review the environmental studies undertaken by the Government/State and other funding agencies and identify additional works to comply with State's environmental safeguard policy.

(ii) Based on environmental studies reports prepared by the Government/State and other funding agencies as well as civil environmentalist organizations, undertake an exercise to confirm the scope of the environmental impact assessment (EIA) study to determine

(a) environmental aspects that will be affected by the project;

(b) which environmental data should be collected as data primer and which data from secondary data sources will be adequate; and

(c) the boundary of the project area and the affected areas.

The scope of the EIA study should be set by consulting relevant stakeholders that may include local communities.

(iii) Gather necessary environmental data and describe systematically the environmental conditions of the study area, i.e., project areas and affected areas. For ecological conditions, collect primary data for water conditions as well as the bottom sediments of the river.

(iv) Work closely with the project engineers to identify project activities that would generate environmental impacts.

(v) Assess the environmental impacts of the proposed project in detail by following the order of the project cycle (impact during preconstruction/associated with location, environmental impact during construction and operation). The assessment should cover direct and indirect impacts and main project activities as well as supporting activities such as construction of bunds to regulate river flow, if any; construction of approach roads, if any; construction for river training; dredging; and others.

(vi) Classify the significance of the identified impacts.

(vii) Prepare mitigating measures in detail for technical, social, and institutional aspects of all expected environmental impacts.

(viii) Work closely with the project economist of the team to provide a detailed assessment of alternatives, and undertake environmental cost and benefits analysis.

(ix) Prepare a detailed environmental management plan and a monitoring plan.

(x) Undertake adequate consultation with local communities when preparing the EIA study. Two-step consultations are needed:

(a) to determine the public's concerns;

(b) to inform the public of the findings of the study.

(xi) Prepare concise EIA.

3 Overview of the AHP Method

In this section we describe the major characteristics of the AHP in short. The most effective form used to structure a decision problem is a hierarchy consisting usually of three levels: the goal of the decision at the top level, followed by a second level containing the criteria by which the alternatives, located in the third level, will be evaluated. Hierarchical decomposition of the given complex system is central to AHP.

The AHP is used to derive the most advanced scales of measurement, called ratio scales, from both discrete and continuous paired comparisons in multilevel hierarchic structures. These comparisons may be taken from actual physical measurements or from subjective estimates that reflect the relative strength of preferences of the experts. Since the number of the participants (experts) in such a decision making group is usually 5-15, there is a need for aggregation, which is called the process of synthesizing group judgments. By synthesizing the particular priorities with the average weighting factors of the attributes, the ultimate output is yielded in the form of a weighted priority ranking indicating the overall preference scores for each of the alternatives under study. Thus, AHP is a method that can be used to establish measures in both the physical and human domains. The AHP is especially concerned with departure from consistency, and the measurement of this departure and dependence within and between the groups of elements of its structure.

The AHP utilizes relative comparisons to derive ratio scales of measurement. Here, the alternatives are compared in pairs according to a common attribute. The relative measurement, w_i, i=1,…,n, of each n elements is a ratio scale of values assigned to that element and derived by comparing it in pairs with the others. In paired comparisons, two elements i and j are compared with respect to a property they have in common. The smaller i is used as the unit and the larger j is estimated as a multiple of that unit in the form $(w_i\ /\ w_j)\ /1$ where the ratio $w_i\ /\ w_j$ is taken from a fundamental scale of absolute values. Thus, such a dominance matrix of these ratio comparisons, denoted by **A**, may be given in the form:

$$\mathbf{A} = \begin{bmatrix} 1 & \frac{w_1}{w_2} & . & . & . & \frac{w_1}{w_n} \\ \frac{w_2}{w_1} & 1 & . & . & . & \frac{w_2}{w_n} \\ . & & . & & & . \\ . & & & . & & . \\ . & & & & . & . \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} & . & . & . & 1 \end{bmatrix}.$$

The process produces a ratio scale score for each alternative. The scores thus obtained of the alternatives can finally be normalized by dividing each of them by their sum.

Paired comparison judgments in the AHP are applied to pairs of homogeneous elements. The fundamental scale of values proposed by Saaty [14] to represent the intensities of judgments is shown in Table 1. This scale has been validated for effectiveness by numerous applications in a variety of professional fields of interest. As a matter of fact, for these ratios, arbitrary positive numbers can also be used, e.g. 4.1 or 6.87, or even beyond the lower and upper boundaries of the proposed scale, e.g. 23.6 or 0.05.

Table 1
The fundamental scale used in the AHP [14]

Intensity of importance, Strength of preference	Definition	Explanation
1	**Equal importance**	Two activities contribute equally to the objective
2	Weak	
3	**Moderate importance**	Judgment slightly favor one activity over another
4	Moderate plus	
5	**Strong importance**	Judgement strongly favor one activity over another
6	Strong plus	
7	**Very strong importance**	An activity is favored very strongly over another
8	Very, very strong	
9	**Extreme importance**	Favoring one activity over another is of the highest affirmation
Reciprocals of above	If activity *i* has one of the above nonzero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	

The major objective of using a scaling method is to derive the vector of weights (termed as decision priorities) from the input data elicited from experts' judgments and/or from measurements. In the AHP, this task is accomplished by an eigenvalue-eigenvector formulation which is well-known in linear algebra. The components of the weights of the alternatives are given by the (normalized) components of the right-hand side eigenvector associated with the maximal eigenvalue of matrix **A**. It should be noted that there are a great number of other methods to generate these priorities, e.g., extremum value procedures, like the least squares optimization method [3, 4], or using the singular value decomposition of the comparison matrix [8]. An excellent review of these procedures can be found in [3]. Of course, there is no perfect scaling method which would outperform all the others with respect to each of the relevant properties. One of the most important features is the consistency condition, commonly interpreted in practice as the degree of inconsistency of the matrix of comparisons. This measure is directly related to the variance of the error incurred in estimating the entries of the matrix by the respondents. The AHP includes a consistency index for both the single matrices and also for the entire hierarchy.

We now give the formal description of the mathematics of the AHP in a concise form:

Let the finite set of alternatives (systems, objects) be denoted by A_i, i=1,2, ...,n. Let C_k, k=1,2, ...,m, denote a criterion (attribute) with respect to which every alternative is being evaluated. Let an $n\times n$ matrix $\mathbf{A}=[a_{ij}]$ with all entries positive numbers ($n\geq3$) be introduced. Matrix **A** is called a *symmetrically reciprocal* (SR) matrix if the entries satisfy $a_{ij}a_{ji}=1$ for $i\neq j$, $i,j=1,2, ...,n$, and $a_{ii}=1$, $i=1,2, ...,n$. The use of these matrices was first proposed by Saaty [12]. Here an entry a_{ij} from R^n represents a *ratio*, i.e., a_{ij} indicates the strength with which alternative A_i dominates alternative A_j with respect to a given criterion C_k. Such a matrix is called a *pairwise comparison* matrix (PCM) and is usually constructed by eliciting experts' judgments. The basic objective is to derive implicit *weights* (priority scores), $w_1,w_2, ...,w_m$, with respect to each criterion C_k. A vector of the *weights*, $\mathbf{w}=[w_i]$, $w_i>0$, $i=1,...,n$, may be determined by using the eigenvalue formulation $\mathbf{A}\mathbf{w}=\lambda\mathbf{w}$. Since the single criteria are usually not equally important, therefore, a vector of the *weighting factors* of each criterion, $\mathbf{s}=[s_k]$, should also be determined, where s_k, $k=1,2, ...,m$ is often normalized so that $0< s_k <1$.

Further, let an $n\times n$ matrix $\mathbf{B}=[b_{ij}]$ denote an element-wise, positive matrix whose entries are all nonzero numbers. Matrix **B** is called a *transitive* matrix if $b_{ij}b_{jk}=b_{ik}$, for $i,j,k=1,2, ...,n$. In [7] it is proven that any transitive matrix is a one-rank SR matrix. In the AHP, a transitive matrix **B** is usually termed a *consistent* matrix. If the PCM is not transitive, then it is termed *inconsistent*. Saaty [13] proved that the priority score of an alternative, what he called the *relative dominance* of the *i*th alternative A_i, is the *i*th component of the principal right eigenvector of **B**, u_i, i.e., even if the PCM is *not* transitive. The *principal* right eigenvector belongs to the eigenvalue of largest modulus. The eigenvalue of largest modulus will be called the *maximal* eigenvalue. By Perron's theorem, for matrices with positive elements, the maximal eigenvalue is always positive, simple and the components of its associated eigenvector are positive [15]. Since any transitive matrix can be expressed as the product of a column vector **u** and a row vector $\mathbf{v}^T$, **B** can be written in the form of an the outer product: $\mathbf{B}=\mathbf{u}\mathbf{v}^T$ (the superscript indicates the transpose). This way, it can be shown that the characteristic polynomial of **B**, $p_n(\lambda)$ can be obtained in the form: $\lambda^{n-1}(\lambda-1)$. From this expression it is apparent that **B** has a zero eigenvalue with multiplicity $n-1$ and one simple positive eigenvalue: $\lambda=n$, with its corresponding right and left eigenvectors, **u** and $\mathbf{v}^T$, respectively. The weights w_i, $i=1,...,n$, of the alternatives are given by the components of **u**. This solution for the weights is *unique* up to a multiplicative constant. Conventionally, it is normalized so that its components sum to unity.

In the transitive case the eigenvector method provides the true relative dominance of the alternatives. In reality, however, an individual cannot give his/her estimates such that they would conform to perfect consistency. Recognizing this fact, Saaty [12] proposed a *measure* for the *inconsistency* of a PCM: $\mu=(\lambda_{\max}-n)/(n-1)$. Results might be accepted if $\mu\leq0.08$. Otherwise the problem should be reconsidered and the associated PCM must be revised [13]. Obviously, for a consistent PCM: $\mu=0.00$, since this fact apparently follows from the above considerations (i.e. in that case: $\lambda_{\max}=n$).

To compute the components of the *overall priority scores*, $\pi_1, \pi_2, ..., \pi_n$, (or overall weights) for the set of the alternatives (i.e. when taking into account the weighting factors of each of the criteria) the AHP utilizes an *additive* type aggregation function: $\pi_i=\sum^{m}_{k=1}s_k w_{ik}$, i=1,2, ...,n. We note that there are other ways of computing the overall priorities, e.g. a *multiplicative* weighted-geometric-mean aggregation is proposed in [2].

4 Structural Modeling – Kane Simulation (KSIM)

A specific mathematical language (KSIM) originally called Kane simulation [10] has been developed and designed for interactive team use. Many features of the different versions of KSIM make it particularly appropriate for use in project planning, investment analysis, formulating environmental policy, etc., since the

(1) KSIM is easily grasped by the nonmathematical specialist and can communicate the workings of complex, nonlinear feedback systems to such people,

(2) KSIM allows for ready entry of such 'soft' subjective variables as environmental quality,

(3) KSIM emphasizes the significance of structural relations rather than exact numerical prediction,

(4) KSIM is flexible and it can be easily generalized, and

(5) KSIM is sufficiently powerful that it can express the interaction of variables in an easily interpretable way and graphic fashion.

Realistic problems involve a multiplicity of interacting variables, presenting a complexity of behavior that usually dwarfs human capacity for comprehension. The direct use of non-quantitative variables within the KSIM framework is one of its main advantages, so they are usually incorporated in the model of the complex systems to be analyzed by the procedure. Such models can be formulated and run not only by highly skilled computer scientists; project managers and policy makers may also use them without having specific knowledge in applied informatics.

The procedure is simplicity itself. First, all the relevant variables (both the tangible and the intangible ones) x_i, i= 1,2,...,N are selected and listed. Each of these variables is assigned an appropriately chosen *initial value*, $x_i(0)$. It is the nature of all variables encountered in human experience to be bounded. Invariably there is a minimum below which the variable cannot descend, and at the other extreme there is a maximum beyond which it cannot penetrate. Thus, the range of each of the variables can always be scaled on an interval scale between zero and one.

Second a matrix $\mathbf{M}=[m_{ij}]$, $i,j= 1,2,...,N$, is developed, called a *cross-impact* matrix, elements of which are real numbers positive and negative integers. The entries m_{ij} of this matrix **M** are elicited from subjective judgments made by the members of the decision making group. **M** summarizes the interactions between the variables. The estimation procedure is done in the following manner. At each location we enter the action of the column heading upon the row heading. A plus entry indicates that the action of variable *A* upon variable *B* is positive. In other words, *A* (or more properly the change in *A*) induces *B's* growth and such an effect will be proportional to both the relative size of *A* and the magnitude of the interaction coefficient (not necessarily integer values). Similarly, a minus entry indicates that the action of the impacting variable gives rise to decay in the impacted variable. Self-interactions appearing at the main entries are mostly zeros indicating the lack of autocorrelation, or they can be positive in accord with the idea that a variable may tend to foster its own growth. An exception is when a variable is set as minus. This is to suggest that this variable has reached a stage of obsolescence in its evolution.

There is an extremely important pedagogical value in choosing the matrix entries as combinations of pluses and minuses rather than numerical entries. By not asking for numerical coefficients at the outset psychological barriers are greatly reduced, stimulating group participation and discussion. Furthermore *subjective* variables can very easily be introduced and there is no inhibition in making them plays their proper role. Of course, ultimately the pluses and minuses are translated into specific numbers. These numbers express not only the direction of the impacting effects, but their magnitudes. In this respect Saaty's propositions can be used (see in Table 1), i.e., for the relationship between a particular numerical value and the strength of an effect. In line with the real-world occurrences, the entries in the cross-impact matrix **M** are not necessarily symmetric, the action of *A* upon *B* is not usually the same as *B* upon *A*. In KSIM, each interaction is weighted proportionately to the strength of the interaction and also to the relative size of the variable producing the interaction. Although the model seems to imply that the impact coefficients are constants, this need not be so, since they are changing in the course of the iteration process. Also, and most important, growth and decay follow logistic type growth variations, i.e. they are sigmoidal curves rather than exponential ones, *automatically limiting reaction rates near threshold and saturation.*

The properties of the original version of KSIM and the mathematics with which it achieves these features is outlined below (quoted from [10]):"

(1) System variables are bounded. It is now widely recognized that any variable of human significance cannot increase indefinitely. There must be distinct limits. In an appropriate set of units these can always be set to one and zero.

(2) A variable increases or decreases according to whether the net impact of the other variables is positive or negative.

(3) A variable's response to a given impact decreases to zero as that variable approaches its upper or lower bound. It is generally found that bounded growth and decay processes exhibit this sigmoidal character.

(4) All other things being equal, a variable will produce greater impact on the system as it grows or it declines larger.

(5) Complex interactions are described by a looped network of binary interactions.

With these conditions consider the following mathematical structure. Since state variables are bounded above and below, they can be rescaled to the range zero to one. Thus for each variable we have

$$0 < x_i(t) < 1 \qquad \text{for all } i = 1,2,..., \text{N and all } t > 0. \tag{1}$$

To preserve boundedness, $x_i(t + \Delta t)$ is calculated by the transformation

$$x_i(t + \Delta t) = x_i(t)^{p_i}, \tag{2}$$

where the exponent $p_i(t)$ is given by

$$p_i(t) = \frac{1 + \frac{\Delta t}{2}\sum_{j=1}^{\mathrm{N}}\left(\left|\alpha_{ij}\right| - \alpha_{ij}\right)x_j}{1 + \frac{\Delta t}{2}\sum_{j=1}^{\mathrm{N}}\left(\left|\alpha_{ij}\right| + \alpha_{ij}\right)x_j}, \tag{3}$$

where α_{ij} are the matrix elements (also denoted by m_{ij}) giving the impact of x_j on x_i and Δt is the time period of one iteration. It can be seen how Equation (3) guarantees that $p_i(t) > 0$ for all $i = 1,2, \ldots,$ N and all $t = 0$. Thus the transformation (2) maps the open interval (0,1) onto itself, preserving boundedness of the state variables (condition 1 above). Equation (3) can be made somewhat clearer if we write it in the following form:

$$p_i(t) = \frac{1 + \Delta t\left|\text{sum of negative impacts on } x_i\right|}{1 + \Delta t\left|\text{sum of positive impacts on } x_i\right|}. \tag{4}$$

When the negative impacts are greater than the positive ones, $p_i > 1$ and x_i decreases; while if the negative impacts are less than the positive ones, $p_i < 1$ and x_i increases. Finally, when the negative and positive impacts are equal, $p_i = 1$ and x_i remains constant. Thus the second condition holds. To demonstrate conditions (3-5) let us first observe that for small Δt, Equations (2) and (3) describe the solution of the following differential equation:

$$\frac{dx_i}{dt} = -\sum_{j=1}^{\mathrm{N}}\alpha_{ij}x_i x_j \ln x_i. \tag{5}$$

From Equation (5) it is clear that as $x_i \rightarrow 0$ or 1, then $dx_i /dt \rightarrow 0$ (condition 3). Thus, the expression $x_i \ln(x_i)$ may be said to modulate the response of variable x_i to the impact it received from x_j. Considering x_j individually, we see that as it increases or decreases the magnitude of the impact of x_j upon any x_i increases or decreases (condition 4). Finally, it is seen that condition (5) holds since system behavior is modeled, through the coefficients α_{ij}, each of which describes the binary interaction of x_j upon x_i."

Although the model seems to imply that the impact coefficients are constants, this need not be so. Any of these coefficients may be a function of the state variables and time. The system exhibits sigmoidal-type growth or decay corresponding to α positive or negative. Such growth and decay patterns are characteristic of many economic, technological, and biological processes.

5 The Selection of a Bridge Type: A Case-Study

Here, we present an application of the use of the AHP and the KSIM for selecting the most appropriate bridge design. This study concerns an actual bridge construction project to provide an alternative route across the Monongahela River in the city of Pittsburgh, USA. More detailed reports of this study have appeared in Saaty and Vargas [14], and in [11] and [5]. The author of the present article participated in one of the seven decision making groups of this project. The three types of bridges considered by The Port Authority of Allegheny County were (n=3):

A = A **Cable-stayed bridge** (Figure 1); it belongs to the group of the longest bridges called suspension bridges. The deck is hung from suspenders of wire rope, eyebars or other materials. Materials for the other parts also vary: piers may be steel or masonry; the deck may be made of girders or trussed. This type of bridge is usually applied with very high tensile strength, which minimizes beam deflection as the span is increased significantly. Moreover, adding several stay cables allows the use of more slender deck beams, which require less flexural stiffness. By decreasing the cable spacing supports, local bending moments in the girders are also reduced. Simple double-edge girders supporting transverse floor beams and top slabs provide a synergistic reinforcing action. The economic viability and aesthetic appeal make this type of bridge very popular.

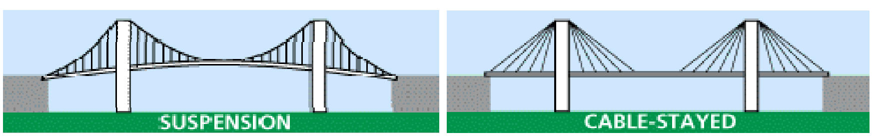

Figure 1

Suspension bridges including their "cousin" the cable-stayed bridge [17]

B = A **Truss bridge** (Figure 2); it allows applied loads to be resisted primarily by axial forces in its straight truss members. Its open web system permits the use of a greater overall depth than for an equivalent solid web girder. These factors lead to an economy in material and a reduced dead weight. Deflection is reduced and the structure is more rigid. However, fabrication and maintenance costs are increased. In addition, a truss bridge rarely possesses aesthetic beauty.

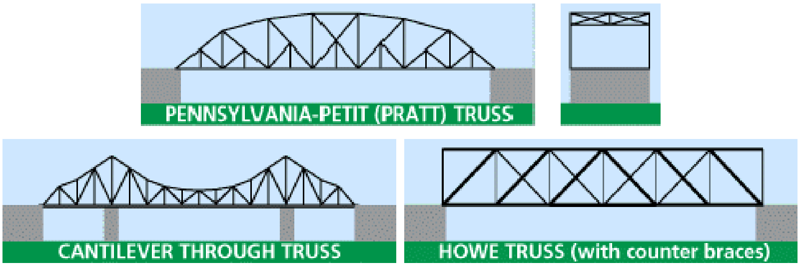

Figure 2
Bridges of Truss type [17]

C = A **Tied-Arch bridge** (Figure 3); it has been used for its architectural beauty and outstanding strength for centuries. With the aid of its inward-acting horizontal components, the arch is capable of distributing loads both above and below its structure. In a tied-arch design the horizontal reactions to the arch rib are supplied by a tie at deck level. It reduces bending moments in the superstructure and is fairly economical. Aesthetically, the arch has been perhaps the most appealing of all bridge types. It has, however, high relative fabrication and building costs.

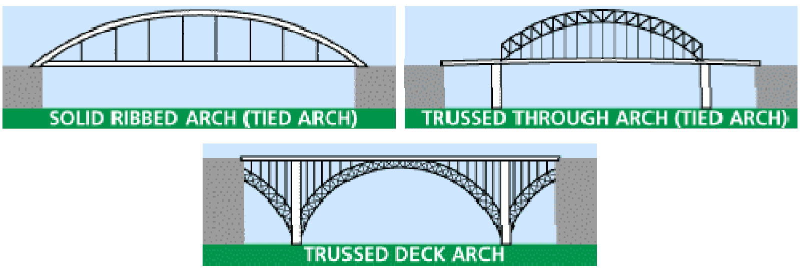

Figure 3
Arch bridges of different configurations including the tied-arch type bridges [17]

The most desirable bridge type would conceivably be the one that brings the most satisfaction to the greatest number of stakeholders. Keeping an eye on this goal, a hierarchy was developed with major stakeholders at the second level, the driving criteria at the third level and the three alternative bridge types at the fourth level. The major stakeholders were then arranged into seven groups each with a number of 8-15 people. These groups are as follows:

FWHA = A Federal Agency, which represents an array of federal departments. It is a key financier of the project and will have dictates with respect to the engineering integrity of any bridge type.

CBD = The Commercial Business District, which broadly represents the businesses in the downtown of Pittsburgh. Its interest implies to maintain the historical appearance of the building site as well.

PUB = The Public, which represents the population of the city that would use the new bridge.

DOT = The Pennsylvania Department of Transportation, which represents the complex interests of the state. These interests are financial (as the state provides part of the capital), political, technical and environmental.

DES = The Designers, who represent engineers, architects and planners and their professional organizations. They provide crucial technical input and so, they have a great influence.

SIG = Special Interest Groups; this means a very broad category with diverse and possibly conflicting interests. They are the concrete suppliers, the steel manufacturers and the environmentalists. The steel industry has declined in size and influence in this region; however, the concrete industry remains strong. Environmentalists are active and vocal.

PAT = The Port Authority Transit; it is the ultimate project owner. This premier stakeholder is concerned with all management issues from conception to construction, as well as maintenance.

In the level below the stakeholders are the six criteria with respect to which the bridge types were evaluated. They are interpreted as (m=6):

$C1$ = Engineering Feasibility (**EF**): The technical knowledge and experience of both the designers and contractors in regard to the bridge type.

$C2$ = Capital Cost (**CC**): Necessary funding. Because the costs were committed, low costs are included in the overall benefits hierarchy as one of the criteria.

$C3$ = Maintenance (**MA**): General cleaning, painting, repair and inspection vary dramatically with bridge type.

$C4$ = Aesthetics (**AE**): Architectural attractiveness.

$C5$ = Environmental Impact (**EI**): The ecological and historical adjustments that must be compromised.

$C6$ = Durability (**DU**): The lifetime of the bridge and the potential major repairs over and above the routine maintenance.

Tangible data supporting the engineering characteristics ($C1$, $C2$, $C3$, $C6$) have been derived partially from measurements, while the ratios for the intangible attributes ($C4$, $C5$) were judged by the groups of stakeholders. Numerical computations were done by the software package Expert Choice. First, the actors were compared to determine their relative importance (weighting factors). The 7×7 sized pairwise comparison matrix **A** is displayed on the next page. Note that matrix **A** is a slightly inconsistent matrix. Its calculated inconsistency measure yielded: μ=0.03.

$$\mathbf{A} = \begin{bmatrix} 1 & 2 & 1/5 & 1 & 1/2 & 1/3 & 3 \\ 1/2 & 1 & 1/6 & 1/2 & 1/3 & 1/4 & 2 \\ 5 & 6 & 1 & 5 & 4 & 3 & 7 \\ 1 & 2 & 1/5 & 1 & 1/2 & 1/3 & 3 \\ 2 & 3 & 1/4 & 2 & 1 & 1/2 & 4 \\ 3 & 4 & 1/3 & 3 & 2 & 1 & 5 \\ 1/3 & 1/2 & 1/7 & 1/3 & 1/4 & 1/5 & 1 \end{bmatrix}.$$

The criteria were then compared according to each factor and the composite priorities computed (see Table 2).

Table 2
Weighting factors and weights (priorities) of the criteria

Weighting factor, s_k	0.135	0.221	0.029	0.136	0.085	0.056	0.337	
Stakeholder / Criterion C_k	FHWA	CBD	PUB	DOT	DES	SIG	PAT	Weight w_i
*C*1 = EF	0.117	0.048	0.037	0.216	0.313	0.033	0.260	0.173
*C*2 = CC	0.340	0.048	0.297	0.082	0.197	0.357	0.100	0.147
*C*3 = MA	0.069	0.116	0.297	0.052	0.118	0.097	0.260	0.154
*C*4 = AE	0.069	0.401	0.074	0.216	0.136	0.224	0.061	0.174
*C*5 = EI	0.202	0.270	0.114	0.352	0.117	0.224	0.061	0.181
*C*6 = DU	0.202	0.116	0.182	0.082	0.118	0.064	0.260	0.171
Inconsistency μ	0.02	0.07	0.05	0.04	0.08	0.06	0.05	

Finally, the alternatives were compared according to each criterion and the composite priority scores (weights) computed. This information was synthesized to yield the overall priority ranking and the overall priorities of the bridges:

Overall ranking and the overall priorities, π_i
B (0.371)
C (0.320)
A (0.309)

Thus, in this project, the most desirable bridge is of a **Truss** type. It is quite interesting to note that a couple of months later this result was reconsidered. The major difference in the duplicated decision making process was the addition of a new stakeholder, the US Coast Guard (USCG), the responsible authority for river traffic, and the deletion of the Public (PUB). Due to the effect of the USCG concerning the reinforcement of the safety aspects of river transportation and the further ecological claims of the environmentalists, the final ranking of the types of bridges changed in favour of a **Tied-arch** type bridge. Since then, the new bridge has been built to the Wabash Tunnel, consisting of three high occupancy vehicle lanes and one for pedestrian traffic.

There are a great number of beneficial properties implied by the AHP which have made it perhaps the most popular scaling method worldwide, although it possesses some shortcomings as well. Especially, its static nature and the implicit independence assumption among the variables (criteria) should be mentioned from the perspective of the comparison of the bridge types. To overcome these difficulties, the author of this paper extended the scope of the investigations of the original study and applied the KSIM technique to this problem, following the steps described in Section 4.

This work has been built upon the subjective assessment of an expert group under the guidance of the author and was based on the preliminary project completion reports for each of the three bridge designs. As an illustration, we now show the results for the **Tied-arch** type bridge. The initial values, $x_i(0)$, of the variables were chosen as:

Engineering Feasibility (**EF**) = 0.8;

Capital Cost (**CC**) = 0.3;

Maintenance (**MA**) = 0.4;

Aesthetics (**AE**) = 0.6;

Environmental Impact (**EI**) = 0.7;

Durability (**DU**) = 0.5.

In the model we introduced six variables. It is apparent that most of them interact with each other. Accordingly, there are thirty potential binary interactions and six possible self-interactions. Choosing these thirty six parameters will define the system. A reasonable first approximation is given in the cross-impact matrix:

$$\begin{array}{cc} & \begin{array}{cccccc} \mathbf{EF} & \mathbf{CC} & \mathbf{MA} & \mathbf{AE} & \mathbf{EI} & \mathbf{DU} \\ \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow \end{array} \\ \mathbf{M} = & \begin{bmatrix} 1 & 3 & 2 & 0 & 1 & 4 \\ 4 & 0 & -1 & -1 & 2 & 5 \\ -2 & -3 & 0 & 1 & 3 & 1 \\ 0 & 1 & 1 & 0 & -3 & 1 \\ -2 & 2 & 2 & 0 & 0 & -3 \\ 1 & 2 & 3 & 1 & 0 & 0 \end{bmatrix} . \end{array}$$

It should be noticed that both the initial values of the variables and the entries of the interaction matrix are somewhat arbitrary. Hence, there is considerable room for disagreement. For example, it would be easy to argue that a variable should be assigned an initial value of 0.8 rather than 0.7. Likewise it could be argued that the action of a variable upon another is negative rather than positive owing to a grounded reasoning. The ease of the model's formulation allows such contrary views to be, expressed easily and in a self-consistent fashion.

Once the model's configuration, i.e., the initial values and the matrix of interactions has been agreed upon it follows the simulation run to project the future states of the system [6]. Figure 4 exhibits the subsequent behavior of the system that emerges from the above assumptions. Here, the increase in time expresses the change in a variable.

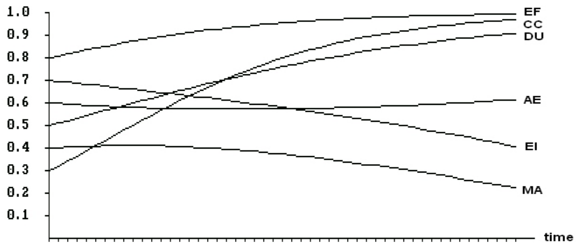

Figure 4
Projected interaction effects as set by the cross-impact matrix **M**

By displaying the dynamic behavior of the system (for the project of the Tied-arch type bridge), further alternative designs or changes of the present plans can be executed; furthermore, new intervention strategies can be implemented in a reasonable way.

Conclusions

In this paper a multiple criteria decision making method and a graphical cross-impact simulation model have been discussed and applied to comparing and evaluating different bridge design projects. Certainly, these qualitative input-based methods and models are hardly conclusive. No doubt many readers would argue for different choices of initial conditions or interactions. This is just what we wanted to be reflected: i.e., controversy and interrelationships. But also any one can use these simple models, even policy makers and citizens. A major objective in devising these models is to show the overriding importance of *structure rather than state* to project managers. The relevance dwells in the *linkages of* any variable to the other variables of the system.

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