Modeling the Multi-Criteria Highway Corridor Selection with Uncertainties Using the Stochastic Analytic Network Process

Mongkut Piantanakulchai
School of Civil Engineering and Technology
Sirindhorn International Institute of Technology, Thammasat University
P.O. Box 22, Thammasat-Rangsit Post Office, Pathumthani 12121, Thailand
Phone (66-2) 986-9009 ext. 1912, Fax (66-2) 986-9009 ext. 1905
E-mail: mongkut@siit.tu.ac.th

Abstract

The planning of highway alignment is a complex decision making that involves many objectives and stakeholders. Previous researches applied the Analytic Hierarchy Process (AHP) to prioritize the alternatives of highway alignments. Standard AHP model could not accommodate the variety of interactions, dependencies, and feedback. The Analytic Network Process (ANP) is a successor of AHP which takes into accounts the dependencies and feedbacks. Recent study [1] applied ANP to the highway corridor selection problem. This study further investigated the approach which could handle the imprecise information in the decision making process. In this study, the Stochastic Analytic Network Process (SANP) is proposed to handle the multi-criteria highway corridor selection problem with uncertainties.

1. Introduction

Highway corridor selection is a vital decision made by the government. A new highway link generally lowers the transportation costs and creates significant effects to the community. Selecting the most appropriate route from a set of alternatives is a multi-disciplinary decision problem. Various objectives are usually in conflict with each other due to different views of stakeholders. Geological and constructional uncertainties make the decision process more complex. Cost/Benefit analysis (CBA) is a technique that has been widely applied to determine the economic feasibility of possible alternative routes.

Nevertheless, the inadequacy of CBA in dealing with intangible factors and strategic concerns is its main disadvantage [2]. In addition, many cost-benefit studies tend to undervalue the importance of the local society where the impact of the project is felt most strongly [3]. In practice, the best alternative is selected by taking into consideration the trade-offs of multiple criteria such as economic, engineering, environmental, and social impact, etc.

Highway corridor planning problem is defined by the selection of the optimum corridor alignment based on multiple criteria, for example, minimization of construction problems, maximization of the operational functionality of the project, minimization of the environmental impact, and maximization of the results of the economic investment [4].

Applications of multi-criteria methods to the highway corridor planning are found in literatures. For instance, Kale et al. made the land suitability map for expressway corridor from Mumbai and Pune cities in India [5]. Bailey applied multi-criteria method with the Geographic Information System (GIS) to corridor selection for a proposed interstate highway connector in the southeastern U.S. [6]. Azis applied multicriteria method to rationally measuring the intangible and complex impacts of the Trans-Sumatra highway built in the late 1970's [3]. Chowdhury et al. proposed the optimization approach based on the Surrogate Worth Tradeoff (SWT) method for continuous problems, and multi-attribute utility and minimum tolerance method for discrete problems [7]. Four case studies were illustrated based on actual project data. However, the

RECEIVED 3 August, 2007
ACCEPTED 24 April, 2008

limitation of their work is the inability to factor in the preferences of multiple decision makers. Other related application included the planning of corridor for power transmission line [8].

Several multi-criteria methodologies have been proposed and practiced in highway corridor planning. For example, AHP [3-4, 6, 9], outranking system [10], surrogate worth tradeoff, multi-attribute utility, and minimum tolerance method [7]. Many previous studies applied the Analytic Hierarchy Process (AHP) in selecting the best highway alignment. However, one of the deficiencies of AHP is that it could not include interrelationship and feedback within the elements in the model. This may result in misleading in the decision making, for example, the famous bridge selection problem [11]. Generally, the criterion of strength is set higher than aesthetics in bridge selection. However, when all bridges are satisfied with the strength requirement, the aesthetic criterion becomes more important no matter how stronger another bridge is. This is an example of a situation when the criterion depends on an alternative. The conventional top-down decision model like AHP does not handle this situation directly and may come out with the decision to select the extremely strong but ugly bridge instead of sufficiently strong and beautiful bridge.

The Analytic Network Process (ANP) is a successor of AHP which takes into accounts the dependencies and feedbacks between decision making elements. Recent study [1] proposed the Analytic Network Process (ANP) model to handle the multi criteria highway corridor selection problem. However the deterministic ANP does not explicitly concern uncertainties of decision being made. This paper proposed the Stochastic Analytic Network Process (SANP) in order to handle the uncertainty in decision making and to provide the confidence interval of the priorities derived from the decision making model.

2. Methodology: The Stochastic Analytic Network Process (SANP)

The fundamentals of the deterministic Analytic Network Process (ANP) and its application to the highway corridor planning problem were discussed extensively in [1]. In brief, ANP is a process to derive priority (weight) of the elements in the decision making problem. The elements could be stakeholders, objectives, indicators, alternatives, etc. ANP consists of the control hierarchies, clusters, elements, interrelationship between elements, and interrelationship between clusters.

Control hierarchies consist of the top level criteria that involves in decision making. Control hierarchy provides overriding criteria for comparing each type of interaction in the network. Saaty proposed four basic control hierarchies, Benefits, Opportunities, Costs, and Risks which are subsequently called BOCR models [12]. It is not required to include all four control hierarchies if some criteria are irrelevant. The determination of relative weights in ANP is based on the pairwise comparison as in the standard AHP, see [13]. With respect to any criteria pairwise comparisons are performed in two levels, the element level comparison and the cluster level comparison.

Elements are the entities in the system that interact with each other. They could be a unit of decision makers, stakeholders, criteria or sub criteria (if exists), possible outcomes, and alternatives etc. In complex system which contains a great number of elements it would be very time consuming to measure relative importance of each element with every single element in the system. Instead, elements which share similar characteristics are usually grouped into cluster. The determination of relative weights mentioned above is based on pairwise comparison as in the standard AHP [13].

Pairwise comparisons of the elements in each level are conducted with respect to their relative importance toward their control criterion based on the principle of AHP. Saaty [13] suggested a scale of 1-9 when comparing two components (see Table 1). The relative weight a_{ij} in the pairwise comparison matrix represents the relative importance of the component on i^{th} row (w_i) over the component on j^{th} column (w_j) as represented in Eq.(1).

Table 1. Scale of relative importance (a_{ij}) suggested by Saaty [13]

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one activity over another
5	Stong importance	Experience and judgment strongly favor one activity over another
7	Very strong or demonstrated importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between adjacent scale values	When compromise is needed
Reciprocals of above	If activity i has one of the above nonzero numbers assigned to it when compared with activity j, the j has the reciprocal value when compared with i	

$$a_{ij} = \frac{w_i}{w_j} \qquad (1)$$

The score of 1 represents equal importance of two components and the score of 9 represents extreme importance of the i^{th} component over the j^{th} component. The reciprocal value of the above expression ($1/a_{ij}$) is used when the j^{th} component is more important than the i^{th} component. If there are n components to be compared the matrix of a_{ij}, A, is defined as in Eq. (2).

$$A = \begin{bmatrix} w_1/w_1 & w_1/w_2 & \cdots & w_1/w_n \\ w_2/w_1 & w_2/w_2 & \cdots & w_2/w_n \\ \vdots & \vdots & & \\ w_n/w_1 & w_n/w_2 & \cdots & w_n/w_n \end{bmatrix} \qquad (2)$$
$$= \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{bmatrix}$$

The weights can be obtained by the eigenvector of the pairwise comparison matrix which can be numerically estimated by Eq.(3).

$$\lim_{k\to\infty} \frac{A^k e}{e^T A^k e} = cw \qquad (3)$$

Where e^T is a unit row vector; c is a constant; and w is the eigenvector corresponding to the principal eigenvalue of the matrix A.

The weights are then put into the supermatrix that represents the interrelationships among elements in the system. The matrix obtained at the initial step (without cluster weighted) is called the initial supermatrix.

As stated earlier, the pairwise comparison is performed in two levels. The eigenvector obtained from cluster level comparison with respect to the control criterion is applied as the cluster weights. Each element in the initial supermatrix is weighted by its cluster weight. This results in a matrix which each of its columns sums to unity. This matrix is called the weighted supermatrix (W).

The weighted supermatrix is raised to limiting power ($\lim_{k\to\infty} W^k$) to get the global priority vectors. If the supermatrix has the effect of cyclicity, there may be two or more N limiting supermatrices. In this case, the Cesaro sum ($\lim_{k\to\infty}\left(\frac{1}{N}\right)\sum_{i=1}^{N} W_i^k$) is calculated to get the average priority weights. In the deterministic ANP the expert gives only a single weight in each pairwise comparison and the model gives only a single set of weights without confidence bounds.

In the Stochastic ANP the expert who gives the pairwise comparison could express his preference including the uncertainty of the specific problem. In this study, the preference is modeled by the triangular distribution shown in Fig. 1. In pairwise comparison the expert could provide the relative weight (a_{ij}) of any pair of elements using lower bound (L), mode (M), and upper bound (U) values. The degree of uncertainty in the decision is reflected in the range of lower bound and upper bound values.

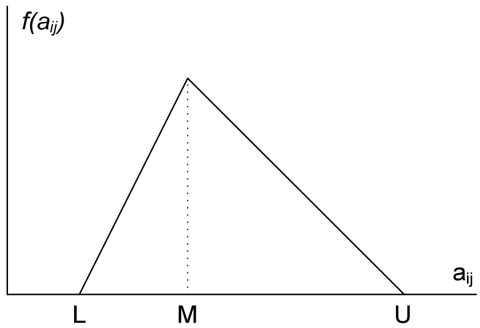

Figure 1 Triangular distributed weights used in SANP

The simulation of triangular distributed weights could be done by using some techniques such as the inversion method as described below. The cumulative probability function (*F(x)*) of the triangular distributed random variable (x) is defined as in Eq.(4).

$$F(x)=\begin{cases}\dfrac{(x-L)^2}{(U-L)(M-L)} & if\ L\le x\le M\\[2ex] 1-\dfrac{(U-x)^2}{(U-L)(U-M)} & if\ M\le x\le U\end{cases} \quad (4)$$

The uniform distributed random variable $Z=U(0,1)$ can be simulated simply using standard algorithms or softwares. Then the triangular distributed random variable (x) with lower bound (L), mode (M), and upper bound (U) could be simulated using Eq.(5).

$$x=\begin{cases}L+\sqrt{(Z(U-L)(M-L))} & if\ x\le M\\ U-\sqrt{(1-Z)(U-L)(U-M)} & if\ x\ge M\end{cases} \quad (5)$$

The simulated value using the above process is taken as the relative weight (a_{ij}) in the pairwise comparison matrix (*A*). The process is repeated until half of all comparisons are done while the rest are defined by

$$a_{ji}=a_{ij}^{-1} \quad (6)$$

The pairwise comparison matrix (A) is solved to find the normalized eigenvector as the synthesized relative weight vector. The consistency of judgment is checked by the standard AHP method suggested in [13]. The process is repeated until the simulated comparisons are logically consistent.

The next step is to put the simulated vector of relative weights into appropriate row and column of the supermatrix which are relevant to the decision context. The initial supermatrix is then weighted and raised up obtained the global priority weights.

The simulations are carried out repeatedly to collect the statistics of the priority weights. The model includes the expert's uncertainty in the decision by giving multiple sets of weights. Some statistical parameters such as mean and standard deviation of weights could be obtained. The confidence interval of the priority weights could be derived according to the degree of confidence needed.

The above mentioned process of the SANP is summarized in Fig. 2.

3. The Stochastic Analytic Network Process for Highway Corridor Planning

This section explains the formulation of Stochastic ANP to the highway corridor planning. The original thoughts and extensive discussion could be found in [1]. In this study, the complexity of the original problem was reduced for the purpose of illustration. However, the concept presented here could be easily extended to more complex problems.

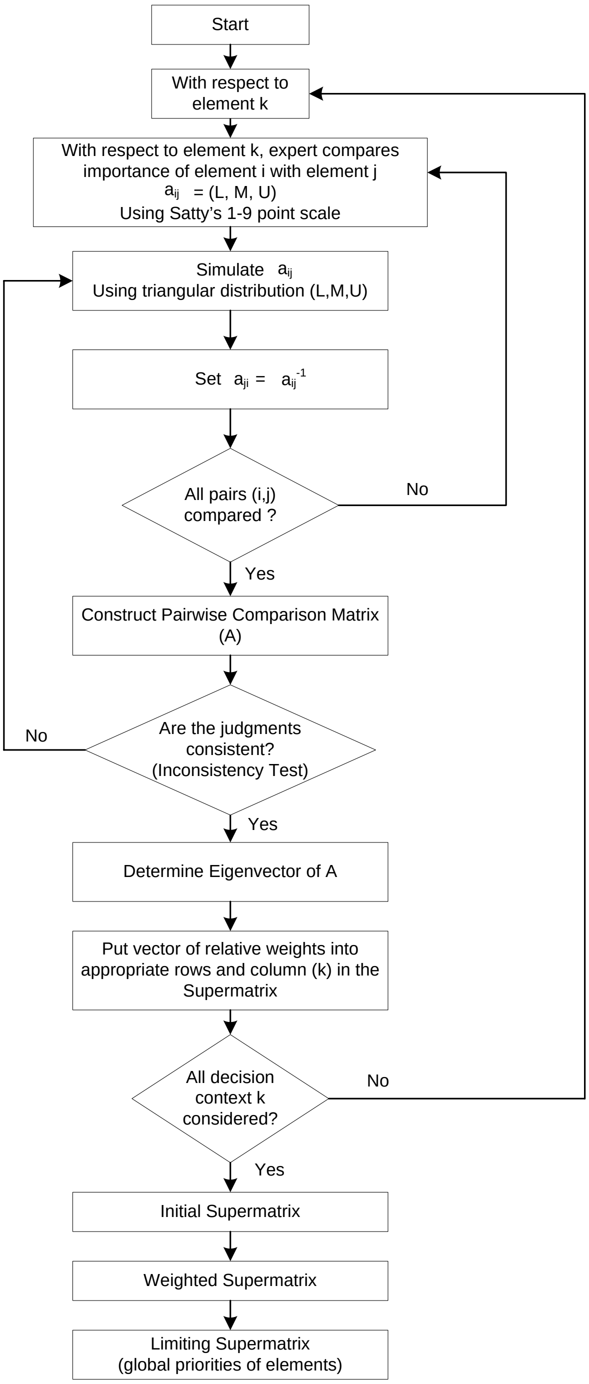

Figure 2 Process of the SANP

The decision structure is defined as the objectives and alternatives clusters with dependency feedbacks. Fig. 3 shows an example of the weighted supermatrix. Blank cells in the supermatrix are zero elements which represent independence. Because the weighted supermatrix is stochastic, therefore, the matrix shown in figure is based on mode values.

		I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	A	B	C
Travel benefits (travel time saving, etc)	I1				0.10							0.03	0.04	0.21
Tourism development (indicator)	I2	0.05	0.31		0.04							0.04	0.04	0.09
Future expansion and improvement	I3			0.18								0.04	0.09	0.23
Traffic volume (indicator)	I4	0.20			0.04	0.10	0.10		0.50	0.50	0.11	0.28	0.23	0.04
Average speed	I5	0.08	0.10	0.32	0.11						0.12	0.09	0.09	0.09
Average delay	I6	0.08			0.05						0.13	0.09	0.10	0.10
No. of accessible communities	I7	0.04	0.09		0.12			0.44			0.15	0.09	0.10	0.11
PCU-km	I8	0.02						0.06				0.11	0.11	0.04
V/C	I9					0.40	0.40					0.11	0.10	0.04
Energy saved	I10	0.02			0.05							0.11	0.11	0.05
Alternative A	A	0.22	0.12	0.15	0.04	0.04	0.04	0.06	0.07	0.05	0.06			
Alternative B	B	0.21	0.16	0.15	0.17	0.16	0.39	0.21	0.17	0.14	0.16			
Alternative C	C	0.06	0.22	0.19	0.28	0.30	0.07	0.22	0.26	0.31	0.29			

Figure 3 Mean value of the weighted SANP supermatrix

Fig. 4 shows an example of stochastic pairwise comparison matrix excerpted from the supermatrix. In the above example, the matrix represents the relative influence of element I2, I5, and I4 to element I2. This can be explained as the potential of tourism development (I2) depends on itself (I2), highway average speed (I5), and number of accessible communities (I7). It is noted that self comparisons represented by the diagonal elements in the pairwise comparison matrix are assigned to non-stochastic values of 1.

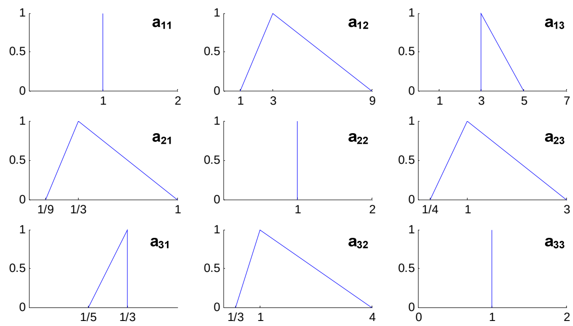

Figure 4 An example of the elements of the stochastic pairwise comparison matrix

4. Example of Results from SANP for Highway Corridor Planning

The normalized priority weights of three alternative highway routes (w_1, w_2, and w_3) can be plotted on the 3-D decision plane ($w_1+w_2+w_3=1.0$). The 2-D projection of the above 3-D decision plane is shown in Fig. 5. The diagram can be partitioned into six regions according to the priority's rank patterns. In this illustrative example, the result shows that 99.65% of simulated decisions give the rank of the alternative route to 3, 2, and 1, respectively ($w_3>w_2>w_1$). The result can give useful information to the decision maker under the decision environment when uncertainties are specified.

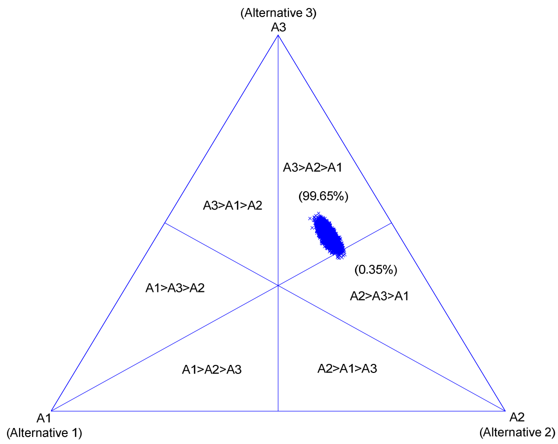

Figure 5 Decision diagram by 2-D projection of the decision plane

Statistics can be derived from the simulations, for example, means, variances, and confidence intervals. Fig. 6 shows the distributions of the priority weights of three alternatives. In this case the alternative 3 is probably most preferred when considered all preference information including uncertainties.

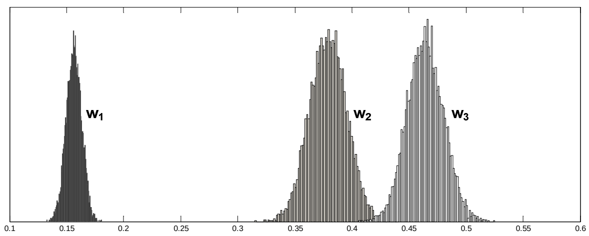

Figure 6 Distributions of the priority weights of three alternatives

5. Conclusion

This study proposed SANP as an approach to tackle the multi-criteria highway corridor selection problem with uncertainties. The general structure of SANP was discussed in the paper. A simple numerical example was shown to illustrate the application of the model presented. With the proposed approach, uncertainties could be included in the decision making model and statistical inference of preferences could be derived. The proposed SANP model is useful to deal with the complex infrastructure decision making with uncertainties such as highway corridor planning. To apply the model to real world applications, the experience in formulating the decision making problem into SANP structure is the key success factor.

References

[1] M. Piantanakulchai, "Analytic Network Process for Highway Corridor Planning" Proceedings of the Eight International Symposium on the Analytic Hierarchy Process (ISAHP), The University of Hawaii, July 8-11, 2005.
[2] J.S. Shang, Y. Tjader and Y. Ding, "A Unified framework for multicriteria evaluation of transportation projects" IEEE Transactions on Engineering Management, Vol. 51, 2004, pp.300-313.
[3] I.J Azis, "Analytic Hierarchy Process in the benefit-cost framework: A post-evaluation of the Trans-Sumatra highway project" European Journal of Operational Research, Vol. 48, 1990, pp.38-48.
[4] G.S. Kalamaras, L. Brino, C. Carrieri, C. Pline, and P. Grasso, "Application of multicriteria analysis to select the best highway alignment", Tunnelling and Space Technology, Vol. 15, 2000, pp.415-420.
[5] M. Kale, S. Ravan, and A. Kaushal, "GIS development of knowledge corridor along Mumbai-Pune expressway" Proceedings of the Map India 2004 Conference.
[6] K. Bailey, "AMIS: Development and Application of a GIS/Multicriteria Corridor Evaluation Methodology" Proceedings of the Map Asia 2003 Conference.
[7] M.A. Chowdhury, P. Tan, and S.L. Willam, "An Interactive multiobjective decision support framework for transportation investment", Research Report, U.S. Department of Transportation Research and Special Programs Administration, 2002.

[8] K. Bailey, T. Grossardt, and W. Jewell, "Participatory routing of electric power transmission lines using the EP-AMIS GIS/Multicriteria Evaluation Methodology" Proceedings of the 10th international symposium on information and communication technologies in urban and spatial planning and impacts of ICT on physical space, 2005, pp.137-142.
[9] M. Piantanakulchai, "Computer based planning of intercity motorway alignment considering social and environmental impacts" Proceedings of the 15th International Road Federation (IRF) world meeting, 2005.
[10] M. Rogers and M. Bruen, "Using ELECTRE III to choose route for Dublin port motorway" Journal of Transportation Engineering, Vol. 126, 2000, pp.313-323.
[11] E. Forman, and M.A. Selly, "Decision by Objectives" Expert Choice Inc., 2001.
[12] T.L. Saaty, "Fundamentals of the Analytic Network Process", Proceedings of ISAHP, Kobe, 1999.
[13] T.L Saaty, "The Analytic Hierarchy Process", McGraw-Hill, New York, 1980.