Computer-aided bridge design and selection of construction methods using fuzzy logic

Computer-Aided Bridge Design and Selection of Construction Methods Using Fuzzy Logic

Moisés RAMIREZ-MARQUEZ
Researcher Assist.
School of Civil Eng.
Barcelona, Spain

Moisés Ramirez Marquez, born in 1967, got his civil engineer degree form the Iberoamerian Univ. (UIA) in 1991. Since 1995 he has been a doctoral student at the Techn. Univ. of Catalonia (UPC). His research field is application of the fuzzy-set theory in bridge projects.

Juan R. CASAS
Assoc. Prof.
School of Civil Eng.
Barcelona, Spain

Juan R. Casa, born in 1960, received his Civil Eng. degree form the Techn. Univ. of Catalonia (UPC) in 1984 where he completed his doctorate in 1988. Since then, he has been professor of bridge engineering at UPC. His research includes dynamics analysis and testing of bridges as well as bridge reliability.

Summary

The paper develops a multi-criteria decision model for selecting the best bridge design from the technical and economical points of view. The model considers the current "state of art" in bridge engineering, organizes hierarchically the different construction alternatives and determines the ranking of the best structural design and construction method using fuzzy logic. The fuzzy combined programming method has been developed according to the fuzzy sets theory, which has been thoroughly proven in the resolution of engineering problems where uncertain information with multiple solutions exist. The multi-objective programming method considers the fuzzy information provided by specialists as well as a data base of 495 bridges built in Spain during the last 25 years.

1. Introduction

Due to the different design criteria, the election of the structural configuration and the construction method are the most important decisions of a bridge project. Depending on the specialist's experience, the decisions can vary in function of the project constraints such as the geographical conditions, execution term, service life, cost, etc., therefore such decision can vary depending on each case and the specific requirements of the client.

Traditionally during the selection of a bridge design, the construction cost is one of the most important factors. However, a proposal with a high cost can result from a high degree of technical quality, while a proposal with lower cost may not provide the minimum technical requirements. Therefore the minimization is in conflict with maximizing the technical factors and a long service life. This study outlines a solution through analysis of uncertain variables with the application of the fuzzy-set theory. The method is applied to the resolution of an explanatory example.

2. Concept of Fuzzy Logic

The central concept of fuzzy logic is the membership function $\mu(x)$, which represents numerically the degree in which an element belongs or not to an specified set. The membership function can range from 0 to 1, therefore the transition between member and non-member of a set appears by gradual way. When the membership function of an element has only values of 0 or 1, the fuzzy set theory is reduced to the classical set theory. The fundamental characteristic of the fuzzy sets is the possibility to quantify vagueness of the human thinking as the common sense, experience, or language ambiguities such as "more and less" or "tall men", which are not possible to quantify in classic logic. Therefore it is feasible to imitate the human reasoning and to take decisions based on fuzzy data [1,2,3].

3. Fuzzy-combined methodology

Many objectives in bridge design are difficult to arrange since their values contain a high degree of uncertainty and subjectivity. The fuzzy-combined model here proposed defines the basic criteria of bridge design, groups the values of each criterion hierarchically, evaluates the possible solutions and finally ranks the options obtaining the most adequate solution. The method combines the fuzzy sets theory with the analytic hierarchy process (AHP) and with the built bridges data and is fully explained in [4]. Highway prestressed concrete and composite bridges are considered for the analysis of each construction choice. The model divides the bridges in deck, piers and abutments. This possibility was outlined in order to obtain independent results from each structural element in case of having some constraints.

The first step of the model consists on the identification of the most representative variables involved in bridge design and construction (Table 2). Once defined the elements of the basic criteria, they are joined by sets (Fig. 1). The 82 variables that form the first level represent the basic criteria (33 for the deck, 28 for the piers and 21 for abutments). They are grouped to form the second level. For example, the elements of the first level for bridge deck (slenderness , span, adequacy to longitudinal slope and curvature) can be grouped into geometry in longitudinal section, which is an element of the subset of second level (see Table 2). By this way, the variables that integrate the second level as geometry in longitudinal section, construction method, etc. are grouped into technical valuation (third level). Finally, the solution (fourth level) is formed by technical valuation, service life and cost. Analogous diagrams have been made for piers and abutments.

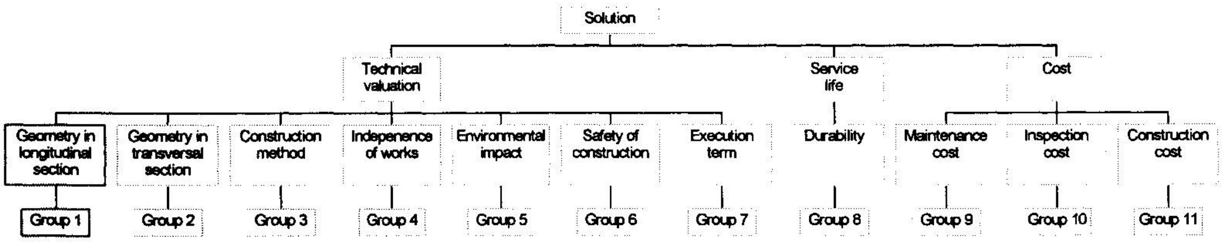


Fig. 1 Diagram of deck bridge basic criteria (see Table 2)

3.1 Quantification of fuzzy values

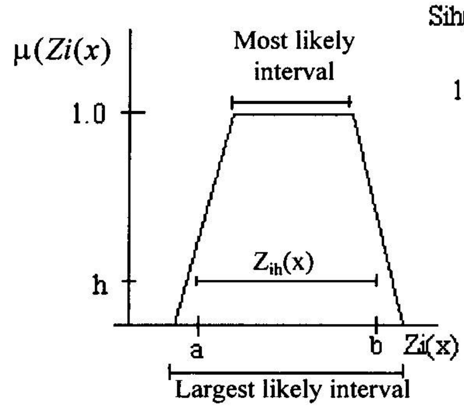
To obtain the fuzzy values and the membership function of the basic criteria and their relative importance, a survey was developed among a group of Spanish experts in design and bridge construction. The purpose was to establish the recommendation in the use of construction systems for specific situations such as prevention of alignment mistakes, adaptability to technical problems, environmental constraints, etc. which are the level 1 of basic criteria. The specialists answered the questions according to linguistic scales. In the same way, regarding safety and relative importance a different scale was adopted (Table 1). The values given by the experts have been completed with the existing data base of bridges built in Spain in the last 25 years. The data base contains a summary of the "state of the art" of bridge design and construction in Spain.

Intensity of recommendation	Definition	Intensity of security	Definition	Intensity of importance	Definition
1	Not recommendable	1	Unsafe	1	Equal importance
2	Low recommendable	2	Not much secure	3	Weak importance
3	Recommendable	3	More and less secure	5	Strong importance
4	Very recommendable	4	Secure	7	Demonstrate importance
5	Absolutely recommendable	5	Very secure	9	Absolute importance
				2,4,6,8	Intermediate values

Table 1 Linguistic measures

3.2 Analysis of fuzzy values

The values of the basic criteria are fuzzy numbers represented by $\mu(x)$, where x is a discreet element of the set. Be $Z_i\,(x)$ a fuzzy value for the ith basic criterion, and its membership function $\mu[Z_i\,(x)]$ a trapezoid (Fig. 2) [5].



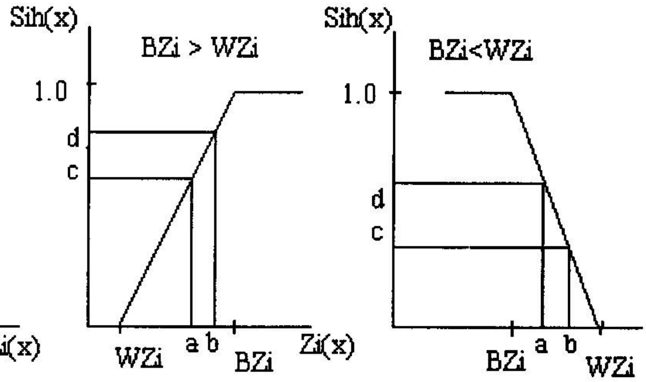


Fig. 2 Fuzzy calculation of basic criteria *Fig. 3 Tranfering value $Z_{ih}(x)$ into $S_{ih}(x)$*

Because of the units of the basic criteria are different, since for some the best value is the highest while for other is the opposite (the best price is the lowest and the best constructive yield the highest), the value of each basic criterion $[Z_{i,h}(x)]$ in Fig. 2 is transformed into a index $S_{i,h}(x)$ in the following way [6]:

If $BZ_i > WZ_i$, then $S_{i,h}(x) =$

$$\begin{bmatrix} 1, & Z_{i,h}(x) \geq BZ_i \\ [Z_{i,h}(x) - WZ_i]/\,(BZ_i - WZ_i) & WZ_i < Z_{i,h}(x) < BZ_i \\ 0, & Z_{i,h}(x) \geq WZ_i \end{bmatrix} \quad (1)$$

If $BZ_i < WZ_i$, then $S_{i,h}(x) =$

$$\begin{bmatrix} 1, & Z_{i,h}(x) \geq BZ_i \\ [Z_{i,h}(x) - WZ_i]/\,(BZ_i - Z_i) & WZ_i < Z_{i,h}(x) < BZ_i \\ 0, & Z_{i,h}(x) \geq WZ_i \end{bmatrix} \quad (2)$$

$Z_{i,h}(x)$ is an interval with lower bound a and upper bound b, therefore the index value $S_{i,h}(x)$ ranges between bounds c and d (Fig. 3). BZ_i and WZ_i, are the best and worst values of Z_i.
To calculate the following levels of the basic criteria, the expressions (3), (4) and (5) are used:

$$\text{Second Level: } L_{j,h}(x) = \left\{ \sum_{i=1}^{nj} W_{i,j}[S_{i,h,j}(x)]b_j \right\}^{1/bj} \qquad ....(3)$$

$$\text{Third Level: } L_{k,h}(x) = \left\{ \sum_{i=1}^{nk} W_{j,k}[L_{j,h,k}(x)]b_k \right\}^{1/bk} \qquad ....(4)$$

$$\text{Fourth Level: } L_h(x) = \left\{ W_1\,[L_{1,h}(x)]b + W_2\,[L_{2,h}(x)]b + W_3\,[L_{3,h}(x)]b \right\}^{1/b} \qquad ....(5)$$

Where n_j, n_k = number of elements in the "xth" level-group. $S_{i,h}$,= index value for the ith basic criterion in the second level-group j. $L_{j,h,k}$ = index value for the second level group j in the third level group k. W = weight coefficient representing the relative importance of the four levels of the basic criteria. $L_{1,h}(x)$, $L_{2,h}(x)$, $L_{3,h}(x)$ = index values of technical valuation, service life and cost. b = balancing factors for the level groups [7], representing the variability between the values of the different levels ($b \geq 1$). The larger the value, the greater the variability.

3.3 Determination of Weights

The values of W represent the judgement of the surveyed group of experts and are obtained applying AHP which compares each criterion of the different groups [7]. The comparison between criterion i and criterion j gives the value a_{ij} of matrix A. If $a_{ij} = \delta$, then $a_{ji} = 1/\delta$, where $\delta \neq 0$ and $i \neq j$; if $i=j$, then $a_{ij} = a_{ji} = 1$. For example, regarding group 4 and according to table 1, if the importance of *interference of local transit* (IT) for a construction method is *strong* ("5") compared to *provision of materials to the construction site* PM, then IT/PM = 5 and PM/CI = 1/5.

$$A = \begin{array}{c} \\ IT \\ PM \\ CA \end{array} \begin{array}{c} \begin{array}{ccc} IT & PM & CA \end{array} \\ \begin{bmatrix} 1 & 5 & 1 \\ 1/5 & 1 & 1/3 \\ 1 & 3 & 1 \end{bmatrix} \end{array}$$

IT interference of local transit
PM provision of materials to the construction site
CA compatibility with other construction activities

Starting from the eigenvalue of matrix **A**, the desired weights are obtained [7]. For the case of group 4 (independece of works) an according to the expert's opinion the weights coefficients are: W = 0.481, 0.114, 0.405 for IT, PM and CA respectively.

4 Ranking of the possible solutions

Once obtained the fourth level (5), let $L(x)$ be the fuzzy number representing the final composite indicator of alternative x, $L_{h=1}(x)$, $L_{h=0}(x)$ = index value. The membership function of the fuzzy number $L(x)$, is calculated in the following way:

$$\mu[L(x)] = \begin{bmatrix} 1, & r_{min} \leq L(x) \leq r_{max} \\ (L(x)-R_{min})/(r_{min}-R_{min}) & R_{min} \leq L(x) < r_{min} \\ (L(x)-R_{max})/(r_{max}-R_{max}) & r_{max} < L(x) \leq R_{max} \\ 0 & \text{otherwise} \end{bmatrix} \qquad ...(7)$$

where r_{min} and r_{max} = lower and upper bounds of $L_{h=1}(x)$ of the final indicator obtained by using $Z_{i,h=1}(x)$. R_{min} and R_{max} = lower and upper bounds respectively of $L_{h=0}(x)$ of the final indicator calculated by using $Z_{i,h=0}(x)$. The fuzzy numbers L(x) will be limited according to (7). The ranking of all the possible solutions are calculated maximizing and minimizing sets [8].

5 Example

The multi-criteria model evaluates the most suitable structural configuration (cable stayed, arch, frame and continuous beam) with more than 20 possible construction systems that have been applied for deck, piers and abutments. As an example, suppose that a consulting firm have to evaluate four projects for the construction of a deck bridge with the following characteristics: 300 m of total length, 15 m deck width and crossing a precipice of 100 m. The alternatives are: long span arch built by the cantilever method with temporary stays (A), incrementally launched continuous beam (B), cable-stayed bridge using formwork supported on the ground (C) and isostatic spans cast in situ using a self-supported movile formwork. (D). As shown in table 2, the span-length varies as function of the construction system (from 25 to 250 m for proposal A, from 40 to 80 m for proposal B, etc.). The largest likely interval is the range between the minimum and maximum values of the alternatives and the most likely interval is the range of the most common values of the alternative. The intervals represent the uncertainty in each criterion and establish the membership function $\mu[Z_i(x)]$. When the values of the variables are single numbers such as slenderness (group1), or deck width (group 3), are analyzed as non-fuzzy numbers.

Group	Basic Criteria	Proposal 1		Proposal 2		Proposal 3		Proposal 4	
		Least likely	Most likely	Least likely	Most likely	Least likely	Most likely	Least likely	Most likely
1	Slenderness l/h	16.7-16.7	16.7-16.7	6.67-6.67	6.67-6.67	16.67-16.67	16.67-16.67	3.33-3.33	3.33-3.33
1	Span	25.0-250.0	25.0-250.0	25.00-100.00	40.0-80.0	40.0-80.0	25.00-250.00	25.00-50.00	25.00-50.00
1	Adequacy to longitudinal slope	1.0-3.0	2.04-2.86	3.00-5.00	3.82-4.72	3.00-5.00	3.82-4.72	3.00-5.00	3.82-4.72
1	Adequacy to curvature in plant	1.0-1.0	1.00-1.00	1.00-1.00	1.00-1.00	1.00-1.00	1.00-1.00	1.00-1.00	1.00-1.00
2	Adequacy to functional platform	2.0-3.0	2.11-2.62	3.00-5.00	3.82-4.72	3.00-5.00	3.82-4.72	3.00-5.00	3.82-4.72
2	Width/Span ratio	15.0-21.0	15.0-21.0	15.0-21.0	15.0-21.0	18.0-25.0	18.0-25.0	18.0-25.0	18.0-25.0
2	Adjustment to variable cross-section	2.00-3.00	2.14-2.66	4.00-5.00	4.24-4.76	4.00-5.00	4.24-4.76	4.00-5.00	4.24-4.76
3	Adequacy to horizontal layout	2.00-3.00	2.11-2.62	3.00-5.00	3.82-4.72	3.00-5.00	3.82-4.72	3.00-5.00	3.82-4.72
3	Adequacy to cross-section geometry	1.00-3.00	2.04-2.86	3.00-5.00	3.82-4.72	3.00-5.00	3.82-4.72	3.00-5.00	3.82-4.7
3	Adequacy to cross-section depth	2.00-3.00	2.14-2.66	4.00-5.00	4.24-4.76	4.00-5.00	4.24-4.76	4.00-5.00	4.24-4.76
3	Adequacy to different span lengths	1.00-4.00	1.89-3.02	3.00-5.00	3.81-4.56	3.00-5.00	3.81-4.56	3.00-5.00	3.81-4.56
3	Adequacy to variable cross-section	1.00-2.00	1.11-1.62	4.00-5.00	4.49-4.96	3.00-5.00	4.04-4.86	4.00-5.00	4.49-4.96
3	Deck width	15.0-15.0	15.0-15.0	15.0-15.0	15.0-15.0	15.0-15.0	15.0-15.0	15.0-15.0	15.0-15.0
3	Prevention of alignment mistakes	3.00-5.00	3.89-4.71	3.00-5.00	3.88-4.67	2.00-4.00	2.74-3.66	2.00-4.00	2.66-3.54
4	Interference on local transit	4.00-5.00	4.59-5.00	4.00-5.00	4.74-5.00	1.00-3.00	1.89-2.71	3.00-5.00	3.65-4.58
4	Provision of materials to const.site	3.00-4.00	3.52-3.98	4.00-5.00	4.56-5.00	3.00-5.00	3.29-4.11	3.00-4.00	3.23-3.77
4	Compatib. with other const. activities	3.00-5.00	3.55-4.45	3.00-5.00	3.90-4.77	2.00-4.00	2.48-3.12	3.00-5.00	3.29-4.11
5	Aesthetics	3.00-5.00	3.55-4.45	3.00-5.00	3.81-4.56	3.00-5.00	3.44-4.19	3.00-5.00	3.44-4.19
5	Conceptual design of the bridge	8.00-9.00	8.00-9.00	8.00-9.5	8.00-9.50	7.00-8.50	7.00-8.50	8.50-9.00	8.50-9.00
5	Adequacy to landscape	3.00-5.00	3.89-4.71	4.00-5.00	4.46-4.94	1.00-4.00	2.18-3.28	3.00-5.00	3.66-4.54
5	Adaptability to the enviroment	8.50-9.00	8.50-9.00	8.50-9.50	8.50-9.50	7.50-8.50	7.50-8.50	7.50-8.00	7.50-8.00
5	Slenderness	31.7-37.7	31.7-37.7	20.3-26.3	20.3-26.3	34.7-41.7	34.7-41.7	21.3-28.3	21.3-28.3
6	Safety of the construction system	3.00-5.00	3.44-4.19	4.00-5.00	4.38-4.89	3.00-4.00	3.70-4.05	3.00-5.00	3.56-4.26
6	Safety of specific works	2.67-4.78	3.35-4.24	3.20-4.60	3.61-4.22	2.60-5.00	3.33-4.31	3.00-5.00	3.77-4.51
7	Adaptability to unexpected problems	2.00-3.00	2.72-3.06	2.00-4.00	2.41-3.19	3.00-5.00	3.46-4.34	2.00-4.00	3.67-2.88
7	Yield of construction system	14.0-18.0	14.0-18.0	35.0-40.0	35.0-40.0	15.0-20.0	15.0-20.0	55.0-60.0	55.0-60.0
8	Durability of structure	1.00-5.00	1.00-5.00	5.00-9.00	5.00-9.00	5.00-9.00	5.00-9.00	5.00-9.00	5.00-9.00
8	Inspection facility	7.00-7.50	7.00-7.50	9.00-10.00	9.00-10.00	9.00-10.00	9.00-10.00	8.50-9.00	8.50-9.00
8	Aesthetics	9.00-9.00	9.00-9.00	10.00-10.00	10.00-10.00	8.50-8.50	8.50-8.50	8.00-8.00	8.00-8.00
8	Simplicity of design	4.00-4.50	4.00-4.50	6.00-6.50	6.00-6.50	6.50-6.50	6.50-6.50	7.50-8.50	7.50-8.50
9	Inspection cost	150-164	150-164	133-144	133-144	138-156	138-156	110-130	110-130
10	Maintenance cost	225-246	225-246	199-216	199-216	227-234	227-234	170-200	170-200
11	Construction cost	750-820	750-820	665-720	665-720	690-780	690-780	700-730	700-730

Table 2 Deck bridge basic criterion values

The final result of the classification is in table 3, showing that the most appropriate in this case is the launching alternative (B).

Ranking	Construction alternatives	Final value
1	"B"	0.561
2	"D"	0.462
3	"C"	0.409
4	"A"	0.389

Table 3 Ranking of design and construction alternatives

6 Conclusions

1. The paper presents the most important features of the proposed fuzzy combined programming method. The method can be applied to determine the most feasible structural system and construction technique to be used in highway prestressed and composite bridges as a function of the input-values (design constraints) for each specific case.
2. The model can be applied separately (deck, piers and abutment) or in a complete way, according to the design constraints of the location.
3. It can be used as a tool to evaluate construction options, since permits to change the values of the basic criteria and adjust the importance W to specific constraints.

7 Acknowledgements

The research has been financially supported by the Spanish Ministry of Education (*Dirección General de Enseñanza Superior*) through Research Project PB95-0769.

8 References

[1] Zadeh, Lofti Asker (1965) "Fuzzy Sets" *Information and Control* 8, 338-353.
[2] Zadeh, Lotfi A. (1975) "Fuzzy Sets" *Encyclopedia of Computer Science and Technology* 325-363.
[3] Terano, T./Asai, K./Sugeno, M. (1992) "Fuzzy Systems Theory and Its Applications" *Academic Press.*
[4] Ramírez M., "Decision making in design and construction of bridges using fuzzy logic" *Doctoral Thesis. Technical University of Catalonia* (in progress)
[5] Dong, Wimin/Sha, Haresh C. (1987) "Vertex Method for Computing Functions of Fuzzy Variables" *Fuzzy Sets and Systems* 24, 65-78.
[6] Paek, J.H./Lee, Y.W./Napier, T.R. (1992) "Selection of Design/Build Proposal Using Fuzzy-Logic System" *Journal of Construction Engineering and Management*, ASCE,118(2), 303-317.
[7] Saaty, T.L. (1996) "The Analytical Hierarchy Process", University of Pittsburgh.
[8] Chen, Shan-Huo (1985) "Ranking Fuzzy Numbers with Maximizing Set and Minimizing Set" *Fuzzy Sets and Systems*, 17, 113-129.