COMBINING EXPERTS' DECISIONS AND DECISION TREE ANALYSIS TO SELECT THE OPTIMUM BRIDGE SUPERSTRUCTURE TYPE

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Abstract: Selecting the most suitable bridge superstructure type forms a very important aspect for a successful planning of the bridges and infrastructure projects. Different criteria need to be considered and large set of data must be analyzed in the conceiving stage of bridge design. Thus it's always important to benefit from experts' opinions, experiences and recommendations in order to reach an optimum decision. As an efficient approach, the decision tree analysis is largely used to compare, evaluate and analyze different structural alternatives towards selecting the best scenario option. In this paper, a novel integrated optimization approach is proposed to assist in selecting the best bridge superstructure design alternative. First, the Client's requirements are categorized and assigned an associated level of importance (IL). Each level of importance is given a specific weight. Secondly, a team of experts will evaluate both: i- the suitability level of each bridge superstructure type to meet the design requirements, and ii- the probability that each bridge type would maintain the Client's requirements. Then a decision-tree-analysis model will integrate the combined distribution of the experts' decisions with the Client's requirements and design requirements to reveal the best scenario for the bridge superstructure type. The implementation of the proposed methodology is illustrated through a case study. The obtained results encourage bridge planners and designers to adopt the proposed model, in bridge and infrastructure projects, as a decision-making tool.

1. INTRODUCTION

Several researchers invested valuable efforts towards optimizing the bridge design processes (Hong, 2007, Siriniva and Ramanjaneyulu, 2007). From their investigations it can be concluded that planning and designing bridges are partly art and partly compromise for the most significant aspects of structural engineering (Malekly et al, 2010). Selecting the bridge superstructure type is a sensitive and important step in the conceptual phase of bridge planning and design process particularly for short and medium span bridges. Although it takes up to 10-15% of the design process, the conceptual phase influences the entire design output and quality (Wood and Agogino, 1996). Inefficient conceptual design concept will lead to design shortcomings that will be difficult to rectify in the detailed design stage (Xu et al , 2005). As the superstructure represents about 70% of the total bridge cost (Menn, 1990), therefore, an improper superstructure selection may lead to uneconomical project results besides reducing the quality of the structure. This paper presents a new optimization model designed as a decision making tool, for the selection of the bridge superstructure type in the conceiving stage. To our best knowledge, no previous research attempt has been made to utilize the decision tree analysis in deciding about best scenario for a bridge superstructure type. This paper proposes a new methodology for selecting the optimum bridge superstructure type by integrating Expert Decision Analysis and Decision Tree Analysis.

2. METHODOLOGY

A new computer-aided model is proposed to assist in selecting the optimum type of bridge superstructure, by integrating expert's opinion in the decision-tree analysis.The parameters that influence the selection of the bridge superstructure type can be categorized into two groups:

- Client's requirements: for any final product, the client's requirements generally fall into *Cost, Time, Quality* and *Availability*.
- Design requirements: it is reasonably possible to classify the main factors affecting the bridge design processes as the *Geometric Conditions, Functional Requirements, Aesthetic, Constructability,* and *Legal and Environmental Conditions* (Barker & Puckett, 2013).

The flow chart in Figure 1 clarify the steps of the proposed methodology. The chart highlights the importance to collect the information that are necessary for the experts to build their assessments. Among those information are the geometrical data related to the road profile, vertical and horizontal clearances,etc. Data related to the site conditions has an influence on the preferred bridge type. Any available data about the geotechnical conditions, usually taken from the soil investigation reports, will also help the decision maker to decide about the bride type.

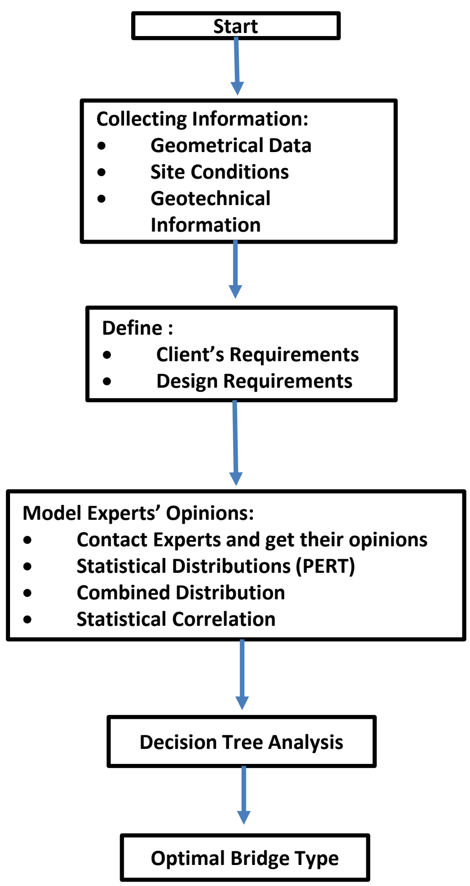

Figure 1: Flow chart of the proposed methodology

2.1 Client's Requirements

It is the responsibility of the designer to provide a structural solution that maintains the Client's requirements. In bridge design processes the Client's requirements can be generally defined as follows:

- Cost: for every project, the client has a specific allocated budget. The design drawings and specification of the bridge structure should be determined in such a way that it would ensure the project could be successfully completed within the budget limits. A general rule is that the bridge with the minimum number of spans, fewest deck joints, and widest spacing of girders will be the most economical structure for the given project (Barker & Puckett, 2013).
- Time: it is a major concern for the Client to put a new bridge into service within a pre-planned schedule. The designer should consider this time requirement when selecting the bridge type, deciding on the design detailing, and agreeing on the project specifications.
- Quality: it is important that the project output meets the aims and objectives for which it was undertaken. Also, the project deliverables shall meet the durability and sustainability requirements.
- Availability: the project should be planed, through its various phases, to assure and maintain proper accessibility to its various elements.

Although these requirements are of essential importance to the Client, it is still valid to ask the following question: “Are those requirements of equal priority to the Client in every project?”. According to numerous previous projects records and to the historical data, the answer is “No”. Love and Earl, (1998) conducted surveys of 41 clients and 35 consultants to obtain the experience data to be implemented in the methods and criteria of the project selection. Their findings indicated that, contrary to the expectations, similar clients generally do not have similar procurements needs. Also the findings show different appropriate weighting for different needs.

In our proposed methodology, an *Importance Level* (IL) is suggested to represent the strength of each of the Client’s Requirements. As shown in Table 1, linguistic terms associated with fuzzified scale (from 1 to 5) were used to define the strength of those the Client’s Requirements. The Client can prioritize the importance of his needs accordingly.

Importance Level (IL)	Weight
Very Poor	1
Poor	2
Fair	3
Good	4
Very Good	5

Table 1: Importance levels associated with Client’s Requirements

2.2 Design Requirements

The design processes are directly influenced by the following design requirements:

- Geometric Conditions: the horizontal and vertical profiles of the highway routes were taken into consideration besides the vertical clearance requirements form the essential geometric parameters to decide the suitable bridge type.
- Functional Requirements: A properly designed bridge will reveal a structure which would function efficiently to carry present and future volumes of traffic. To maintain this requirement, decisions must be made on the number of lanes, inclusion of sidewalks and/or bike paths, provision of medians, drainage of surface water, snow removal, and future wearing surface (Barker & Puckett, 2013).
- Aesthetic: As a grade-separation structure, every bridge has a visual effect and appearance impact on the area where it exists. One objective, a bridge designer should consider, is to obtain a positive aesthetic response to the bridge type selected. An aesthetically-designed bridge can be achieved when uninterrupted lines, clean lines, and uncluttered appearance are provided for the bridge shape (Malekly, H. et al, 2010).
- Constructability: the construction and erection considerations have a great influence when choosing a bridge type. For example, the project duration and economy for precast girder bride is totally different from those of cast-in-place concrete bridge or steel plate girder bridge.
- Legal and Environmental Conditions: Federal, governmental, provincial, and municipal regulations always exist. These regulations are usually beyond the designer control but they are real and should be taken into consideration. Among those regulations, environmental-impact limitations are usually specified by the authorities and the designer should always consider.

2.3 Correlation Between Client's Requirements and Design Requirements

Understanding the client's requirements will lead to an efficient design outputs that address the project's budget and time constraints. This will require establishing the design criteria and design requirements in an early stage of the project. Therefore, there is an interaction and a bilateral influence between the Client's Requirements and the Design Requirements. In the proposed methodology, this interaction was considered in the form of the correlation matrix. Statistical ddistributions in a model will often have to be *correlated* to ensure that only meaningful scenarios are generated for each iteration of the model (Vose, D., 2008).

2.4 Proposed Model

In this paper, a new method for the selection of the optimal bridge superstructure type is proposed. The computer-aided model integrates the experts' opinion analysis and decision tree analysis to revel the best case scenario for a certain bridge type.

2.4.1 Modeling Experts' Opinion

When the quantity modelled involves uncertainties, a Subject Matter Expert (SME) is consulted to provide an estimate for to account for these. The Expert opinion is an important source of information for quantifying the model parameters and the variables, particularly when insufficient data are available to specify completely the uncertainty of these parameters and variables (Vose, 2008).
Therefore the proposed model involves approaching a team of experts with the inquiry regarding their opinion or recommendation concerning:

- i- To which extent a specific type of bridge superstructure can satisfy the Client's Requirements. For this purpose, a Suitability index (SI) will be defined.
- ii- To which extent a specific type of bridge superstructure can satisfy the Design Requirements. For this purpose, another Suitability index (SI) will be defined.

It is well known that expert's opinion usually has inherent uncertainties. To model these uncertainties, different statistical distribution is utilized. Although different types of distributions, (e.g. PERT, Triangular, Uniform, Cumulative, Discrete, etc.) can mode the uncertainty inherent in the expert's opinion, the PERT (*also known as Beta PERT*) distribution is the most commonly used for expert estimation. In the proposed model the Beta PERT distribution is used (Vose, 2008). The formulation of this distribution requires three estimate values: Absolute Pessimistic (a), Most-likely (b), and Absolute Optimistic (c).

$$\text{PERT}(a, b, c) = \text{Beta}(\alpha 1, \alpha 2) * (c - a) + a \quad (1)$$

Where:

$$\alpha 1 = \frac{(\mu - a) * (2b - a - c)}{(b - \mu) * (c - a)} \quad (2)$$

$$\alpha 2 = \alpha 1 * \frac{(c - \mu)}{(\mu - a)} \quad (3)$$

$$\text{The mean } (\mu) = \frac{a + 4 * b + c}{6} \quad (4)$$

$$\text{The Variance } (v) = \frac{(\mu - a)(c - \mu)}{7} \quad (5)$$

For any point (x) within the domain: $a < x < c$

$$\text{The } Probability\ Density\ Function\ f(x) = \frac{(x-a)^{\alpha 1-1}(c-x)^{\alpha 2-1}}{B(\alpha 1, \alpha 2)(x-a)^{\alpha 1+\alpha 2-1}} \quad (6)$$

Where $B(\alpha 1, \alpha 2)$ is a beta function.

An Excel Add-In Software, ModelRisk (Vose, D., 2008), was used to model the statistical distribution of each expert. The model allows appointing weights that represent the confidence level associated with each expert opinion. Figure 2 shows an example of the PERT distribution for the decisions of a team of four experts. The horizontal axis shows the range of values of the experts' assessments (pessimistic, most-likely and optimistic). The vertical axis refers to the density function.

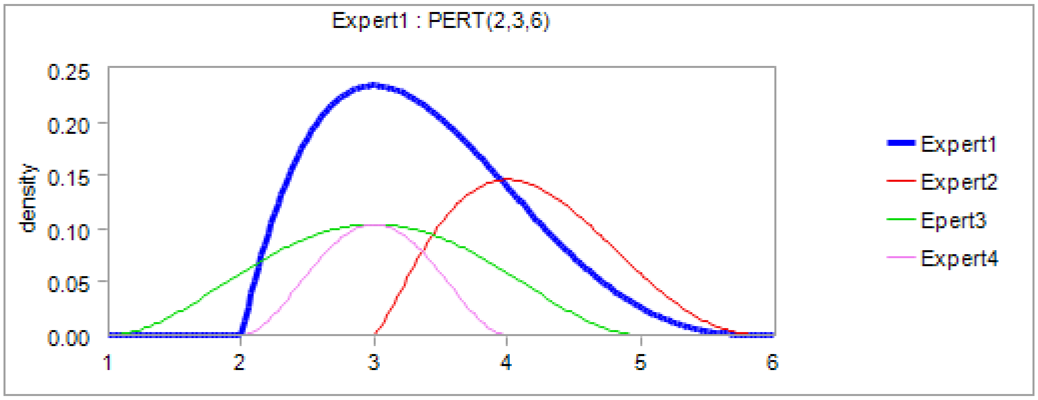

Figure 2: PERT distribution of the opinions of four experts

The next step is to combine the opinion distribution of all the experts and determine the combined probability by calculating the weighted average of the density function, i.e. if there were four experts A, B, C and D, (as in Figure 2), the density function F(x) of the combined distribution at x is given be equation (7):

$$F(x) = \frac{(fA(x) * wA + fB(x) * wB + fC(x) * wC + fD(x) * wD)}{wA + wB + wC + wD} \quad (7)$$

Where fA is the density of expert A's estimate, and wA is the weight assigned to this expert's opinion**.** Figure 3 below shows the combined distribution related to the Expert's decision analysis already defined in Figure 2 above. The vertical axis of Figure 3 scales the combined density function.

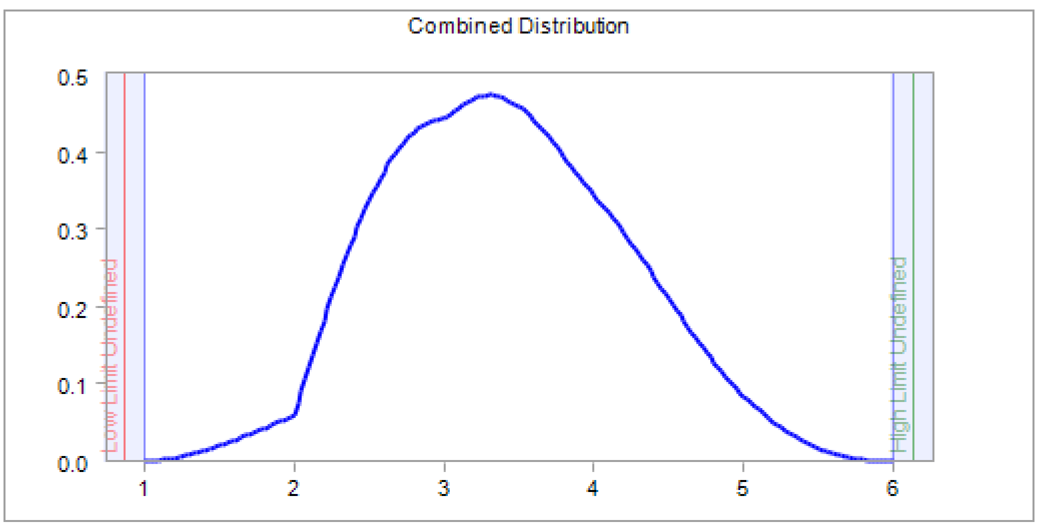

Figure 3: Combined distribution and density function

According to the above graph, for each bridge type under consideration, a combined probability distribution function representing the expert team is allocated to each variable used in the model. As stated earlier, there are two sets of variables: the Client's Requirements and the Design Requirements.

2.4.2 Decision Tree Model

Several researchers, from different engineering fields, used the Decision Tree Model as a decision making tool, (McCloudet al, 1992). In the present paper, a new method is proposed to select the optimal bridge type by integrating the experts' opinions with the Decision Tree Analysis.
In the proposed model, the tree consists of a trunk, main branches, secondary branches, and twigs. The trunk represents the optimal bridge type that will be revealed as an output. Each main branch represents a bridge type. Therefore, if thirteen bridge types are investigated, then the model should have thirteen main branches. From each main branch, two secondary branches will be developed, one for the Client's Requirements and one for the Design Requirements. From every secondary branch, a number of twigs will form. The number of twigs represents the number of variables under consideration. As we stated earlier, we have four Clients Requirements as variables, so four twigs should form out from the secondary branch related to the Client's Requirements. Similarly, we should have five twigs for the Design Requirements. For clarity, figure 4 shows a zoom-in part of a complete Decision Tree that models several bridge types. It is clearly shown that every main (parent) branch has two secondary (baby) branches. One secondary branch is for the Client's requirements which consists of four twigs (variables). The other secondary branch is for the Design Requirements which consists of five twigs (variables). On the top of the each twig of the Client's Requirements, the combined probability, P_i , of experts team is allocated. On the bottom of that branch the Importance Level, $(IL)_i$ is allocated. On the top of each twig from the Design Requirements, the combined probability, P_j ,of experts team is allocated. On the bottom of that twig the correlation coefficint, Cr_j , taken from the correlation matrix, is allocated.
For the proposed model, the technique used to generate rank order correlated input distributions was invented by Iman and Conover (1982). The elements of the correlation matrix contain Spearman's rank correlation coefficient (Spearman's *rho*) between each pair of samples Iman and Conover (1982). Spearman's rho is a non-parametric measure of the degree of correspondence between two variables. Spearman's rank correlation is carried out on the *ranks* of the data, i.e. what position (rank) the data point takes in an ordered list from the minimum to maximum values, rather than the actual data values themselves. The sample estimator of Spearman's *rho* is defined by Iman and Conover (1982) :

$$\rho = \frac{12}{n(n^2-1)} \sum_{i=1}^{n} [\, rank(X_i\,) - \frac{n+1}{2}]\, [rank(Y_i\,) - \frac{n+1}{2}\,] \tag{8}$$

As each sample has a correlation of 1.0 with itself, the top left to bottom right diagonal elements are all 1.0. Furthermore, because the formula for the rank order correlation coefficient is symmetric the matrix elements are also symmetrical about this diagonal line.

The Expected Monitory Value, EMV, of a twig in the Clients Requirements equals:

$$EMV = P_i * (IL)_i \tag{9}$$

While, for Design Requirements variables, the Expected Monitory Value, EMV, equals:

$$EMV = P_j * Cr_j \tag{10}$$

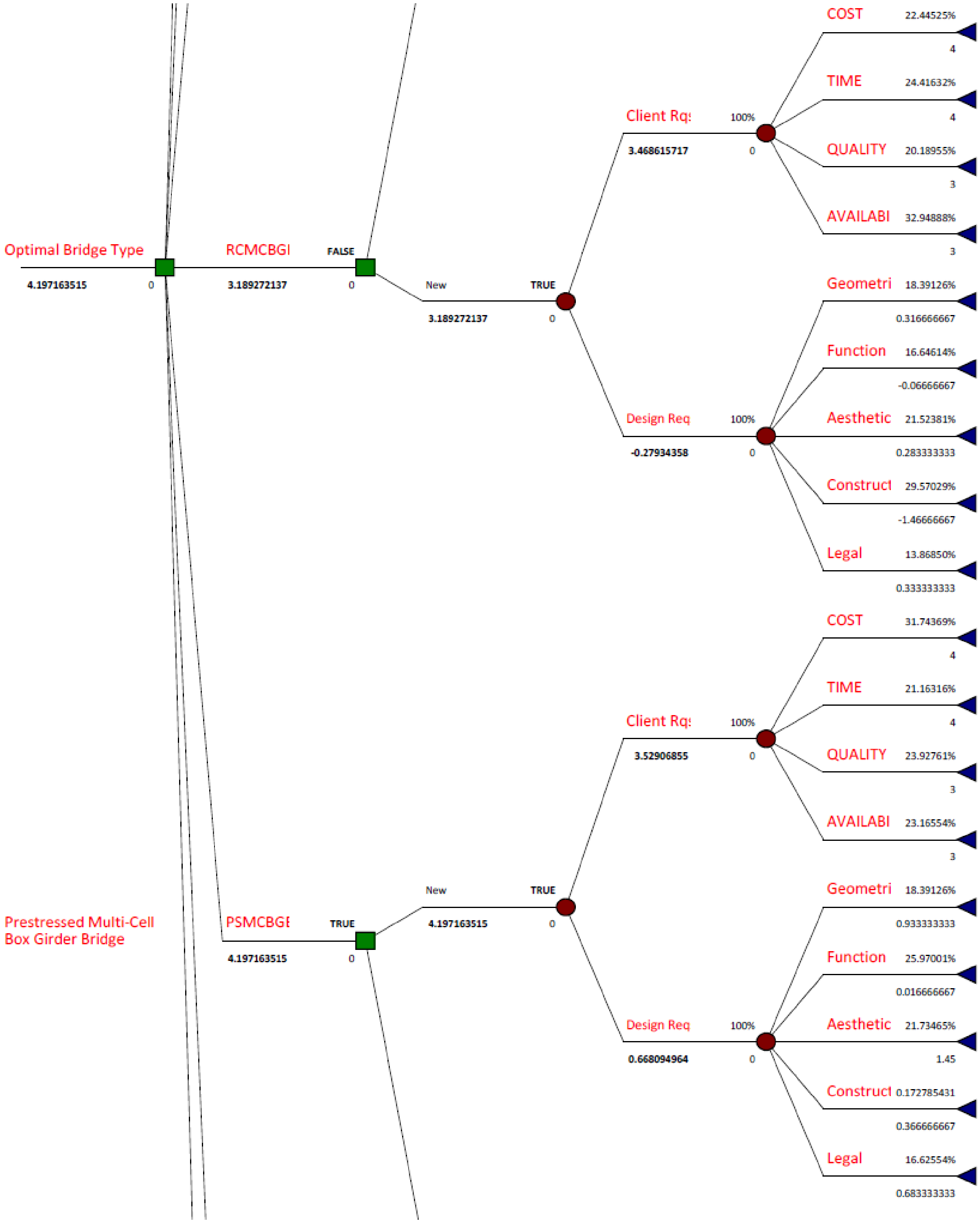

Figure 4: A zoom-in part of a complete Decision Tree

Generally, for a number of bridge types, the optimal bridge type is that one having the maximum EMV. The maximum EMV is defined by equation (11).

$$\max (EMV) = \sum_{q=1}^{n} [\sum_{i=1}^{4} \sum_{j=1}^{5} \{ (P_i * (IL)_i) + (P_j * Cr_j) \}]_q \quad (11)$$

3. CASE STUDY

For the purpose of validating the proposed methodology, a case study was modeled. The Roads and Transportation Authority, RTA, of the Government of Dubai announced a bridge project, in 2007. The project is to build a bridge crossing over the Sheikh Zayed Road in order to link Al-Barsha Quarter (East) with Al-Safouh area (West). The optimum type of bridge superstructure was selected based on a comprehensive *Value Engineering Analysis* conducted by a well reputed consultant, PARSONS International., The Value-Engineering study thoroughly examined the clients requirements, design requirements, the profile of the existing Sheikh Zayed Road, the roadway profile of the proposed bridge, the available geotechnical data, and the Clients future plans for the roads network development in that area. Seven types of bridge superstructures were examined:

1- Reinforced Concrete Slab Bridge (RCSB).
2- Pre-Stressed Concrete Slab Bridge (PSSB)
3- Monolithic T-Beam Bridge (MTBB)
4- Reinforced Concrete Multi-Cells Box Girder Bridge (RCMCBGB)
5- Pre-Stressed Concrete Multi-Cells Box Girder Bridge (PSMCBGB)
6- Precast Concrete Girder Bridge (PCGB)
7- Steel Plate Girder Bridge (PGB)

The finding of the study revealed that the fifth option (PSMCBGB) is the best scenario for the type of bridge superstructure. The bridge was designed and constructed accordingly. The bridge was opened to traffic in 2009.

In order to check the validity of our proposed methodology, we examined a general identical scenario (for an assumed bridge) with exactly the same conditions. We wanted to see what type of bridge our model would reveal. For that purpose, a team of four experts, in Dubai, was consulted. This team consists of a senior Bridge designer from AECOM Consultant, the Head of Bridge Design Section in Hyder Consultant, a professor in the American University in Dubai, (AUD), who has a deep experience in bridge engineering, and the Senior Design Manager of Al-Nabooda Liang Contracting Company in Dubai. An interview session was held with each expert separately. Based on the nine variables considered in our proposed model, every expert was requested to give his/her opinion as pessimistic, most-likely, and optimistic value. These values are relative to a scale from 1 to 10 scores (1 for very poor suitability and 10 being best suitable). The expert's assessment define the Suitability Index of each bridge type to satisfy the nine variables (four Client's Requirements and five Design Requirements). The experts have been provided with geometrical, geotechnical, environmental, and technical data identical to those used for the *Value Engineering Analysis* made for the RTA's project under consideration. Those data were provided to us by RTA authority. Each expert was interviewed individually and was provided with a detailed questionnaire along with the collected data.

The experts' score assessments were statistically distributed with PERT distribution. A combined statistical distribution has been derived and the probability related to each variable was defined. A correlation matrix is built to determine the correlation coefficients. A decision Tree model was then made and given all the data derived from the experts' opinion analysis. The decision tree analysis revealed a Maximum Expected Value, MEV, to the type of pre-stressed concrete multi-cell box girder bridge (PSMCBGB) which is in total agreement with the findings of the comprehensive value-engineering study (refer to Figure 5).

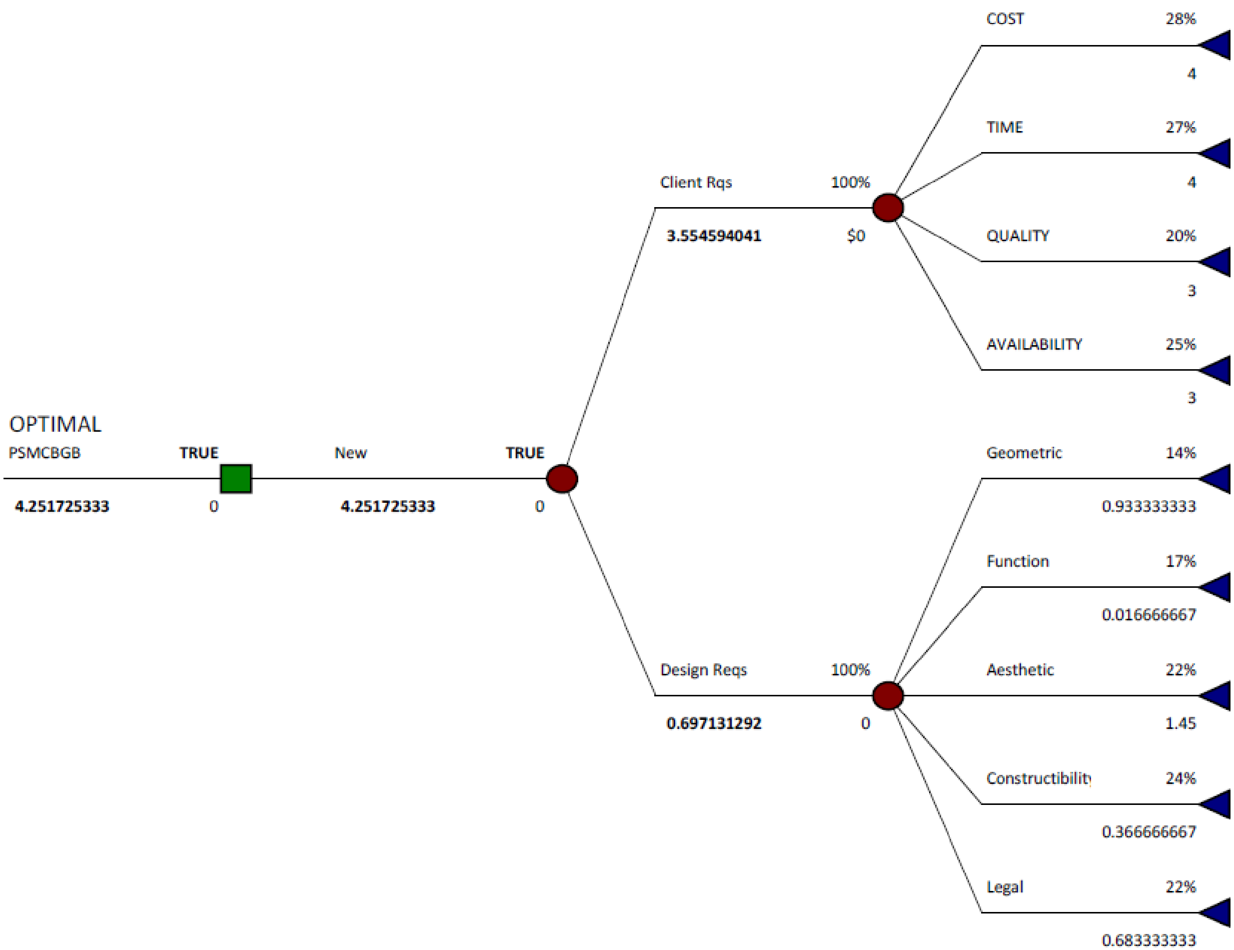

Figure 5: The optimal Type (PSMCBGB) according to the case study

4. CONCLUSIONS AND FUTURE WORK

The proper selection of bridge type, in the early stages of the project, forms an important step. A new method is proposed to predict the optimal bridge superstructure type by integrating the Experts' opinions analysis and decision Tree Analysis. The proposed model incorporates the Client's needs which are in correlation with the Design requirements. The validity of proposed model has been verified through a case study. The results encourage bridge planners and designers to adopt the proposed model, in bridge and infrastructure projects, as a decision-making tool.

Future work of this research will include conducting sensitivity analysis to examine how different values of independent variables will impact a specific dependent variable throughout the optimization process.

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