Contractor Selection Model for Highway Projects Using Integrated Simulation and Analytic Network Process

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Abstract: Selecting the appropriate contractor is a significant step to highway project success. The process of selection is subjected to uncertainty and influence of criteria other than bid price. This paper presents an approach to prioritize competitive contractors at the prebidding stage for highway projects by utilizing the analytic network process (ANP) and Monte Carlo simulation. Both techniques are integrated on a single platform to build the proposed model. Initially, the main quantitative and qualitative criteria affecting the contractors' selection process are identified and studied. The effective criteria in the selection process were obtained from experts and literature. A structured questionnaire was designed and sent to experts in highway projects. The ANP was used to prioritize these criteria subsequently, and Monte Carlo simulation was utilized to develop the selection model. The applicability of the proposed model was tested using four real cases of highway projects. It was concluded that using the lowest bid price as a sole criterion for selecting the best contractors may not result in an optimum solution. **DOI:** 10.1061/(ASCE)CO.1943-7862.0000647. *© 2013 American Society of Civil Engineers.*

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Introduction

The success level of any construction project can be argued to depend largely on selecting the most competent contractor. Accordingly, the selection of a contractor is one of the most important issues in construction projects. The complexity of construction projects makes the selection process of the most competitive contractor that satisfies the project objectives crucial to project performance (Singh and Tiong 2006). Among various contractor selection systems, the competitive bidding system has become the most popular practice around the world. It theoretically assists in selecting the contractor with the most innovative and cost-effective solution and constructing the facility at the lowest construction cost (Gransberg and Ellicott 1996).

Bid price has been the most dominant factor for selecting the highway project contractors (Merna and Smith 1990; Holt et al. 1995). With increasing complexity and dynamics of construction projects, further complications have been added to the contractor selection process. This new environment of construction created a need for new methods and tools to help decision makers to make informed decisions. Evaluating the contractor's bid based on price only does not seem to satisfy decision makers anymore. When contractors are faced with a shortage of work, they desperately quote a low bid price simply to remain in business with the expectation to be offset through claims (Hatush and Skitmore 1997). Contractor selection is a critical decision that influences the project success and should consider multiple criteria. (Holt et al. 1995; Nureize and Watada 2011). It is influenced by hybrid uncertainties that should be considered to indicate the optimum choice (Nureize and Watada 2011). Contractor selection criteria are uncertain; they vary with the different types of projects. As a result, many different attempts have been made for contractor selection to be based on economic and technical criteria. In other words, technical criteria and bid price should be considered when selecting a contractor.

Different methods to select the best value of contractor have been developed (Abdelrahman et al. 2008a, b). The analytic hierarchy process (AHP) and fuzzy set theory have been used extensively to evaluate the contractor's best value. The AHP and analytic network process (ANP) are two analytical tools for multicriteria decision making to quantify the effect of qualitative factors in a specific problem. The AHP is employed to break down large unstructured decision problems into manageable components. The ANP is the general form of the AHP; it has the power to deal with complex decisions and complex relationships between criteria in which AHP fails. The ANP provides inner and outer dependencies between criteria; it deals with the complex relationships between these criteria that account for the interactions of elements and make accurate predictions. Consequently, better contractor selection decisions can be attained. For instance, consider a decision about

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selecting the best contactor. The decision maker may want to decide among several competing contractors. The decision maker might base his decision of contractor selection on three criteria: price, experience, and financial capabilities. Methods of decision making would assume that the three factors are independent of one another, whereas the ANP would allow consideration of interdependency among the three criteria forming feedback loops of cause and effect relationships. For more clarification, Fong and Choi (2000) used a sample of 13 respondents to identify and prioritize eight uncorrelated criteria for contractor selection (tender price, financial capability, past performance, past experience, resources, current workload, past relationship, and safety performance). In fact, the eight criteria are interrelated to a certain extent. For example, good past experience may lead to good safety performance if the past experience includes good safety records. Good past performance and experience are good evidence of successful projects, which in turn results in strong financial capability. Resources and financial capability may be positively correlated. Tender price may negatively be related to other criteria. Therefore, the ANP is more favorable to be employed in this interdependent relationship framework taking a mixture of qualitative and quantitative criteria. Furthermore, it allows the decision criteria to be affected by the traits of the construction project. Despite the variety of the methods developed, none were capable of accounting for factors of interdependency and uncertainty inherited in the contractor's selection.

This research attempts to incorporate criteria other than the bid price in the contractor selection process and to account for the uncertainty inherited in respondents' perception to the criteria weight. The interdependency relationships among influential criteria can create dynamics in the form of cause and effect relationships. Such relationships can severely affect the selection of the best contractor.

To address those issues, this research rigorously identified the main criteria that affect the selection process. The influential criteria are selected based on experts' opinions and from the literature. Experts were asked to list the most influential criteria on the contractor selection; the outcome of this process was in conformity with what had been addressed in the literature. Second, to address the uncertainty and interdependency among criteria, simulation and ANP were utilized, respectively. The simulation is a powerful tool that accounts and quantifies the uncertainty inherited in respondents' weighting of criteria. The ANP's strength is measuring the interdependency among the criteria. Finally, through using those tools, a model to select the most appropriate contractor for highway projects was developed. The validity of the model was tested using four real cases.

Background

Contractor Selection Approaches

Many tools and approaches were developed to assist decision makers in selecting the best contractors for execution of different construction projects. Simulation, ANP, AHP, fuzzy logic, and the multiutility theory are examples of the approaches used to assist in making informed decisions. Simulation models were developed to analyze contractors' pricing behavior and dynamic competition process under the qualification-based selection (QBS) system (Lo and Yan 2009). The power of simulation to account for uncertainty was utilized to quantify factors and combine them into a single score (El Asmar et al. 2009). Other approaches, however, introduced a new concept of best-value modeling that was unique and tailored to each project (Abdelrahman et al. 2008a). Two application methods were used to assess the best value: (1) the weighted average method and (2) AHP. This approach was extended to develop a tool capable of ranking contractors based on the best value using a model to evaluate the best value and a methodology for quantifying the qualitative effect of subjective factors on the selection process (Abdelrahman et al. 2008b).

Fuzzy logic was also introduced, in a fuzzy-logic-based system, to select contractors. The system introduced an assessment model considering different qualitative and quantitative issues that influenced contractors' suitability for constructing a specific project (Bendaña et al. 2008). Procedures that are more systematic were built based on the fuzzy set theory to evaluate the capability of a contractor to deliver the project as per the owner's requirements (Singh and Tiong 2005). Singh and Tiong (2006) identified the contractor selection criteria for inclusion in a multiple criteria decision system and investigated the contractor selection criteria preferences to Singapore construction practitioners. A web-based subcontractor evaluation system called WEBSES was introduced for evaluating subcontractors based on combined criterion (Arslan et al. 2008); the criteria needed to evaluate contractors were selected from the Singaporean construction industry. The ANP was used for contractor selection as an extension for the AHP to allow interdependent influences specified in the developed model (Cheng and Li 2004; Fong and Choi 2000).

Multicriteria evaluation was also incorporated by proposing a multicriteria decision model for construction contractor selection in the Turkish public sector (Topcu 2004). The demand on inclusion factors in the assessment and selection process was on the rise by decision makers. Most of the developed models attempted to enhance the selection process by incorporating more factors for the evaluation (Alarcón and Mourgues 2002; Hatush and Skitmore 1998). Russell and Skibniewski (1990) developed QUALIFIER-1, a computer program to aid decision makers in prequalification, and QUALIFIER-2 (Russell et al. 1990) by adding some extra functions to QUALIFIER-1. A multicriteria decision support system for contractor selection was described in Mahdi et al. (2002) using project conditions using Delphi and AHP.

Minchin and Smith (2005) produced an innovative model quality-based performance rating system. The system generated an index for each contractor to represent the contractor's quality over a specified frame. Albino and Garavelli (1998) proposed a neural network process for subcontractor rating. A framework of fuzzy number theory to solve construction contractor prequalification was proposed in Yawei et al. (2007). Zavadskas et al. (2008) introduced contractors' assessment and selection based on the multiattribute methods. The authors developed a model considering the factors that influence the process of construction efficiency. Holt et al. (1995) presented a review of contractor evaluation and selection methodologies. The authors discussed the application of multiple regression, fuzzy set theory, and multivariate discriminate analysis to achieve their objectives. In addition, Hancher and Lambert (2002) developed an evaluation system for highway engineers to evaluate the performance of contractors to be done at the end of each year of project duration.

Despite the fact that the literature is rich with approaches and models for contractor selection, the two important issues of interdependency and uncertainty were not addressed concurrently. The decision-making process in the bidding stage is influenced by factors or attributes that should characterize any competitive contractor. Furthermore, those factors are not isolated from the bidding system structure and its turbulent environment. The cause and effect loop relationships among factors exist and can be considered a main driver to the whole selection process, which means assuming independency among factors is questionable. The second issue

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concerns the uncertainty inborn because of the subjectivity of factor weighting. Different respondents gave different answers. Using the stochastic approach (simulation) selects the most probable weight from the probability distribution of the respondents. Therefore, the issue of integrating a system of interdependency and simulation has not yet been addressed. The proposed method represents a novel approach in contractor selection and opens new venues for further enhancement of the current practice.

ANP

After introducing AHP in the early 1980s, ANP was introduced by Saaty (1996) to overcome limitations of AHP represented in the assumption of independence between criteria. The AHP establishes decision models through a process that contains both qualitative and quantitative factors. It decomposes the decision problem from a top overall goal to a set of manageable clusters, subclusters, and so on, down to the final level that usually contains scenarios or alternatives. The clusters or subclusters can be attributes, criteria, activities, and objectives. The AHP uses pair-wise comparison to assign weights to the elements at the cluster and subcluster levels and calculates global weights for the assessment that takes place at the final level. Each pair-wise comparison measures the relative importance or strength of the elements within a cluster by using a ratio scale. The AHP involves calculating the consistency ratio (CR) to measure how consistent the judgments have been relative to large samples of purely random judgments. If the CR is much in excess of 0.1, the judgments are untrustworthy because they are too close for comfort to randomness, and the exercise is valueless or must be repeated (Saaty 1996). A suitable example that shows the main features of the AHP is a model that was built to assess water main conditions by Al-Barqawi and Zayed (2006, 2008). Nevertheless, AHP models assume unidirectional relationships between clusters of different decision levels and between clusters. It is not appropriate for models that specify interdependent relationships to use AHP. The ANP was then developed to enhance the tool's analytical power (Cheng and Li 2004). It is a generic form of AHP that allows for more complex interdependent relationships among elements. As shown in Fig. 1, interdependence can occur in several ways (Cheng and Li 2004):

1. Uncorrelated elements are connected;
2. Uncorrelated levels are connected; and
3. Dependence of two levels is two-way (i.e., bidirectional).

By incorporating interdependencies through adding feedback loops in the model, a supermatrix was developed. The supermatrix adjusted the relative importance weights in individual matrices to form a new overall matrix with the eigenvectors of the adjusted relative importance weights. Four main steps are involved in ANP computation (Sarkis 1999):

1. Conduct pair-wise comparisons on the elements at the cluster and subcluster levels;
2. Place the resulting relative importance weights (eigenvectors) in submatrices within the supermatrix;
3. Adjust the values in the supermatrix so it can achieve column stochasticity; and
4. Raise the supermatrix to various powers until weights have converged and remained stable.

According to literature, construction contractor selection received considerable attention from researchers for the last two decades. However, uncertainty and interdependency among the various levels and across the same level of criteria and subcriteria have not yet been studied. Hence, an essential need exists to develop a model that considers the uncertainty and interdependency among criteria. The ANP alleviates the shortcomings of the discussed approaches used in contractor selection. The ANP deals with multiple criteria and further studies the interdependencies between these criteria and measures them quantitatively; it does not rely on binary decision.

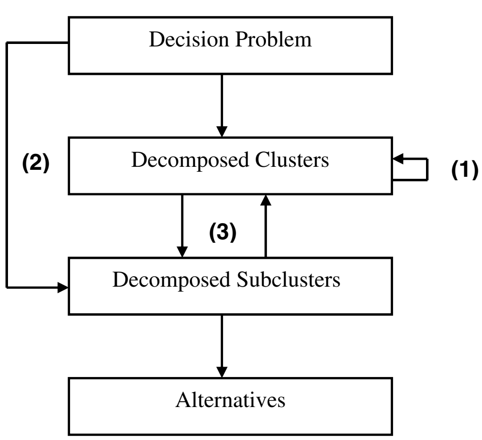

Fig. 1. Interdependencies in ANP

Criteria Affecting Contractor Selection

Using bid price solely to judge the contractors' tenders may result in not selecting the best and most qualified contractor. However, other factors should be accompanied with bid price to select the most appropriate contractor for the intended project. In preparing the most important criteria that affects contractor selection, the authors conducted an interview with experts in contractor selection and were asked to list the most important factors that can affect the selection process. The authors also reviewed the literature and prepared a list of the same type of factors. The two lists were compared, and there was essentially no difference between them. The next step was to develop the questionnaire for the purpose of measuring the effect of each factor and the bond between those factors. The criteria list used in contractor selection is classified into four main groups, as shown in Table 1 (Abdelrahman et al. 2008a, b; Arslan et al. 2008; Bendaña et al. 2008; Singh and Tiong 2006, 2005; Cheng and Li 2004; Topcu 2004; Alarcón and Mourgues 2002; Fong and Choi 2000; Hatush and Skitmore 1998, 1997; Holt et al. 1994). A brief review of the four main groups is illustrated as follows.

1. Project's main requirements. This group measured the essential concerns of owners, which mainly include the proposed contractor's bid price, schedule, and percentage of risk sharing between owner and contractor.
2. Financial capability. This group measured the financial soundness of contractors and their ability to meet current liabilities, long-term financial obligations, and to carry current commitments along with the project under consideration.
3. Past performance. This group mainly assessed the reputation of the contractor from four perspectives: percentage of previous works completed on time, past relationship with owner, response to claims, and health and safety records.
4. Experience. This group evaluated the availability of resources because, for example, equipment shortage and low productivity can cause delays to the project. In addition, the experience level of the contractor's staff can be evaluated and whether or not the contractor has previously handled jobs of similar scope and complexity.

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Table 1. Criteria Affecting Contractor Selection

Group	Main criteria		Subcriteria	Scaling identification method
A	Project's main requirements (PMR)	A1	Project bid price	Lowest price is considered the best eligible (i.e., 10) and other prices are to be prorated
		A2	Project duration	Lowest duration is considered the best eligible (i.e., 10) and other durations are to be prorated
		A3	Risk sharing with the owner	Highest risk contractor's share is considered the best eligible (i.e., 10) and other are prorated
B	Financial capability (FCB)	B1	Financial stability	Based on assessment (i.e., excellent = 10, verygood = 8, good = 5, poor = 3, verypoor = 1)
		B2	Working capital	Highest working capital is considered the best eligible (i.e., 10) and others are prorated
C	Past performance (PPF)	C1	% of previous work completed on time	Highest percentage is considered the best eligible (i.e., 10) and others are prorated
		C2	Past relationship with the owner	Highest number of performed projects with the same owner is considered the best eligible (i.e., 10) and other numbers are prorated
		C3	Response to claims	Based on assessment (i.e., excellent = 10, verygood = 8, good = 5, poor = 3, verypoor = 1)
		C4	Health and safety records	Based on assessment (i.e., excellent = 10, verygood = 8, good = 5, poor = 3, verypoor = 1)
D	Experience (EXP)	D1	Experience with similar types of projects	Highest number of similarly performed projects by the contractor is considered the best eligible (i.e., 10) and others are prorated
		D2	Contractor's staff experience	Highest experience is considered the best eligible (i.e., 10) and others are prorated
		D3	Equipment availability	Based on assessment (i.e., excellent = 10, verygood = 8, good = 5, poor = 3, verypoor = 1)

Research Methodology

The developed methodology, as shown in Fig. 2, starts by performing a brief literature review to illustrate the different approaches utilized by researchers for contractor selection. The criteria needed to enhance the selection process were selected at two stages. The first was requesting experts to fill out a form that asked for a list of the most influential criteria in highway project contractor selection; thereafter, another list was prepared from the literature. A comparison was conducted between the two lists for selecting the intersecting criteria. The most important criteria affecting highway contractor selection were identified. A structural questionnaire survey was conducted within highway construction contractors in the United States, Canada, and the Middle East. The survey was used as an instrument to prioritize the criteria responsible for selecting highway contractors within these organizations. For further assurance that the questionnaire included the most important criteria, an open-ended structured questionnaire was used in which respondents had the freedom to list any factors not included in the authors' list. All respondents were in agreement that the questionnaire included the most important factors. According to the collected data, relative weights of criteria were determined using the ANP technique. The criteria weights obtained from ANP analysis were then used as input for the proposed simulation model for highway contractor selection. Finally, the developed model was tested using four case study projects, and a sensitivity analysis was conducted to show the sensitivity of outputs to any changes in the inputs. It is also essential to note that none of the existing research works integrated Monte Carlo simulation and ANP, i.e., interdependencies and uncertainties. This integration considered factors' interdependency (using ANP), made decisions under uncertainty (using simulation), and handled decisions that involved large numbers of variables (using integrated simulation/ANP).

Model Development

The developed simulation model for highway contractor selection will simply simulate the mathematical model shown in Eq. (1). This model provides the final contractor's score such that the evaluator can easily select the best contractor based on the highest score. The general utilized mathematical formula is as follows:

$$\mathbf{CI}_j = \sum_{i=1}^{n} \mathbf{CS}_i * \mathbf{W}_i \qquad (1)$$

where CI_j = contractor index (CI) for contractor j; CS_i = contractor score for criterion i; W_i = final global weight of criterion i; n = number of criteria; and CI_j, CS_i, and W_i = random variables.

The final global weights of criteria are determined using ANP, as illustrated in the data analysis and model implementation sections. The contractor score ranges from 1–10 for each criterion, where 1 indicates a contractor's worst eligibility for this criterion, and 10 is the best. Although the score ranges are similar for all criteria, their identification methods differ, as explained in Table 1. The model was developed using @Risk 5.5.1 software, which is typically based on the Monte Carlo simulation approach. The Monte Carlo method or algorithm is a technique employed to randomly generate input variables and accordingly assess the value(s) of outputs. Four steps were employed to build the simulation model for the present research, as follows:

1. The criteria and subcriteria that affect a contractor's selection were identified and analyzed. The final global weights (W_i) of the criteria and subcriteria were determined, and their probability distributions were fitted;
2. The contractor's score (CS_i) for each criterion was determined using a value from 1–10. Their probability distributions were fitted based on the collected data;
3. The model in Eq. (1) was utilized to determine the contractor's index (CI_j); and
4. The developed model is step 3 was simulated for several iterations using the Monte Carlo simulation algorithm to assess the contractor's index.

Data Collection

First, a list of the most influential factors was prepared from open-ended questionnaires (unstructured) filled out by experts. Then, checking the list with what is available in the literature, a structural questionnaire was designed and distributed through telephone calls and e-mails to experts. The questionnaire respondents had a minimum of 5 years of practical experience. The questionnaire was sent to a sample of 60 experts associated with contractor selection and tender evaluation exercise and contract and/or construction

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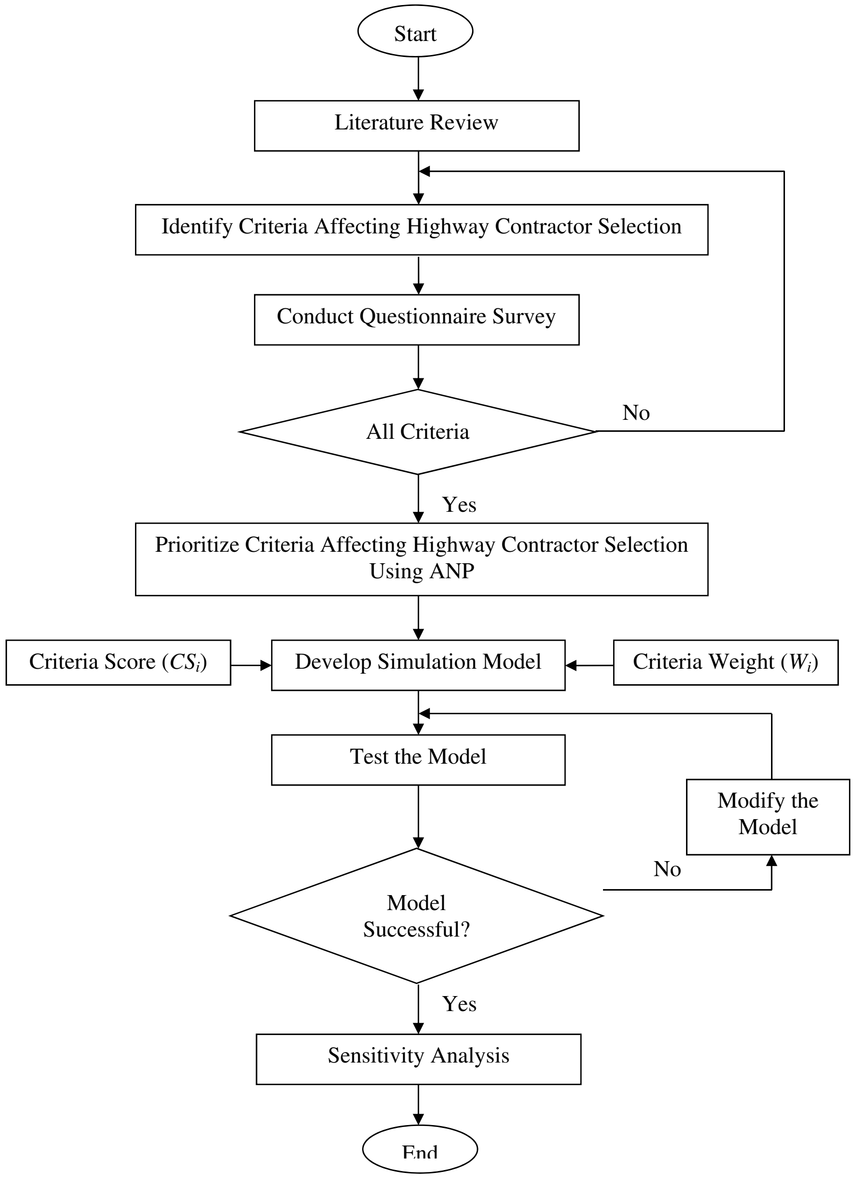

Fig. 2. Study methodology

management in the field of highway construction projects. Out of the 60 distributed questionnaires, 25 completed questionnaires were received from the targeted sample, which represents 41.6% of the total sample. The respondents' occupation varied between organization manager, project manager, construction manager, and others, with an experience level of 6 years to more than 20 years. It should also be noted that seven of the responses were collected from the United States and Canada, and the other 18 responses were collected from the Middle East region.

To identify the importance of each criterion—being a main or a subcriterion—in the selection process, the questionnaire used a pair-wise comparison method. This comparison was conducted on three levels, as follows:

1. Comparison among main criteria with respect to highway contractor selection;
2. Comparison among subcriteria within each main criterion; and
3. Comparison among main criteria with respect to one another.

The aforementioned third level is one of the main features that ANP adds to the well-known AHP method, in which it allows to create an inner interdependency. The three levels can also be illustrated as shown in Fig. 3(a). The pair-wise comparison for each level was designed in a very simple way in which each respondent decides based on his/her own experience the degree of importance of each criterion (X) or (Y) over the other(s) with respect to the goal under question. The degree of importance was scaled according to Saaty's (1996) scale from 1–9. An assigned value of 1 indicates that there is no significant importance of a criterion over the other, whereas a value of 9 indicates that there is an absolute importance for a criterion over the other. For example, for a level one comparison, as shown in Table 2, the respondent sees that the project's main requirements has very strong importance over the financial capability with respect to highway contractor selection, he should check the appropriate box that shows such a comparison. The same method was repeated for the past performance and experience in addition to other factors.

The remarks column shown in Table 2 was left blank for the respondents to give them the flexibility of entering an intermediate value of preference. However, it can be observed that three comparisons that should be made were not listed in the table—these

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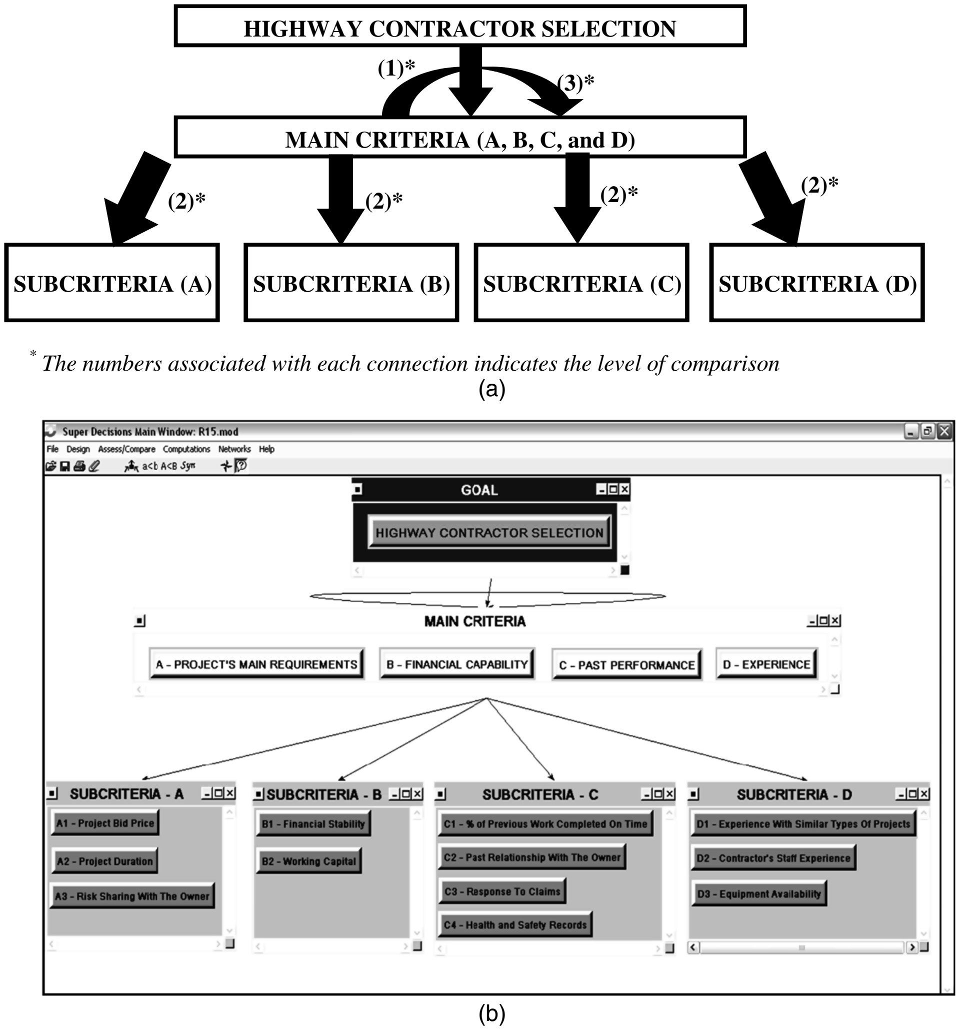

Fig. 3. ANP network for highway contractor selection: (a) ANP network components; (b) ANP network hierarchy

Table 2. Questionnaire Sample

With respect to highway contractor's selection											
	Degree of importance or preference										
Criterion (X)	(9) Absolute	(7) Very strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very strong	(9) Absolute	Criterion (Y)	Remarks
Project's main requirements		*x*								Financial capability	
					x					Past performance	
							x			Experience	

are experience and financial capability, experience and past performance, and financial capability and past performance. A logical way of determining such comparisons was concluded using the comparisons already made between the project's main requirements with the financial capability, past performance, and experience, as shown in Table 2. In other words, this table was also used to determine the comparison among the other main criteria and subcriteria, which saved the time and effort needed by the expert to answer the questionnaire.

Finally, data on four case study projects were collected to test the model after its development. The data of an existing project constructed in Egypt in addition to three projects constructed in the United States were collected and analyzed using the model. They will be described in detail in the case study section.

Data Analysis and Model Implementation

Weight (W_j) Determination for Criteria and Subcriteria

The steps of the ANP process were followed to determine the final global weights of selection criteria using the data collected through questionnaires. The implementation of the ANP process is briefly illustrated using the following seven steps.

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Table 3. Portions of Various Types of Supermatrix

		Unweighted supermatrix					Weighted supermatrix					Limit supermatrix				
			Main criteria					Main criteria					Main criteria			
With respect to		Goal	A	B	C	D	Goal	A	B	C	D	Goal	A	B	C	D
Goal		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Main criteria	A	0.716	0	0.745	0.745	0.745	0.716	0	0.373	0.373	0.373	0.213	0.213	0.213	0.213	0.213
	B	0.080	0.778	0	0.106	0.106	0.080	0.389	0	0.053	0.053	0.176	0.176	0.176	0.176	0.176
	C	0.102	0.111	0.106	0	0.149	0.102	0.056	0.053	0	0.075	0.050	0.050	0.050	0.050	0.050
	D	0.102	0.111	0.149	0.149	0	0.102	0.056	0.075	0.075	0	0.061	0.061	0.061	0.061	0.061
Subcriteria (A)	A1	0	0.797	0	0	0	0	0.399	0	0	0	0.169	0.169	0.169	0.169	0.169
	A2	0	0.114	0	0	0	0	0.057	0	0	0	0.028	0.028	0.028	0.028	0.028
	A3	0	0.089	0	0	0	0	0.045	0	0	0	0.016	0.016	0.016	0.016	0.016
Subcriteria (B)	B1	0	0	0.875	0	0	0	0	0.438	0	0	0.154	0.154	0.154	0.154	0.154
	B2	0	0	0.125	0	0	0	0	0.063	0	0	0.022	0.022	0.022	0.022	0.022
Subcriteria (C)	C1	0	0	0	0.673	0	0	0	0	0.337	0	0.034	0.034	0.034	0.034	0.034
	C2	0	0	0	0.096	0	0	0	0	0.048	0	0.004	0.004	0.004	0.004	0.004
	C3	0	0	0	0.135	0	0	0	0	0.068	0	0.008	0.008	0.008	0.008	0.008
	C4	0	0	0	0.096	0	0	0	0	0.048	0	0.004	0.004	0.004	0.004	0.004
Subcriteria (D)	D1	0	0	0	0	0.745	0	0	0	0	0.373	0.045	0.045	0.045	0.045	0.045
	D2	0	0	0	0	0.106	0	0	0	0	0.053	0.006	0.006	0.006	0.006	0.006
	D3	0	0	0	0	0.149	0	0	0	0	0.075	0.010	0.010	0.010	0.010	0.010

1. Employing the pair-wise comparisons. The elements of each level of network hierarchy were rated using the pair-wise comparison according to Saaty's (1996) scale of measurement mentioned previously. After all elements have been compared with the priority scale pair by pair, a paired comparison matrix was developed.
2. Estimating relative weights. After the pair-wise comparison matrix was developed, a vector of priorities in the matrix was calculated and then normalized to sum to 1.00 or 100%. This was done by dividing the elements of each column of the matrix by the sum of that column (i.e., normalizing the column). Elements of each resulting row were added to obtain a row sum and then divided by the number of elements in the row to obtain the relative weight or priority.
3. Determining CR. Because humans are sometimes inconsistent in answering questions, CR was used to validate the results and measure the consistency in the pair-wise comparison process. Saaty (1994) set acceptable CR values for different sizes of matrices as follows: (1) $CR \leq 0.05$ for a 3×3 matrix; (2) $CR \leq 0.08$ for a 4×4 matrix; and (3) $CR \leq 0.1$ for larger matrices. The CR values were calculated for all matrices, which showed all of them to be consistent.
4. Developing the unweighted supermatrix. With interdependent influence, the system consisting of cluster and subcluster matrices was translated into a two-dimensional supermatrix. The unweighted portion of the supermatrix, shown in Table 3 (for one of the questionnaire responses), was constructed from the priorities (relative weights) derived from the different pair-wise comparisons done in the previous steps. The nodes, grouped by the clusters they belong to, were the labels of rows and columns of the supermatrix. The entire supermatrix is not presented because of paper size limitations. Therefore, only the main criteria part in the column side is presented against main and subcriteria in the row side part of the matrix, as shown in Table 3.
5. Developing the weighted supermatrix. The weighted supermatrix was obtained by dividing each entry in each row in the unweighted supermatrix by the total summation of its relative intersecting column. For example, the summation of column B in Table 3, unweighted supermatrix, is equal to 2.00, and the corresponding entry in row C is 0.106; therefore, dividing those values by one another results in the weighted value of this entry, which is 0.053. This value was entered into the intersecting cell of row B and column C in Table 3, weighted supermatrix. Similarly, the other corresponding values of the weighted supermatrix were determined as shown in Table 3. The summation of each column in the weighted supermatrix is 1.0.
6. Developing the limit supermatrix. After entering the submatrices into the supermatrix and completing the column to determine the weighted supermatrix, it is then raised to a sufficiently large power until convergence occurs to obtain the limit supermatrix, as shown in Table 3. It is noted that the number in all columns of the limit supermatrix are identical because of convergence.
7. Calculating final global weights. From the limit supermatrix, the final weights could be obtained by proportioning the elements of each cluster to themselves. For example, as shown in Table 3, the cluster of main criteria has the project's main requirements, financial capability, past performance, and experience with values of 0.213, 0.176, 0.050, and 0.061, respectively, which results in a total value of 0.50. Therefore, their final weights were calculated by dividing each of these values by 0.50. The same procedure was followed with each subcriteria cluster to obtain the local weight, which was then multiplied by the final weights of each corresponding main criteria to obtain the global weight. The average main and subcriteria's final local and global weights are shown in Table 4 for the collected data from questionnaire responses. To facilitate the application of the previously discussed steps, Super Decisions software was used. The network's components and relations were identified as shown in Fig. 3(b), and then the pair-wise comparison for each level was entered. The model can be used for evaluating more than one contractor at a time.

Probability Fitting for Weights of Criteria and Subcriteria

Table 5 summarizes the statistical information for different distributions that are selected for each criterion. Statistical tests—the chi-squared (Ch-Sq), the Anderson–Darling (A-D), and the Kolmogorov–Smirnov (K-S) tests—were performed to check

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Table 4. Average Final Local and Global Weights for Main and Subcriteria

Main criteria	Global weight (%)	Subcriteria	Local weight (%)	Global weight (%)
(A) Project's main requirements	31.6	A1: Project bid price	63.9	20.2
		A2: Project duration	15.5	4.9
		A3: Risk sharing with the owner	20.6	6.5
(B) Financial capability	25.8	B1: Financial stability	75.3	19.4
		B2: Working capital	24.7	6.4
(C) Past performance	19.2	C1: Percentage of previous works completed on time	25.0	4.8
		C2: Past relation with the owner	36.2	6.9
		C3: Response to claims	16.2	3.2
		C4: Health and safety records	22.6	4.3
(D) Experience	23.4	D1: Experience with similar types of projects	38.3	8.9
		D2: Contractor's staff experience	24.7	5.8
		D3: Equipment availability	37.0	8.6

Table 5. Summary of Statistical Analysis Results for Criteria Weights

Criterion	Parameter	A1	A2	A3	B1	B2	C1	C2	C3	C4	D1	D2	D3
Distribution		Normal	Gamma	Lognormal	Uniform	Maximum extreme	Gamma	Exponential	Log logistic	Lognormal	Beta	Exponential	Exponential
Mean weight (μ)		0.202	0.049	0.065	0.195	0.064	0.048	0.069	0.031	0.043	0.089	0.058	0.086
Standard deviation (σ)		0.098	0.043	0.061	0.110	0.057	0.034	0.061	0.035	0.053	0.063	0.043	0.083
Variance (σ^2)		0.010	0.002	0.0004	0.012	0.003	0.001	0.004	0.001	0.003	0.004	0.002	0.007
Standard error (ε)		0.003	0.001	0.003	0.003	0.002	0.001	0.002	0.001	0.004	0.002	0.002	0.003
Chi-square test	Test value	1.600	2.800	1.200	10.000	10.000	4.000	2.000	11.600	1.600	7.600	2.000	4.800
	P-value	0.449	0.094	0.273	0.007	0.002	0.046	0.572	0.001	0.206	0.022	0.572	0.187
A-D test	Test value	0.492	0.568	0.183	1.527	1.184	0.343	0.388	1.510	0.213	0.676	1.154	0.440
	P-value	0.209	0.610	0.899	0.098	0.073	0.869	0.651	0.305	0.877	0.075	0.071	0.570
K-S test	Test value	0.124	0.153	0.077	0.245	0.196	0.158	0.121	0.210	0.079	0.168	0.208	0.116
	P-value	0.425	0.610	0.963	0.059	0.184	0.458	0.663	0.001	0.972	0.058	0.058	0.722

whether or not the fitted distributions were statistically sound based on the maximum P-value for each criterion's distribution. Tables 4 and 5 also show that A1 (project bid price) and B1 (financial stability) are the most important criteria, with a mean weight value of 0.202 and 0.195, respectively. The mean weight values of A1, 0.202, and B1, 0.195, form 0.397 (39.7%) of the total weight of all criteria. In addition, D1 (experience with similar types of projects) and D3 (equipment availability) showed a sound importance with a mean weight value of 0.089 and 0.086, respectively. The C3 (response to claims) was found to be the least important criterion with a weight of 0.031 (3.1%), and other criteria were approximately similar in importance.

Contractor Score (CSi_i) Determination

To determine the competitive contractor's score for each criterion, the contractor's scaling identification methods illustrated in Table 1 are to be applied. As shown in Table 1, two methods of identification exist. The first method is based on selecting the best eligible contractor j for criterion I, depending on its real value, and assigning this criterion a score of 10 for contractor j. Therefore, the scores of other competing contractors for this specific criterion will be scaled (i.e., prorated) to the best eligible contractor proportionally. For example, assume there is a number of contractors who provided their own project bid price for a specific project. The contractor with the lowest bid price is considered to be the best eligible, and hence he/she will be assigned a score of 10 for the criterion project bid price, whereas the rest will have scores proportioned to the lowest bid price out of 10. This method applies to the criteria in A1, A2, A3, B2, C1, C2, D1, and D2. The second method depends directly on the evaluator's assessment in which he/she grades a certain criterion for each contractor based on his/her point of view and experience. As shown in Table 1, the developed grading system has the following matching scores: 10, 8, 5, 3, and 1 for excellent, very good, good, poor, and very poor, respectively. This method applies to the criteria in B1, C3, C4, and D3.

Contractor Index (CI_j) Determination

The last part of model implementation is to determine the contractor index, which will decide the contractor to be selected for a given project. This is done by applying Eq. (1) for all competing contractors simultaneously using the developed simulation model. The model simply runs by multiplying each contractor's score for each criterion by the final global weight of the corresponding criterion, which is obtained from the ANP implementation explained previously. The results of these multiplications are then added up to determine the contractor index for each contractor. This process is repeated for a number of iterations as defined by the user. It shows the robustness of Monte Carlo simulation algorithm in which in each iteration a random final global weight is chosen based on the probability distribution defined for each criterion. This randomness ensures that uncertainty is considered and that the mean value of the contractor index (CI_j) obtained throughout the iterations is the final index value for each contractor. Finally, the contractor with the highest index is to be considered the winner.

Model Testing

Four real construction project cases were used to test the developed model's applicability and highlight its benefits. The steps involved in the testing process are summarized as follows:

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Table 6. Characteristics, Score, and Index for Contractors, Case Study 1

Criteria	Contractor's characteristics			Contractor's score (out of 10)		
	Contractor A	Contractor B	Contractor C	Contractor A	Contractor B	Contractor C
A1: Project bid price	CAD$ 73.5M	CAD$ 83.5M	CAD$ 85.5M	10	8.8	8.6
A2: Project duration (months)	18	24	26	10	7.5	6.9
A3: Risk sharing with the owner	Excellent	Very good	Good	10	8	5
B1: Financial stability	Excellent	Excellent	Good	10	10	5
B2: Working capital	CD$ 734.2M	CD$ 587.4M	CD$ 367.1M	10	8	5
C1: % of previous work completed on time	N/A	N/A	N/A	10	9	8.5
C2: Past relationship with the owner	N/A	N/A	N/A	8	10	7
C3: Response to claims	Very good	Excellent	Very good (-)	8	10	7
C4: Health and safety records	Very good	Excellent	Very good (-)	8	10	7
D1: Experience with similar types of projects	N/A	N/A	N/A	10	8	7
D2: Contractor's staff experience	N/A	N/A	N/A	5	10	8
D3: Equipment availability	Good	Excellent	Very good	5	10	8
Parameter						
Mean index (μ) out of 10	—	—	—	8.876	9.041	6.871
Standard deviation (σ)	—	—	—	2.26	2.39	1.83
Variance (σ^2)	—	—	—	0.51	0.57	0.33
Standard error (ε)	—	—	—	0.7	0.7	0.5

Note: N/A = exact characteristic is not available; (-) = characteristic is between very good and good for compromising.

1. The main characteristics for each contractor were determined based on the selected criteria and subcriteria;
2. A contactor's score is obtained for each selection criteria according to the methods identified in Table 1; and
3. The contractor's scores obtained along with the previously defined weight distributions of the selecting criteria were input into the model to obtain each contractor's index.

Case Study 1: Freeway Construction Project

This project included the construction of a 200-km freeway to connect major cities in upper Egypt. The main project scope included the full road construction of a 200-km, 6-lane, two-way freeway with a total width of 55 m. Crossing tunnels at intervals of 30 km were constructed to serve the U-turns and connect the main road with different towns along the freeway. The required data were provided by an expert involved in the design of the project. Because of the large project scope, only three large companies were qualified, and for confidentiality reasons, the three companies will be named contractor A, B, and C.

Following the model testing methodology, the main characteristics for each contractor, as shown in Table 6, were determined based on the selected criteria and subcriteria. A contactor's score was obtained for each selection criteria according to the methods identified in Table 1. For example, the project duration given by contractors A, B, and C were 18, 24, and 26 months, respectively. According to the scaling method for this criterion, the lowest duration (i.e., 18 months) is given a score of 10. Therefore, contractor A's score for project duration is 10, whereas contractor B is $(18/24) \times 10 = 7.5$ and contractor C is $(18/26) \times 10 = 6.9$. The same procedure is followed when dealing with other criteria for each contractor. It was difficult for the expert to identify the exact characteristic requirement for criteria in A3, C1, C2, D1, and D2. As a result of the expert's experience, a direct approximate contractor's score for these criteria was estimated. Finally, the contractor's scores obtained in Table 6, along with the previously defined weight distributions of the selecting criteria, were input into the model to obtain each contractor's index. The results obtained from the simulation model are summarized in Table 6 and Fig. 4.

Based on the index values only, contractor B should be selected because they had the highest mean index of 9.041 (90.41%), although the difference is very small when compared to contractor A with a mean index of 8.876 (88.76%). Contractor C, however, is obviously rejected because their index value is too far from contractors A and B, with the lowest mean index of 6.871 (68.71%). In such situations, experts' judgment should be employed to assess the trade-off between the difference in bid price among contractors and their index values in which qualifications are added to bid price. At this point, the decision is left to the owner and/or their representative. Because the mean index difference is very small between contractor A and B, the owner may ignore this difference and select contractor A because they provided the lowest bid price. Despite of that, the main concept of the lowest bid price not being the best choice still exists.

Case Study 2: TH-113 Project

The data for case studies 2 and 3 were adopted from the published work of Abdelrahman et al. (2008a, b). The primary purpose of this project was to reclaim state highway TH-113 (Mahnomen County, Minnesota) from the junction of TH 32 to the Norman/Mahnomen County line. District 4 out of Detroit Lakes added a 3.75-cm (1.5-in.) overlay from the Norman/Mahnomen County line to the city of Waubun. The project included extending centerline reinforced concrete pipe (RCP) culverts to improve safety. The goal of this project was to extend the life of TH-113 for 12–15 years from the current expected life. Not all the identified criteria in the present research were available in the published work. To make the comparison between cases 1 and 2 feasible, only the available criteria in the two cases that are compatible are considered. Therefore, the final global weights of the new updated criteria were adjusted relatively to keep the summation of weights equal to 100%.

Project duration for the project under study was not available; therefore, this criterion was not considered despite the fact that it is compatible with current research's criteria. The analysis of the contractor's scores and indices are shown in Table 7 for case study 2. It shows that contractor C has the highest index value (8.07); however, they did not submit the lowest bid price compared to contractor A. The difference in the contractor's index value between C and A is significant with almost similar standard deviation (C: 2.12 versus A: 2.34) and error (C: 0.7 versus A: 0.8).

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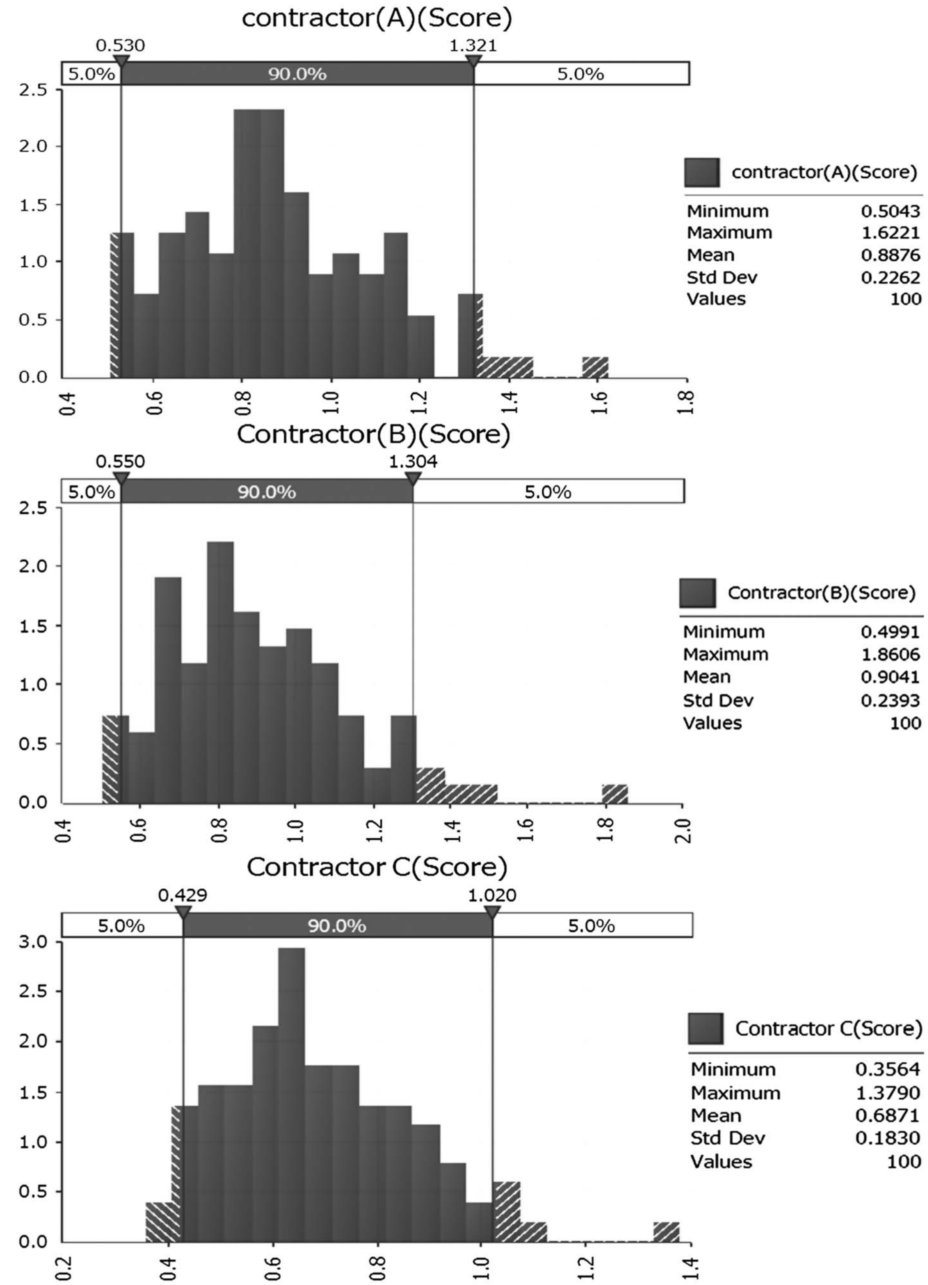

Fig. 4. Contractor's index probability distribution (case study 1)

Table 7. Contractor's Score and Index, Case Studies 2 and 3

Criteria	Contractor's score (out of 10)					
	Case study 2			Case study 3		
	Contractor A	Contractor B	Contractor C	Contractor A	Contractor B	Contractor C
A1: Project bid price	10	9.513	9.11	10	9.783	9.715
A2: Project duration	N/A	N/A	N/A	9	10	6.667
A3: Risk sharing with the owner	0.167	0.143	10	5	2.5	10
C3: Response to claims	10	0.4	0.025	7.5	5.769	10
D2: Contractor's staff experience	5	10	6.667	10	10	6
Parameter						
Mean index (μ) out of 10	7.44	7.15	8.07	9.21	8.65	9.23
Standard deviation (σ)	2.34	2.29	2.12	2.47	2.36	2.22
Variance (σ^2)	0.55	0.52	0.45	0.61	0.56	0.49
Standard error (ε)	0.8	0.6	0.7	0.7	0.7	0.8

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Case Study 3: TH-494 Project

This project was a new Valley Creek Road interchange with interstate I-494 in Woodbury, Minnesota. The project included grading, concrete and bituminous surfacing, and a signal system. A similar procedure to the one adopted in the previous case studies was followed and repeated for case study 3. The results of contractor's scores and indices are shown in Table 7. It shows that contractor C has the highest index value (9.23); however, they did not submit the lowest bid price compared to contractor A, with a similar index value of (9.21). The difference in the contractor's index value between C and A is insignificant, with nearly similar standard deviation (C: 2.22 versus A: 2.47) and error (C: 0.8 versus A: 0.7). In such a case, the authors would prefer selecting contractor A for the following reasons: (1) having the lowest bid price, (2) shorter project duration, and (3) better staff experience.

The methods used in those previous studies (for case studies 2 and 3) were the weighted average method (WAM) and the AHP. Each of those methods was applied using two different options. In the first option, the contractor's scale and criteria's weights are generic, whereas in the second option, the contractor's scale and criteria's weights are oriented to project specifics.

As an additional comparison between the previous studies and the current study, the contractor's scores in the previous studies were recalculated by taking into account only the criteria that are compatible with the current study. This step was taken to check what would be the possibility of obtaining a different contractor's ranking by eliminating the incompatible criteria. It should be noted that it was taken into consideration to redistribute the compatible criteria's weights to keep the summation equal to 100%. It was found that the contractor's ranking for the WAM method using the first option in case studies 2 and 3 turned out to be C-B-A and A-C-B, respectively, instead of C-A-B. Also, the contractor's ranking for the AHP method using the first option changed from C-A-B to A-C-B.

Case Study 4: I-35W Project

This project was considered a replacement of the I-35W bridge that collapsed over the Mississippi River in Minneapolis in 2007. The main features of the new bridge constructed in 2008 are as follows:

- 10 lanes of traffic, five in each direction—two lanes wider than the former bridge;
- 57.6 m wide—the previous bridge was 34.4 m wide;
- 4-m-wide right shoulders and 4.3-m-wide left shoulders; the previous bridge had no shoulders; and
- Light rail transport–ready, which may help accommodate future transportation needs.

The project was a design-build type of which five contractors were prequalified for its construction, and four of them submitted their proposals. The submitted project bid price and duration for each of the four contractors are shown in Table 8.

In addition to the project bid price and duration, some criteria on which the contractors were evaluated was compatible with this study, as shown in Table 9. Again, the same procedure followed in the previous case studies was applied; the results of the contractors' scores and indices are also shown in Table 9. Despite the fact that contractor B proposed the highest project bid price and duration whereas contractor C proposed the lowest in both (see Table 8), it can be noticed from the simulation results in Table 9 that contractor B had the highest mean score of 8.64 whereas contractor C came directly next in the rank with a mean score of 8.55. Contractor B was actually awarded the contract, which matches what happened in reality. The government agency utilized other evaluation criteria, such as enhancements and aesthetics; however, they arrived at the same rank of the contractors. The developed models and methodology in the present research is flexible enough to accommodate any requirement for the government agency(ies) in ranking contractors. They also provide these agencies with information needed to negotiate contracting packages. For example, the authors are supporting the fact that contractor C might not have the best index value; however, he is very close to the best index with a difference of 0.09. Knowing that, the agency might be able to select contractor C because he is competent in qualifications with the lowest cost bid.

Table 8. Submitted Proposals for Case Study 4

Contractor	Project bid price ($)	Project duration (days)
A	178,489,561	392
B	233,763,000	437
C	176,938,000	367
D	219,000,000	437

Discussion and Limitations

Based on the results obtained from case studies 2 and 3, contractor C was found to have the highest index, although their bid price was the highest, which again proves the main concept of this research. Contractors A and B were ranked the second and third, respectively. The previous studies performed by Abdelrahman et al. (2008a, b) produced different values for contractor indices among the different methods and options used; however, it ranked them in the same order in which contractor C got the highest score followed by A then B. However, after eliminating the incompatible criteria in the previous studies and recalculating the new contractor's scores accordingly, the contractor's ranking was changed in some of the

Table 9. Contractor's Score and Index, Case Study 4

	Contractor's scale (out of 10)			
Criteria	Contractor A	Contractor B	Contractor C	Contractor D
A1: Project bid price	9.91	7.57	10	8.08
A2: Project duration	9.36	8.4	10	8.4
C4: Health and safety records	8.57	8.6	7.63	7.43
D1: Experience with similar types of projects	5.715	9.415	6.035	7.165
D2: Contractor's staff experience	5.715	9.415	6.035	7.165
Parameter				
Mean score (μ) out of 10	8.46	8.64	8.55	7.92
Standard deviation (σ)	0.326	0.338	0.312	0.297
Variance (σ^2)	0.106	0.114	0.097	0.088
Standard error (ε)	0.10	0.11	0.10	0.09

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methods and options used, as mentioned previously. This indicates that some of the previous studies' models are sensitive, and their results can be affected when not taking into consideration all the criteria studied. The model in the current study shows its robustness by getting the same ranking as the previous model, even though some criteria were removed.

For case study 4, contactor B was awarded the contract. Although the actual evaluation method adopted took extra criteria into account that were not compatible with this study, such as enhancements and aesthetics, the main concept of this study can still be proved. The complexity of the problem does not appear clearly from these case study projects because only a few contractors are listed and not many criteria were considered. It is therefore anticipated that the developed model, through considering the uncertainties in decision variables and the interdependencies among them, will generate a robust solution in large-scale projects with a high number of competitors when sufficient information is available to enrich the analysis and generate informed decisions. Another concern that may arise is the implication of awarding public projects to a contractor who might not have the lowest price. This issue requires further studies in which a what-if scenario can be analyzed. In other words, if the developed model determined the best contractor for a project whose submitted price is not the lowest price, then an analysis should be done to show what-if scenarios for the contractor with the lowest price if he/she is awarded the contract instead. The analysis can include the response to claims for this contractor, the rework that may occur during the project because of inadequate past experience, for example, or any other weak points for the contractor with the lowest price that may result in an extra cost beyond the original price. These extra costs might include (1) rework because of bad quality, (2) delays because of incompetence, (3) short life cycle because of bad quality material, (4) operation and maintenance problems because of inadequate experience, and (5) many claims because of bad management. Therefore, the lowest priced contractor is not always the best to spend public money on because it might cost the public more than the other contractors on the long run. Awareness is mandatory to show the public and tax payers the drawback of such a decision and its implications. It is worthy to depict here that the contractor selected by the best value technique will save a lot of money even though he/she does not submit the lowest bid.

Sensitivity Analysis

The final global weights of all criteria were calculated from questionnaires using the ANP. However, the owner or consultant evaluating contractors might have a different opinion regarding the weights of various models' criteria. Therefore, it was essential to perform a sensitivity analysis to observe the effect of changing these weights on models' results. Sensitivity analysis focuses only on the effect of changing weights of the two most important criteria (i.e., project bid price and contractor's financial stability) on the developed model's output. For case study 1, the weight of the two criteria was changed from 0 (the criterion is not considered in the selection procedure) to 1 (the criterion is the only one considered in the selection procedure) independently. For example, if changing the mean value of the final global weight of the project bid price criterion to 0.6 instead of the original average value of 0.202 is considered, as shown in Table 4, the weight of other criteria are left with a total mean weight of 0.4 (i.e., 1–0.6 = 0.4). As a result, the mean values of these criteria are to be changed proportionally according to their average mean values shown in Table 4 to sum up to 0.4. For each change, whether it is in the project bid price or the

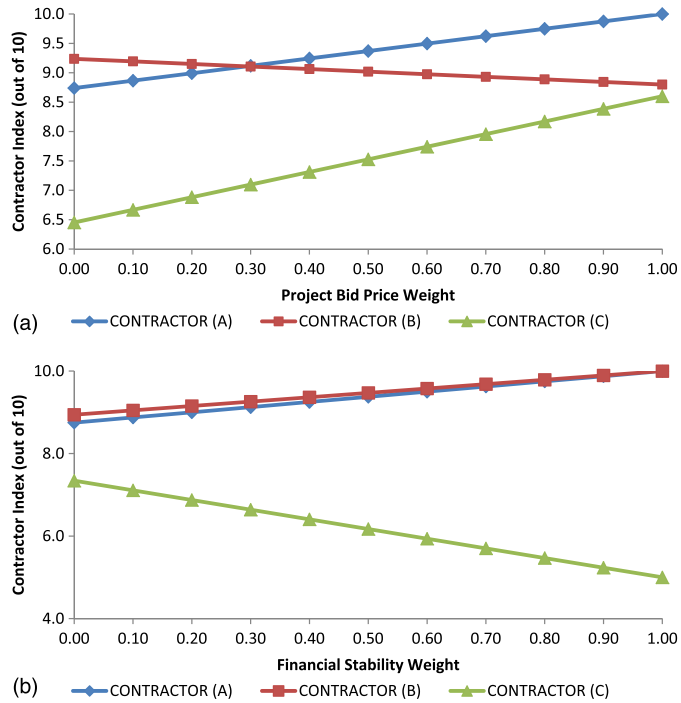

Fig. 5. Sensitivity analysis of contractor index to (a) project bid price; (b) financial stability

financial stability criterion, the contractor's index is determined and plotted against weight, as shown in Figs. 5(a and b).

The sensitivity analysis is also supposed to show the mean weight of the criteria project bid price and financial stability at which the values of those criteria have an effect equal to other qualification parameters, which is the intersection point between the lowest bid line and highest qualification bid. In Fig. 5(a), any change made to the project bid price mean weight up to 0.288 will not have any effect on the results, because the best contractor remains contractor B and any increase above that value will result in changing the decision to select contractor A instead of contractor B. This is obvious because increasing the project bid price weight means that this criterion has a major importance that will be in favor of contractor A because he provided the lowest bid price. In Fig. 5(b), both contractors A and B have nearly the same score, but still contractor B is higher. Obviously up to a financial stability weight of 1.00, both contractors become almost equal. It is clear that contactor C is out of competition in both cases because the financial stability of contractor C cannot compete with others (see Table 6).

Conclusion

This study proposes a novel approach of a multicriteria contractor selection process while considering uncertainties and interdependencies among criteria and subcriteria. Twelve quantitative and qualitative criteria having major impact on highway contractor selection were identified. The ANP was used to rank and weight the criteria according to their importance. This allowed for considering the inner interdependencies between criteria. The project bid price and contractor's financial stability had the highest impact when selecting contractors for highway projects with a combined weight of 39.7%. Sensitivity analysis was performed on these two criteria only because they represent the two most important criteria.

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Changing the weight of the bid price beyond 28.8% was found to affect the contractor's ranking. An integrated simulation/ANP model was developed to select the best contractor. This integration provided three main benefits: (1) making decisions under uncertainty, (2) encompassing interdependencies among criteria, and (3) handling decisions that involve a large number of variables. Four case study projects were chosen to test the developed model. Results obtained from testing illustrate that the lowest bid price is not always sufficient for selecting a suitable contractor; other technical criteria should be considered.

Although this paper contributes in enhancing the contractor's selection process by presenting a novel approach that integrates simulation for uncertainty with ANP for interdependency among criteria, this model is limited to highway projects that share similar influence criteria. The presented approach can be applicable to most project delivery systems. The selected criteria are sensitive to different classes of projects, locations, and respondent characteristics. Further, enhancement of the model is needed through increasing the respondents sample size, criteria, and respondent characteristics. The developed model can be used for prequalification and final bid evaluation stages. However, in many cases, the final contractor selection process might be very strict and not flexible. In this case, it is recommended to apply the model in the prequalification phase of the contractor selection process.

This research is expected to be of value in adopting a new approach that accounts for uncertainty and interdependency among criteria for the contactor selection process in the construction industry. This allows for enhancing the decision support tools and improves the cost and duration of the project through selection of the most competitive contractor.

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