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Integration of Simulation-Based Cost Model and Multi-Criteria Evaluation Model for Bid Price Decisions

Wei-Chih Wang,* Ren-Jye Dzeng & Yu-Huang Lu

Department of Civil Engineering, National Chiao Tung University, Taiwan

Abstract: *Several criteria affect bidding decisions. Current bidding models determine a markup based on a fixed project construction cost. This work presents a novel bid price determination procedure that is built by integrating a simulation-based cost model and a multi-criteria evaluation model. The cost model is used to consider cost uncertainties and generate a bid price cumulative distribution, whereas the multi-criteria evaluation model applies pairwise comparisons and fuzzy integrals to reflect bidder preferences regarding decision criteria. The relationship between the two models is based on a practical phenomenon in that a bidder has a high probability of winning when criteria evaluations favor his bid, and, consequently, the bidder would bid a low price, and vice versa. The merits of the proposed procedure are demonstrated by its application to two construction projects in Taiwan.*

1 INTRODUCTION

Bidding decisions often include whether to bid (Han and Diekmann, 2001; Wanous et al., 2000, 2003; Lin and Chen, 2004) and what bid markup to allocate (or what bid price to use). This study focuses on the second decision. Making suitable decisions regarding the bid price of a lump-sum-based construction project is essential for a bidder to win the project contract and achieve a reasonable profit, regardless of the type of bid-award method used (e.g., lowest bid versus multi-criteria evaluation bid). A high bid price that maximizes profit conflicts with the interest of the bidder in winning the contract. On the other hand, a low bid price that increases the probability of winning the contract jeopardizes profit (if awarded). The dilemma for the bidder is to set a bid price that is sufficiently high to maximize profit, while simultaneously being sufficiently low to successfully win the contract.

In practice, the markup (or bid price) of a construction project is frequently determined based on intuition and experience, and involves emotional responses to current pressures (Fayek, 1998; Xu and Tiong, 2001). Nevertheless, this experience-based bid price decision explicitly or implicitly considers numerous criteria related to environmental conditions, company conditions, and project conditions (Dozzi et al., 1996; Chua and Li, 2000; Dulaima and Shan, 2002). Consequently, a suitable bid price decision must deal with the evaluations of these criteria.

Current bidding models determine bid markup by assuming that project construction cost is fixed. However, construction costs typically vary due to variations in several cost uncertainties such as inflation rate, financing interest rate, quantity takeoff and price quotes. By considering project construction cost as probabilistic and assuming that bid price decisions should go through a variety of criteria evaluations, this investigation proposes a novel hybrid bid price determination procedure that combines a simulation-based cost model and a multi-criteria evaluation model. The cost model considers the criteria involving cost uncertainties and derives a cumulative distribution of project bid price. The multi-criteria evaluation model is utilized to identify the preferences for other decision criteria. A bid price is recommended from the bid price distribution according to a project expected utility value as assessed by the multi-criteria evaluation model.

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*To whom correspondence should be addressed. E-mail: *weichih@mail.nctu.edu.tw*.

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The rest of this article is organized as follows. The next section reviews the literature on bidding and tendering practices, and then describes the proposed procedure. The detailed workings of the proposed procedure are demonstrated using two projects (i.e., case studies I and II). Finally, research significance is discussed, and directions for future research are suggested.

2 REVIEW OF PERTINENT RESEARCH

Relevant bidding and tendering research addresses assessment of bidder capability to complete a contract (Russell and Skibniewski, 1988; Lo et al., 1999), selection of a method for awarding contracts (Herbsman and Ellis, 1992; Ioannou and Leu, 1993), tests to minimize subjective bias in best value procurement (Kashiwagi and Byfield, 2002a, 2002b), determination of the project ceiling price (Wang, 2002a; Wang, 2004), evaluation of competitive bids for examining the decision to accept or reject the lowest project bid (Crowley and Hancher, 1995; Skitmore et al., 2001), and determination of bid markup. The research most relevant to this work is that for determining project ceiling price and bid markup.

From the perspective of project clients, Wang (2002a) created a procedure (called SIM-UTILITY) to obtain a project ceiling price or cost threshold to use as a reference for accepting and rejecting construction project bids. Any bid over this cost threshold was generally disqualified under the Taiwanese Procurement Law (Wang, 2002a). Wang's procedure was based on a utility theory and facilitated by a cost simulation approach. The utility theory was applied to reflect client preferences regarding the determination criteria affecting project cost threshold, whereas the simulation technique was utilized to yield objective project cost data to support the execution of utility theory. For simplicity, Wang (2004) further devised a mathematically derived cost model that substituted the simulated-derived cost model to support SIM-UTILITY.

Existing models for determining bid markups can be classified into three groups (Marzouk and Moselhi, 2003): (1) statistical models, (2) artificial intelligence based models, and (3) multi-criteria utility models. Among the statistical models, for example, Carr (1983) designed a general bidding model by considering the influence of the number of involved bidders on the markup. Carr (1987) further illustrated how competitive bid analysis can include resource constraints and opportunity costs.

Considering that markup decisions have difficulty in going through a sequence of deep reasoning steps, several bidding models using Artificial Neural Network (ANN) related tools have been designed to support markup decisions (Moselhi et al., 1993; Li and Love, 1999). Additionally, believing that bidding decision problems are highly unstructured and no clear rules can be found for delivering a bidding decision, Chua et al. (2001) devised a case-based-reasoning bidding model for helping contractors.

Several decision criteria guide bidders in determining how to price their work in relation to estimated construction costs (Ahmad and Minkarah, 1988; Dozzi et al., 1996; Chua and Li, 2000; Dulaima and Shan, 2002). For example, Dozzi et al. (1996) applied a multi-criteria utility theory to implement construction project bid markup decisions. Moreover, based on the analytic hierarchy process (AHP), Cagno et al. (2001) proposed a simulation model to assess the probability of winning in a competitive bidding process in which competing bids were evaluated based on multiple criteria. Furthermore, Marzouk and Moselhi (2003) designed a model for estimating markup and evaluating bid proposal using multi-attribute utility theory and AHP.

Generally, statistical models have difficulty capturing specific project characteristics (e.g., project complexity and market conditions); the ANN-related models require numerous training cases or suitable rules to represent the bidding strategies of individual bidders. The multi-criteria evaluations meet the real-life situations closely (Marzouk and Moselhi, 2003). Finally, all current models produce bid markups based on an assumption of fixed project costs.

3 PROPOSED PROCEDURE

3.1 Modeling strategies

The goal of most bidding models is to maximize the chance of winning a bid under the criterion of expected profit maximization (Car, 1987; Moselhi et al., 1993; Cagno et al., 2001; Chua et al., 2001). However, like other models (Dozzi et al., 1996; Li and Love, 1999; Marzouk and Moselhi, 2003), the proposed procedure attempts to improve the quality of a bid price decision-making process by incorporating the assessments of a variety of decision criteria and by treating project construction costs as variables to fit real-world situations.

This study divides bid price decision criteria into two groups: (1) the group-1 criteria (cost uncertainties) directly influence estimations of project construction costs; and (2) the group-2 criteria address subjective preferences of decision-makers. Based on a review of several current studies (Dozzi et al., 1996; Cagno et al., 2001; Dulaima and Shan, 2002), Figure 1 displays an example hierarchical structure for these two groups of criteria. Each group of criteria is classified into two levels: level-1 criteria and level-2 subcriteria. The level-1 criteria for each group are related to environmental conditions, company

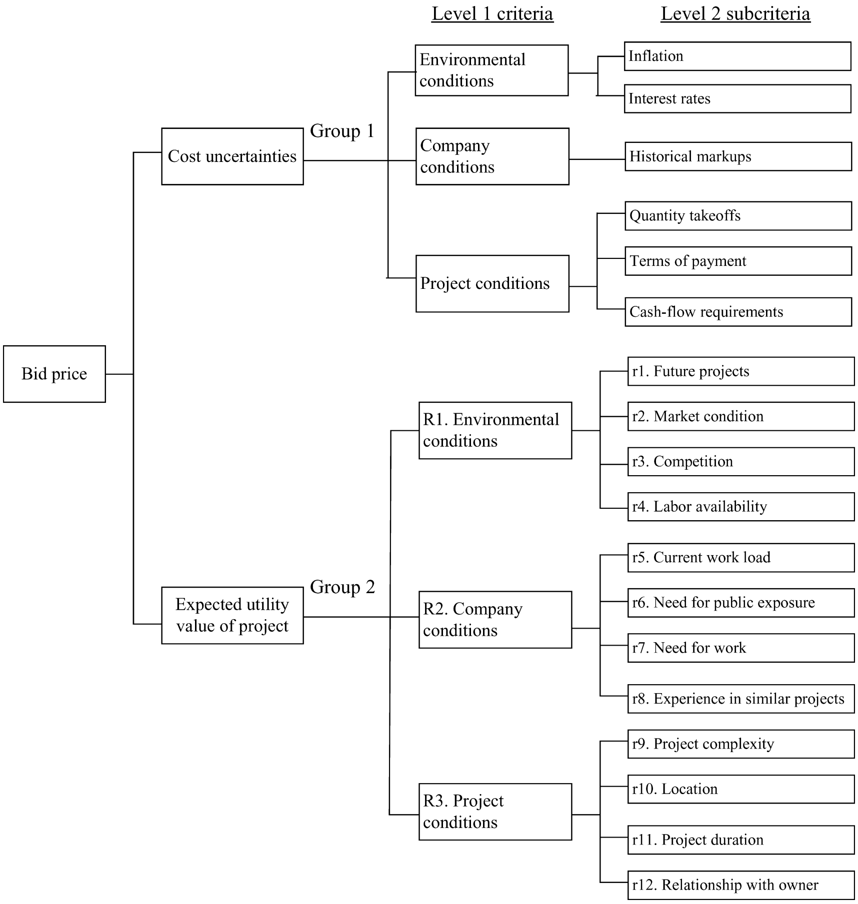

Fig. 1. Example of the hierarchical structure of criteria and subcriteria.

conditions, and project conditions. A simulation-based cost model is applied to assess the group-1 criteria, whereas a multi-criteria evaluation model is designed to evaluate the group-2 criteria. The integration of both models for supporting bid price decisions is described in the following section.

3.2 Modeling steps

Figure 2 shows the modeling steps of the proposed hybrid procedure achieved by modifying the procedure in Wang (2002a). (The differences between the two procedures are described in Section 6.1.) The right of the figure illustrates a simulated cumulative probability distribution of project bid price, whereas the left part presents a utility function generated based on the multi-criteria evaluation model. The proposed procedure is executed via the following three phases, which consist of nine steps.

- Phase I: cost model
    1. Estimate the construction costs, including the direct and indirect costs.
    2. Conduct a simulation analysis to include cost uncertainties and then generate a cumulative distribution of bid price.
    3. Identify the maximum and minimum bid prices of the project (namely, the upper and lower boundaries of the project bid price).
- Phase II: multi-criteria evaluation model
    4. Set the lowest expected utility value for the bidder, Eu(w), to 0. Additionally, set the probability of not winning (PONW) for Eu(w) at 1. The point (Eu(w) $= 0$, 1) thus corresponds to the probability of 1 of the cumulative distribution of bid price, and then corresponds to the maximum bid price. (See Figure 2.) Submitting the maximum bid price implies that probability of winning is zero ($=1 - \text{PONW} = 1 - 1$). This setting reflects a practical phenomenon: a bidder assumes a high risk if the criteria evaluations are unfavorable to him; and he would bid a high bid price (with less chance of winning the project contract).

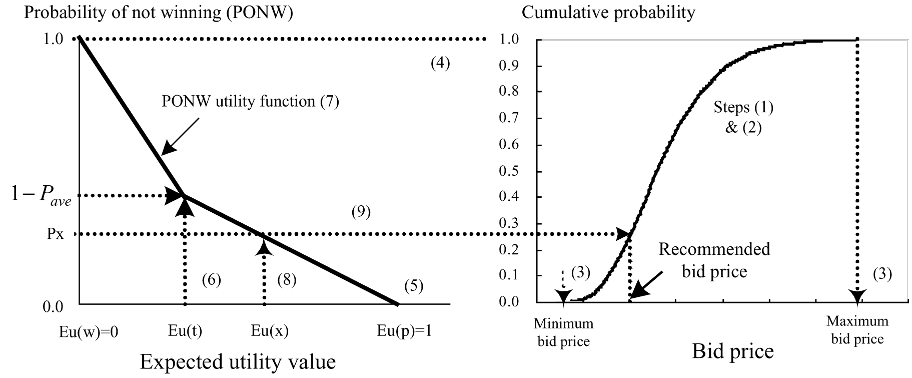

Fig. 2. Proposed procedure.

5. Set the highest expected utility value for the bidder, Eu(p), to 1. Furthermore, set the PONW with respect to Eu(p) at 0. Thus, the point (Eu(p) = 1, 0) corresponds to the probability of 0 for the cumulative distribution of bid price, and then corresponds to the minimum bid price. (See Figure 2.) Submitting the minimum bid price indicates that probability of winning is 1 (=1 − PONW =1 − 0). Restated, a bidder would prefer to make a lowest price bid to gain a high chance of winning the project contract in situations where the criteria evaluations favor that bidder.
6. Set a particular value of PONW (= 1.0 – average winning probability = 1.0 – P_{ave}) corresponding to the threshold expected utility value (Eu(t)). The value of P_{ave} equals the number of earned bids divided by total number of submitted bids in a given period for the bidder. The value of Eu(t) is calculated using threshold utility scores for the bidder's subcriteria. The threshold utility score of a subcriterion is considered as the acceptable utility score for the subcriterion for the bidder to bid on a project. It is assumed that the bidder would submit a bid if the criteria evaluation of the project was Eu(t).
7. Assuming a straight-line relationship, develop the PONW utility function based on the following three points; that is, (Eu(w) = 0, 1), (Eu(t), 1 − P_{ave}), and (Eu(p) = 1, 0).

- Phase III: integration of two models

8. Calculate the expected utility value of project scenario x, Eu(x) after assessing the utility value of each criterion of the project. According to the PONW utility function developed above, a value of PONW, Px, is identified with respect to Eu(x).
9. Based on the value of Px, find a recommended bid price from the cumulative distribution of the project bid price.

In establishing the PONW utility function, the two points, ((Eu(w) = 0, 1) and (Eu(p) = 1, 0)), are applicable to all bidders, whereas the threshold point (Eu(t), 1 − P_{ave}) is used to reflect a particular bidder's uniqueness. The PONW utility function assumes that the relation between the PONW values and the expected utility values for previously submitted bids (notably, the PONW utility function) does not consider profitability of historical projects. Restated, this utility function represents a way to transform a particular expected utility value for a given project (Eu(x)) into a predicted value of probability of not wining (Px).

The relationship between the cost model and multicriteria evaluation model is constructed based on practical phenomenon (refer to steps (4) and (5)): a bidder has a high probability of winning (low Px) when the criteria evaluations are favorable, thus, the bid price would be low, and vice versa. Moreover, the meaning of Px is consistent in both models. That is, on the right of Figure 2, there is also a Px chance that a bid price will be below the recommended bid price.

3.3 Cost model

3.3.1 Project construction cost. The total cost of a construction project includes direct costs, indirect costs and markup (Adeli and Wu, 1998; Wang, 2002b; Wang et al., 2005). In this investigation, the total construction cost (i.e., the bid price), C_{Tot}, of a project is represented as,

$$C_{Tot} = (C_1 + \ldots + C_j + \ldots + C_J) \times (1 + C_1 + \ldots + C_k + \ldots + C_k) \times (1 + t) \tag{1}$$

$$= \left(\sum_{j=1}^{J} C_j\right) \times \left(1 + \sum_{k=1}^{K} C_k\right) \times (1+t) \qquad (2)$$

$$= \left(\sum_{j=1}^{J} C_j + \sum_{j=1}^{J} C_j \times \sum_{k=1}^{K} C_k\right) \times (1+t) \qquad (3)$$

where C_j is the cost of direct cost component j, and J denotes the number of direct cost components. C_k is the cost of indirect cost component k, and K denotes the number of indirect cost components. Thus $\sum_{j=1}^{J} C_j$and $\sum_{j=1}^{J} C_j \times \sum_{k=1}^{K} C_k$ represent the total direct and indirect project costs, respectively. The value t represents the tax as a percentage (constant value, usually 5% in Taiwan) of the sum of the total direct costs and the indirect costs.

The direct costs, measured in dollar terms, are such as excavation, structure, finishes, doors, windows, painting, and furnishing. The indirect costs, measured in percentage terms, include costs such as installing temporary water and electricity supplies, field and home office overheads, insurance, and markup. Notably, markup can be expressed as a percentage of C_{Tot} (Dozzi et al., 1996; Wang et al., 2005). In this study, according to the typical practice in Taiwan, markup is treated as an indirect cost and measured as a percentage of total direct cost.

Notably, modeling step (1) develops a bid estimate according to bid documents (such as bid forms, drawings, and specifications) and the construction procedures devised by the bidder (Peurifoy and Oberlender, 2002). This bid estimate encompasses estimating tasks of quantity takeoffs and vender/subcontractor quotes for estimating labor, materials, equipment, and subcontracting costs for each detailed cost item in the bid project. The cost of each C_j (e.g., sitework) in Equation (1) represents the sum of costs of several detailed cost items (e.g., clearing, excavation, compaction, etc.).

3.3.2 Cost uncertainty. The proposed cost model assesses the first group of criteria and subcriteria that directly affect estimations of project construction costs. The subcriteria are, for example, inflation, interest rates, historical markups, quantity takeoffs, payment terms, and cash flow requirements. These subcriteria are treated as cost uncertainties, and variations of such subcriteria impact direct and indirect cost components. Thus, C_j s and C_k s are variables in costs and percentages, respectively. This cost model uses three point estimates (optimistic, most likely, and pessimistic costs) to acquire a Beta distribution for each cost component. For example, the optimistic cost for C_j is the cost that would be lowest once out of 20 times if the cost component could be repeated under the same conditions (Moder et al., 1983). Similar definitions can be applied to the pessimistic cost. Furthermore, each indirect cost component is evaluated in terms of optimistic, most likely, and pessimistic percentages.

This study suggests that costs (or percentages) estimated in modeling step (1) can be considered the most likely costs (or percentages) of C_j (or C_k). Moreover, a bidder subjectively estimates the optimistic and pessimistic costs (or percentages) for each C_j (or C_k) based on experience or knowledge of the requirements of C_j (or C_k) learned from the bid estimation process in modeling step (1).

3.3.3 Simulation and computer implementation. Monte Carlo simulation involves the generation of random costs according to C_j and C_k distributions, and then totals these costs to derive the project bid price (C_{Tot}) according to Equations (1)–(3). This process is repeated several hundred times, with C_{Tot} being calculated each time. A cumulative probability distribution of bid price can then be constructed based on the values of C_{Tot}. Notably, the simulated maximum and minimum project construction costs are assumed to be maximum and minimum bid prices, respectively. Additionally, in modeling step (5), the probability of zero ($\text{Px} = 0$) is assumed to be mapped to the simulated minimum value. This assumption is made for simplicity as the probability for this minimum value is only 0.02% (= 1/5,000 simulation iterations).

The cost model is implemented in a simulation language, Stroboscope (Martinez, 1996). Stroboscope can define probabilistic cost data concerning each cost component, and generate a cumulative distribution of project bid price. The cost model is implemented on a Pentium III PC with 768 MB of RAM in a Windows XP environment. It took approximately 2 minutes to analyze the example projects 5,000 times.

3.4 Multi-criteria evaluation model

The multi-criteria evaluation model assesses the group-2 criteria mentioned earlier, which are divided into three categories of level-1 criteria (see Figure 1), namely environmental conditions (R1), company conditions (R2), and project conditions (R3). Each criterion then includes several level-2 subcriteria. For example, the criteria and subcriteria shown in the bottom part of Figure 1 are identified by the bidder for the example project (case study I) and are elucidated in Section 4.2. Notably, the proposed model does not restrict the number of criteria and subcriteria involved.

In the proposed multi-criteria evaluation model, criteria are assumed to be independent, and the importance of criteria is pairwisely compared to derive the criteria weights according to AHP algorithms (Saaty, 1978). Then, assuming that the subcriteria under a criterion are mutually dependent, the fuzzy integral is employed to support subcriteria assessments (Chen and Tzeng, 2001). The assessment result for a subcriterion is a utility score of the subcriterion. The evaluation result for the level-2 subcriteria (e.g., r5, r6, r7, and r8) for a given level-1 criterion (e.g., R2) is a utility value for the criterion. Multiplying the utility value by a corresponding weight yields a weighted utility value for each criterion. The sum of all of the weighted utility values of the criteria is the expected utility value for a specific project scenario. Further details of these utility-related definitions can be found in Clemen (1996).

3.4.1 Weight of criteria. The importance of the three group-2 level-1 criteria is pairwisely compared. The scale used to derive the relative importance from matrices of pairwise comparisons ranges from 1 to 9, as follows (Saaty, 1978): 1—equally important; 3—slightly more important; 5—strongly more important; 7—demonstratedly more important; 9—absolutely more important. 2, 4, 6, 8 denote a degree of importance lying between 1 and 3, 3 and 5, 5 and 7, and 7 and 9, respectively. The matrix of preferences is manipulated via a method that determines the eigenvector corresponding to the maximum eigenvalue of a matrix (Saaty, 1978). The sum of the weights of criteria equals 1.

3.4.2 Fuzzy integral. As mentioned previously, the subcriteria for a criterion are assumed to be interdependent. Thus, unlike criteria evaluations (an additive situation), subcriteria evaluations are non-additive. This work employs a fuzzy integral value to express the utility value ($\int hdg$) of each criterion that is evaluated based on fuzzy measure ($g(\cdot)$) and the utility score ($h(\cdot)$) of each subcriterion.

The fuzzy measure is frequently used with a fuzzy integral for aggregating information evaluation. The λ fuzzy measure is applied to evaluate the importance of the dependent subcriteria (Chen and Tzeng, 2001). The fuzzy measure g is a set of function defined using a power set $\beta(X)$ of X, and g:$\beta(X) \rightarrow [0, 1]$. The function g must possess the following properties (Chen and Tzeng, 2001):

(A) $g(\phi) = 0, g(X) = 1$.
(B) if $A, B \in \beta\ (X)$ and A $\subset$ B, then $g(A) \leq g(B)$

A λ fuzzy measure g_λ has the following properties: $\forall A, B \in \beta(X), A \cap B = \phi$; $g_\lambda(A \cup B) = g_\lambda(A) + g_\lambda(B) + \lambda g_\lambda(A) g_\lambda(B)$; and $-1 < \lambda < \infty$. Then for the definite set $X = \{x_1, x_2, \ldots\ldots, x_n\}$, the density of fuzzy measure $g_i = g_\lambda(\{x_i\})$ ($g_\lambda(\{x_1, x_2, \ldots\ldots, x_n\})$ can be viewed as the importance of considering various subcriteria), can be formulated as follows (Chiou et al., 2005):

$$\begin{aligned} & g_\lambda(\{x_1, x_2, \ldots\ldots, x_n\}) \\ & \quad = \sum_{i=1}^{n} g_i + \lambda \sum_{i1=1}^{n-1} \sum_{i2=i1+1}^{n} g_{i1} g_{i2} \\ & \qquad + \ldots + \lambda^{n-1} g_1 g_2, \ldots, g_n, \text{ for } -1 < \lambda < \infty \end{aligned} \tag{4}$$

In a specific case involving two subcriteria, A and B, if $\lambda > 0$, namely, $g_\lambda(\{A, B\}) > g_\lambda(\{A\}) + g_\lambda(\{B\})$, then A and B have multiplicative effects; if $\lambda < 0$, namely, $g_\lambda(\{A, B\}) < g_\lambda(\{A\}) + g_\lambda(\{B\})$, then A and B have substitutive effects; if $\lambda = 0$, namely, $g_\lambda(\{A, B\}) = g_\lambda(\{A\}) + g_\lambda(\{B\})$, then the evaluation of the set {A, B} equals the sum of assessments for sets {A} and {B}.

Let h be a measurable set function defined on a measurable space, and suppose $h(x_1) \geq h(x_2) \geq \ldots \geq h(x_n)$, then the fuzzy integral (i.e., $\int hdg$ = utility value of a criterion) of fuzzy measure $g(\cdot)$ with respect to $h(\cdot)$ can be defined as follows (Ishii and Sugeno, 1985).

$$\begin{aligned} \int hdg &= h(x_n)g(H_n) + [h(x_{n-1}) - h(x_n)]g(H_{n-1}) \\ &\quad + \ldots + [h(x_1) - h(x_2)]g(H_1) \\ &= h(x_n)[g(H_n) - g(H_{n-1})] + h(x_{n-1})[g(H_{n-1}) \\ &\quad - g(H_{n-2})] + \ldots + h(x_1)g(H_1) \end{aligned} \tag{5}$$

where $h(x_i)$ is the utility score of subcriterion x_i; $H_1 = \{x_1\}$, $H_2 = \{x_1, x_2\}, \ldots, H_n = \{x_1, x_2, x_3, \ldots, x_n\} = X$. Figure 3 illustrates the concept of Equation (5). Namely, the value of $\int hdg$ is the area in Figure 3. The details of $g(\{x_1, x_2, \ldots\ldots, x_n\})$ and $\int hdg$ can also be found in (Chen and Tzeng, 2001; Lin, 2005); an example is presented in Section 4.2.

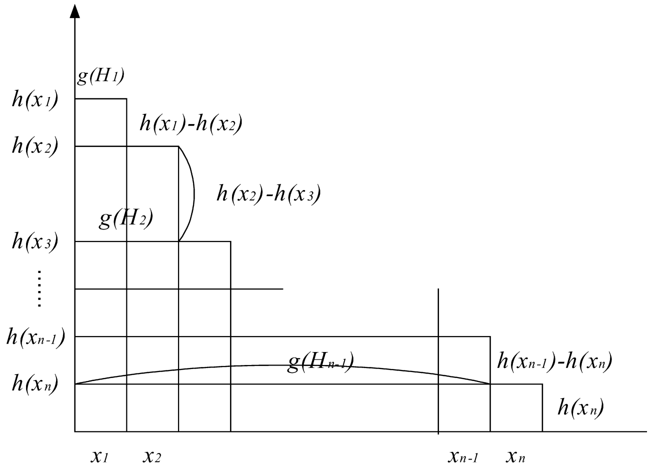

Fig. 3. Concept for fuzzy integral.

4 CASE STUDY I

The mechanical/electrical subproject (termed M/E project herein) of a public construction project in northern Taiwan is used to demonstrate the proposed procedure. Besides two underground floors, the project includes a 5-story high-tech facility building and a 10-story office building. The project was completed by mid-2004. The project was awarded based on a multi-criteria evaluation bid-award method. The bid-award criteria encompassed bid price, technology, quality, function, and commercial terms of a bid. The proposed procedure was applied to support a bidder in determining bid price. This application was conducted following the awarding of the M/E project (namely, after the submission of the bid price). A cost manager who was fully involved in the bid decision-making process for the bidder provided the inputs for executing the proposed procedure. The following subsections describe the assessments of the modeling steps.

4.1 Evaluations of the cost model

Based on bid documents and planned construction procedures, the bidder conducted a bid estimation based on the quantity takeoff and a vender/subcontractor's quote for each detailed cost item in the project. Then, the costs of numerous detailed cost items are aggregated to a summary sheet that includes 11 cost components. Table 1 lists the description and three point cost estimates (optimistic, most likely and pessimistic costs or percentages) for each cost component. Following 5,000 simulations, the minimum and maximum bid prices are NT\$387,345,043 and NT\$419,265,473, respectively. (thirty New Taiwan dollars≅1US dollars. Thereafter, NT dollar is used.) Notably, the generated cumulative probability distribution of the project bid price is displayed on the right of Figure 5.

4.2 Assessments of the multi-criteria evaluation model

The bottom part of Figure 1 shows the group-2 level-2 subcriteria that are qualitatively assessed for the M/E project. Table 2 describes the utility and range of the utility scores for each subcriterion. The subcriterion of r1 (future projects) provides an example. If the bidder forecasts that several new projects are being marketed, then he will have a high chance of obtaining project contracts. Restated, the bidder can still find opportunities to compete for other projects if he does not win the contract of the current project. Consequently, the bidder will submit a comparatively high bid price, leading him to assign a low utility score to subcriterion r1.

Table 3 shows a pairwise comparison and lists the importance of the level-1 criteria. These inputs of importance have passed the consistency index and consistency ratio tests (Saaty, 1978). The eigenvector for the matrix of Table 3 (preferences of criteria) is (0.9628, 0.1067, 0.2483) using the maximum eigenvalue of 3.0649. The normalized weights of the three criteria then are 0.7306, 0.0810, and 0.1884. The sum of the normalized weights of the criteria equals 1.

Next, the fuzzy integral is utilized to evaluate the subcriteria and generate the utility value of each criterion. Table 4 displays the threshold and project utility scores ($h(x_i)$) assigned to subcriteria for computing the threshold expected utility value (Eu(t)) and expected utility value for the project (Eu(x)). For example, the bidder assigns utility scores of 1.0, 0.9, 1.0, and 0.8 of $h(x_i)$ to subcriteria r5, r6, r7, and r8, respectively. That is,

Table 1
Three-point estimates for each cost component of the M/E project

(Currency: NT\$30 ≅ US\$1) *Cost components*	*Optimistic cost (\$NT)*	*Most likely cost (\$NT)*	*Pessimistic cost (\$NT)*
C1. Electrical systems	71,200,000	71,386,677	78,000,000
C2. Water supply/disposal systems	7,100,000	7,434,321	8,500,000
C3. Mechanical systems	41,800,000	41,966,401	47,600,000
C4. Fire protection systems	36,600,000	36,724,514	41,600,000
C5. Clean room and special systems	193,000,000	194,373,567	219,700,000
	Optimistic %	Most likely %	Pessimistic %
C6. Drawing compositions and quality inspection	0.23%	0.25%	0.50%
C7. Temporary water & electricity	0.70%	0.75%	0.90%
C8. Site safety management	0.25%	0.30%	0.60%
C9. Insurance	0.15%	0.20%	0.35%
C10. Markup	3%	4.05%	6.00%
C11. Tax	5%	5%	5%

Table 2
Description of utility and range of utility scores for subcriteria of the M/E project

Subcriteria	*Description of utility*	*Range of utility scores*
R1. Environmental conditions		
r1. Future projects	Forecast of upcoming projects on the market. Many future projects → more opportunities for bidders → low current project value → high bid price → low utility score	(0, 1); Many = 0, Few = 1
r2. Market conditions	Other projects currently being tendered for. Good construction economy → more opportunities for bidders → low current project value → high bid price → low utility score	(0, 1); Good = 0, Poor = 1
r3. Competition	Expected number of competitors bidding for the project. Many competitors → high current project value → low price → high utility score	(0, 1); Few = 0, Many = 1
r4. Labor availability	Is local labor available or difficult to obtain? Many laborers are available → high current project value → low price → high utility score	(0, 1); Few = 0, Many = 1
R2. Company conditions		
r5. Current work load	Volume of all current projects relative to company capacity. High current load → high bid price → low utility score	(0, 1); High = 1, Low = 0
r6. Need for public exposure	High exposure → high current project value → low bid price to win project contract → high utility score	(0, 1); Low = 0, High = 1
r7. Need for work	High need for work → high current project value → low bid price → high utility score	(0, 1); Low = 0, High = 1
r8. Experience in similar projects	Good experience → high current project value → low bid price → high utility score	(0, 1); Poor = 0, Good = 1
R3. Project conditions		
r9. Project complexity	Does the project complexity exceed current firm capabilities? High project complexity → high risk → low current project value → high bid price to meet project specifications → low utility score	(0, 1); High = 0, Low = 1
r10. Location	Is the project located within company operating area? Close location → high current project value → low bid price → high utility score	(0, 1); Far = 0, Close = 1
r11. Project duration	Tight duration → high risk → low current project value → high bid price to meet project deadline → low utility score	(0, 1); Tight = 0, Loose = 1
r12. Relationship with owner	Good relationship → Good communication → high current project value → low bid price → high utility score	(0, 1); Poor = 0, Good = 1

h(r5) = 1.0, h(r7) = 1.0, h(r6) = 0.9, and h(r8) = 0.8. And h(r5) ≥ h(r7) ≥ h(r6) ≥ h(r8).

Then, based on Equation (4), the fuzzy measure $g(\{x_1, x_2, \ldots\ldots, x_n\})$ (namely, the importance considering various subcriteria) is assessed. The criterion R2 (company conditions) provides an example. The evaluation results demonstrate that the importance of r5 = $g_\lambda(\{r5\})$ = 0.0619, the importance of r56 (i.e., considering both subcriteria r5 and r6) = $g_\lambda(\{r5, r6\}) = 0.3966$, the importance of r567 = $g_\lambda(\{r5, r6, r7\}) = 0.6572$, and the importance of r5678 = $g_\lambda(\{r5, r6, r7, r8\}) = 1$. (The detailed computations for $g(\{x_1, x_2, \ldots\ldots, x_n\})$ in this case study can be found in Lin (2005).) The utility value of the criterion R2 (including subcriteria r5, r6, r7, and r8), $\int hdg$, is calculated according to Equation (5) (see Figure 4), namely:

$$\int hdg = \text{utility value of criterion R2 (= the area shown in Figure 4)}$$
$$= 0.8 \times 1 + (0.9 - 0.8) \times 0.6572 + (1.0 - 0.9) \times 0.3966 + (1.0 - 1.0) \times 0.0619 = 0.91 \tag{6}$$

The left of Table 5 shows the weight and utility value for each criterion. The weighted utility value (i.e., weight multiplied by utility value) then can be obtained, and the expected utility value of the project (Eu(x)) equals

Table 3
Pairwise comparisons of group-2 level-1 criteria for the M/E project

Criteria	*R1. Environmental conditions*	*R2. Company conditions*	*R3. Project conditions*
R1. Environmental conditions	1	7	5
R2. Company conditions	1/7	1	1/3
R3. Project conditions	1/5	3	1

Table 4
Threshold and project utility scores assigned to each subcriterion of the M/E project

Subcriteria	*Threshold utility score*	*Utility score of the project*
r1	0.6	0.6
r2	0.4	0.5
r3	0.5	0.5
r4	0.6	0.6
r5	0.6	1.0
r6	0.6	0.9
r7	0.6	1.0
r8	0.7	0.8
r9	0.5	0.9
r10	0.5	0.9
r11	0.5	0.9
r12	0.5	0.8

0.6175 (= 0.3799 + 0.0737 + 0.1639; the sum of the weighted utility values of the three criteria). Similarly, the threshold expected utility value (Eu(t)) equals 0.4870 using the threshold utility scores assigned to subcriteria. (See Table 4.) Additionally, the average winning probability for this bidder was just 10% per year (namely, the bidder won around 10 project contracts out of 100 projects). Thus, $P_{ave}= 0.1$ (i.e., $1 - P_{ave} = 0.9$).

4.3 Results

Figure 5 presents the modeling results based on the evaluations of the cost model and the multi-criteria evaluation model. According to the PONW utility function, the probability Px can be estimated from the following relationship, and Px = 0.671.

$$\frac{P_x}{0.9} = \frac{(1 - 0.6175)}{(1 - 0.4870)} \tag{7}$$

By mapping the value of Px (0.671) to the cumulative distribution of bid price (i.e., the right part of Figure 5), the probabilities of 0.6668 (with a bid price of NT\$400,200,000) and 0.6724 (with a bid price of NT\$400,300,000) are closest to Px. Then, assuming a linear relationship, the recommended bid price (RBP) corresponding to Px can be determined using the following relationship, and the recommended bid price is NT\$400,281,132.

$$\frac{RBP - 400{,}200{,}000}{400{,}300{,}000 - 400{,}200{,}000} = \frac{(0.6710 - 0.6668)}{(0.6724 - 0.6668)} \tag{8}$$

In this project, the bidder's submitted bid price was exactly NT\$390,000,000, which was approximately 2.64% less than the recommended bid price (=(400,281,132 − 390,000,000)/390,000,000). However, the cost manager indicated that the initial estimate exceeded \$400 million. If NT\$400 million is used as another comparison base,

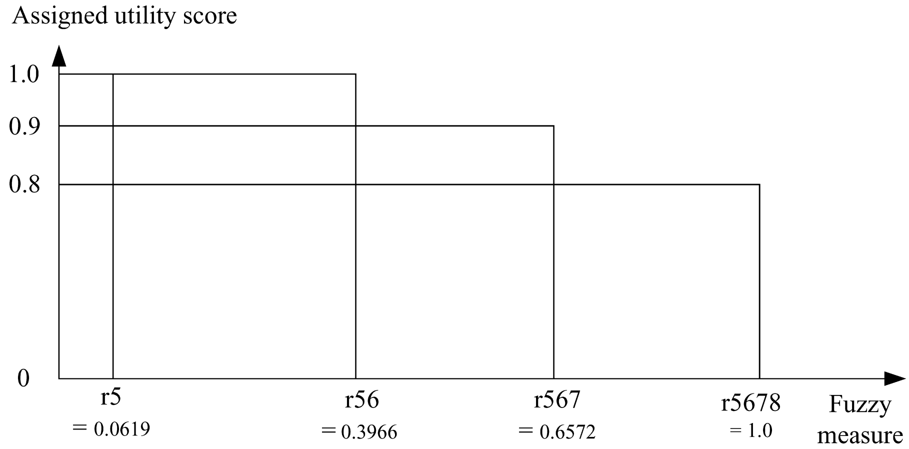

Fig. 4. Fuzzy integral of criterion R2 of the M/E project.

Table 5
Multi-criteria evaluation results of the M/E project

Criteria	*Weight (m)*	*Threshold utility value (n′)*	*Utility value (n)*	*Weighted threshold utility value ($z' = m \times n'$)*	*Weighted utility value ($z = m \times n$)*
R1. Environmental conditions	73.06%	0.47	0.52	0.3434	0.3799
R2. Company conditions	8.10%	0.61	0.91	0.0494	0.0737
R3. Project conditions	18.84%	0.50	0.87	0.0942	0.1639
Expected utility value				Eu(t) = 0.4870	Eu(x) = 0.6175

the bid price recommended using the proposed procedure is around 0.07% above the initial estimate of the bidder (=(400,281,132 – 400,000,000)/400,000,000). Restated, the difference in the estimates (estimated by the procedure and the bidder) is marginal (2.64% or 0.07%).

Notably, NT$390 million (estimated by the project architect/engineer) was the project budget announced in the tendering documents. Any bid price over that budget would be disqualified. The bidder regarded the project budget as tight. However, the bidder decided to submit a bid price of $390 million (instead of the initially estimated $400 million) as the bidder perceived that a chance existed for reducing project construction costs by efficiently allocating resources (primarily laborers) and using certain material equivalents or substitutions to decrease equipment costs. Furthermore, this bidder, who used the project budget as a bid price, could still earn the project contract because he gained favorable results for other bid criteria (i.e., technology, quality, function, and commercial terms) evaluations for the project. Overall, the proposed procedure adds value for this case study because it improves the quality of the bid price decision-making process (in considering multi-criteria evaluations and cost uncertainties) while generating a recommended bid price close to submitted estimates (either NT$390 million or NT$400 million).

5 CASE STUDY II

To examine further the feasibility of the proposed procedure, this study applied the proposed procedure to another case project with characteristics that differ from the first case. This project is related to the civil/structure/architect part of a high-tech construction project (called C/S/A project herein). The C/S/A project is located in southern Taiwan, and was constructed between May 2003 and February 2004 (duration = 10 months). The project was tendered according to a low-bid method. Again, the proposed procedure was applied after the project bid price had been submitted. This application came from a different contractor. The project budget was not made known in advance. A project manager involved in the project bidding process provided the inputs for the proposed procedure.

Following the above modeling steps, Figure 6 displays the evaluation results of this C/S/A project. Namely, after simulating the cost model 5,000 times, the minimum and maximum bid prices of this project are NT$118,866,465 and NT$131,123,626, respectively. In the multi-criteria evaluations, the expected utility values of Eu(t) and Eu(x) are 0.5979 and 0.7990, respectively. Moreover, $P_{ave} = 0.43$ (namely, winning nine project contracts from 21 submissions in a year) and $1 - P_{ave} = 0.57$. This

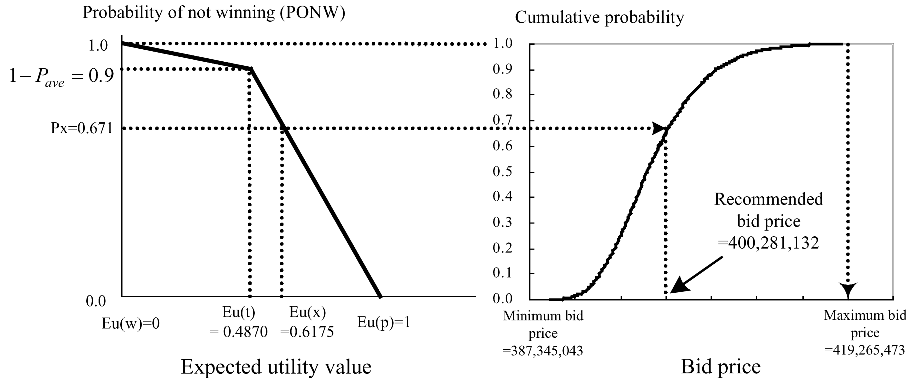

Fig. 5. Modeling results of the M/E project (case study I).

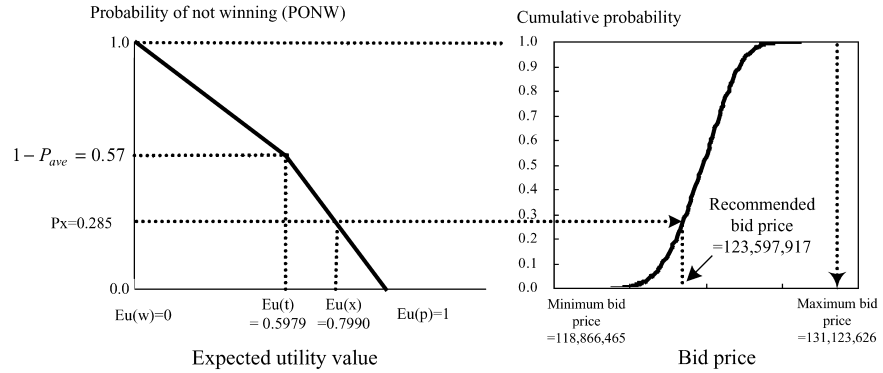

Fig. 6. Modeling results of the C/S/A project (case study II).

average winning probability was comparatively high, because this contractor generally did not compete for a project unless they were highly confident of winning the contract. For example, the bidder considered the location of this project (such as subcriterion r10 in Table 2) favorable owing to having a nearby project that was nearing completion and simply being able to reallocate existing resources (including laborers and equipment) to this C/S/A project, thus saving mobilization costs if awarded the project contract. Additionally, the bidder had considerable experience in similar projects (subcriterion r8 in Table 2). Most importantly, the bidder had a good relationship with the owner of the project (subcriterion r12). The assessments of these subcriteria provided the bidder with an edge, and provided them with increased confidence relative to other potential competitors.

The probability, Px, can be estimated based on the following PONW utility function, and Px = 0.285.

$$\frac{P_x}{0.57} = \frac{(1 - 0.7990)}{(1 - 0.5979)} \tag{9}$$

By mapping the value of Px (0.285) to the cumulative distribution of bid price (i.e., the right portion of Figure 6), the recommended bid price is around NT\$123,597,917 with a winning probability of 0.715 (=1 − 0.285). Meanwhile, the bid price submitted by the bidder totaled NT\$120,000,000. These two prices only differ by around 3% (=(123,597,917 − 120,000,000)/ \$120,000,000). Thus, this C/S/A project achieves reliable application results.

6 RESEARCH SIGNIFICANCE AND FUTURE WORK

6.1 Research significance

As indicated earlier, this proposed procedure modifies the SIM-UTILITY procedure developed by Wang (2004). Both procedures have a cost model and a multi-criteria evaluation model. However, the primary differences in the two procedures are as follows. First, the proposed procedure supports contractors in selecting bid prices, whereas SIM-UTILITY assists clients in determining project cost thresholds. Second, the proposed procedure evaluates bid criteria, whereas the SIM-UTILITY addresses tendering criteria. The proposed procedure includes a markup in cost estimation, and SIM-UTILITY does not. Third, the proposed procedure applies fuzzy integrals, whereas the SIM-UTILITY uses utility theory for multi-criteria evaluations. Fourth, the Y-axis value in the proposed procedure represents the probability of not winning. Conversely, the Y-axis value in SIM-UTILITY is the likelihood of a bidder completing the project profitably.

Three key contributions of this proposed procedure are as follows:

- Although the cost model and multi-criteria evaluation model are not original, integration of these two models is novel within bid decision research.
- The proposed procedure derives bid price decisions considering that project construction costs are uncertain, thereby fitting real-world practices more closely than existing bid models.
- The proposed procedure determines bid prices for meeting a practical decision-making process, whereas current bidding models focus on markups. In Taiwan, a considerable number of decision-makers typically look for methods of reducing construction costs to attain an edge over other bidders. Eventually, such bidders submit low bids without sacrificing a percentage markup. Focusing on percentage markup is not central to winning a project contract. Namely, the bidders look at the total bid price rather than markup when making bid decisions.

6.2 Future work

During the course of this work, the following future research directions arose that may improve the proposed procedure.

- To reduce the computational complexity in the simulation, a statistic-based cost model can be employed. Based on χ^2 (chi-square) tests, the Lognormal and Weibuill distributions have the best goodness of fit to the bid price distributions for case studies I and II, respectively. A normal distribution fails the χ^2 tests in both case studies. Nevertheless, a normal distribution deserves special consideration as it only requires estimating means and standard deviations.
- Previous studies have indicated that correlations between cost components affect construction project costs (Touran and Wiser, 1992; Wang, 2002b). The correlated effects on bid price should be considered to improve cost scheme modeling.
- The proposed procedure suggests a total bid price. However, the procedure does not indicate how direct and indirect costs should be adjusted to arrive at this suggested total bid price. Therefore, future research can explore strategies for cost adjustments.
- The multi-criteria evaluation model uses AHP algorithms to assess the weights of independent criteria and fuzzy integrals to examine mutually-dependent subcriteria. To simplify the modeling, the AHP algorithms can be applied throughout the criteria/subcriteria evaluations by assuming that the subcriteria are also independent. Notably, the consistency measure for inputs of relative criteria and subcriteria importance requires further investigation.
- In the PONW utility function, the value of threshold point $(\text{Eu}(t), 1 - P_{ave})$ is devised to obtain the uniqueness of a specific bidder. Future research should update the values of Eu(t) and P_{ave} when using the proposed procedure for additional projects.
- In the two cases studies, the difference between recommended bid price and actual bid price is utilized to demonstrate the benefits of the proposed procedure in addressing real-world situations. The recommended bid price corresponds to a probability of winning (1 − Px). Future research should extend the current procedure to derive a bid price that meets the goal of maximizing the probability of winning and expected profit.

7 CONCLUSION

To fit real-world situations closely, bid price decisions should be considered via a series of criteria evaluations given that project construction costs are variable. Thus, this study presents a new bid price determination procedure that comprises a simulation-based cost model to assess cost uncertainties and a multi-criteria evaluation model to evaluate numerous decision criteria.

The proposed procedure adds value for the two application projects as it improves the bid price decision quality (in considering multi-criteria evaluations and cost uncertainties) while producing a recommended bid price close to the submitted estimate. However, the effect of the tendering method or the project type (e.g., M/E versus C/S/A) on procedure performance warrants further investigation. For instance, is the proposed procedure more suited to a project tendered using the lowest-bid method (e.g., case study II) than one tendered with a multi-criteria evaluation bid-award method (e.g., case study I)? Furthermore, as indicated earlier, the two applications of the proposed procedure were conducted after bid prices were submitted. Future work should apply this procedure to other projects prior to bid submission.

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