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USING DATA ENVELOPMENT ANALYSIS TO SUPPORT BEST-VALUE CONTRACTOR SELECTION

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Abstract. Selecting an appropriate contractor or supplier is essential to the successful implementation of a public procurement project. The Taiwan government frequently applies the best-value (BV) tendering method, a multi-criteria evaluation method, to procure projects. However, the selection process of the winner for a BV-based procurement project is generally subjective and thus is easily accused of corruptions. To develop a systematic method to support contractor selection, this study proposes using the Data Envelopment Analysis (DEA) to facilitate the criteria evaluations for each bidder during the short-listing stage. The evaluation results of using the DEA are a list of potential BV winners who are then suggested to enter into the final selection stage. Based on three case studies related to service procurement projects, this research finds that the DEA is suitable of assessing the relative efficiencies among bidders when the BV approach is applied. Lessons learned here should be helpful in applying the DEA to aid bid evaluations in other supplier selection problems.

Keywords: best-value tendering method, short-listing stage, contractor selection, data envelopment analysis.

Introduction

In Taiwan, prior to implementation of Taiwan's Government Procurement Act (TGPA) (PCC 1998), nearly all procurement projects were awarded based on the traditional lowest-bid approach. The best-value (BV) tendering method (or called the most advantageous tendering approach) in the TGPA provides the project clients (or owners or procuring entities) with an alternative method for selecting the best-qualified supplier/contractor rather than accepting the lowest bid (PCC 1999; Perng *et al.* 2006; Lin *et al.* 2008; Elyamany *et al.* 2012). Tzeng *et al.* (2006) conducted a questionnaire survey to obtain feedback from project participants who had experience in the BV approach. Their study confirmed that the BV method is generally more effective than the lowest bid method in terms of time, quality, satisfaction, on-site safety and disputes regarding contract fulfillment. Currently, the BV approach has become a popular method for determining who is awarded a contract, especially in service procurement projects.

The BV approach in Taiwan includes two stages to select a winner of a procurement project, namely, basic qualification stage and selection stage (PCC 1999). Conducting basic qualification evaluations is to assess whether bidders meet the minimum requirements of the project. These requirements are such as the bidder's licenses, business registration certificates, and recent tax payment certification. A bidder passing the basic qualification evaluations is then allowed to enter into the selection stage. The selection stage frequently consists of two sub-stages, that is, short-listing stage (or preliminary selection stage) and final selection stage. Short-listing process is performed to evaluate each bidder's competence, which according to a set of predetermined criteria, before the bidder is admitted to enter into the final selection stage. After conducting the short-listing process, a long list of qualified bidders (for example, more than four bidders) will be reduced to a short list of the most competent bidders. A winner is then chosen from this short list during the final selection stage.

In Taiwan, the selection process of the winner for a BV-based public procurement project is generally subjective and is easily accused of corruptions by the public. Thus, any thoughts and methods that can aid any procurement stage of contractor selection process in an

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objective fashion are welcomed. Research on dealing with contractor selection problems can be divided into two broad categories (El-Sawalhi *et al.* 2007; Lam *et al.* 2010), including: (1) determining the evaluation criteria and their associated weightings (Holt *et al.* 1994; Hatush, Skitmore 1997; Egemen, Mohamed 2005; El-Sawalhi *et al.* 2007), and (2) developing models to aid the evaluation process (Russell, Skibniewski 1988; Plebankiewicz 2009, 2010, 2012; Lam *et al.* 2010; Trivedi *et al.* 2011; Aje 2012). The study presented herein relates to the second types of research.

Data Envelopment Analysis (DEA), a deterministic non-parametric model, has become an increasingly popular management tool to assess the relative efficiencies of a number of decision-making units (DMUs) or producers (Charnes *et al.* 1978; Shen *et al.* 2011; Heidari *et al.* 2012). The objective of this work is to develop a DEA-based approach to assess each bidder's competence for deciding whether the bidder is suitable to be in the short list and therefore, to avoid the subjectivity issue of selecting bidders on the short-listing stage. Unlike other existing models which generate rankings of bidders, the DEA produces a list of potential BV winners who are all ranked the same (i.e. called "without-ranking approach" here). Three case projects which belong to the type of service procurement are conducted to illustrate the significance of using the DEA.

1. Research background

1.1. Contractor selection

The contractor selection process for a procurement project usually consists of five stages, including: packaging, invitation, prequalification, short-listing, and bid evaluation (Hatush, Skitmore 1997). Current studies on contractor prequalification problems can be divided into two broad categories (El-Sawalhi *et al.* 2007; Lam *et al.* 2010), including: (1) determining the evaluation criteria and their associated weightings; and (2) developing models to aid the evaluation process.

For example, Hatush and Skitmore (1997) identified five main criteria for prequalification and bid evaluation, including financial soundness, technical ability, managerial capability, safety and reputation. The method and measurement of these criteria were also suggested by their study. Egemen and Mohamed (2005) conducted surveys to show that project owners and consultants (architects or engineers) had various views on the importance of contractor's qualifications and selection criteria. According to an extensive literature review, El-Sawalhi *et al.* (2007) indicated that the commonly used contractor prequalification criteria are financial stability, management and technical ability, contractor's experience, contractor's performance, resources, quality management, health and safety concerns.

Numerous studies have proposed models to support the final selection stage of the BV process. For example, Yang and Wang (2003) developed a quantitative method to assess decision criteria for a BV-based highway project. Tsai *et al.* (2007) designed a new procedure of ranking BV bidders by using fuzzy relations and eigenvector method. Lin *et al.* (2008) devised an adaptive analytic hierarchy process that used a soft computing scheme and genetic algorithms to support the criteria weighting process. Yang *et al.* (2012) further devised an automatic adjustment procedure for seeking a substitute matrix of criteria weightings.

Other studies have focused on the prequalification stage by designing mechanisms to assess a bidder's competence in meeting the specific requirements for a procurement project (Russell, Skibniewski 1988; Plebankiewicz 2009, 2010, 2012; Lam *et al.* 2010; Trivedi *et al.* 2011; Aje 2012). This current work is related to this type of research.

1.2. Best-value tendering approach

1.2.1. Basic concept

Procurement (contract award) methods can be located in a continuum (Molenaar, Gransberg 2001; Trauner Consulting Services 2007). On one end of the continuum is the traditional fixed price, seal-bidding method that is mainly used in public sector and usually adopts low bid to award contracts; on the other is sole source selection that is mostly used in private sector and adopts qualifications-based selection and negotiated procurement process. The BV approach is located in between the two extremes and considers both price and technical aspects. In Taiwan, the method for awarding contracts must be specified in tendering documents according to the TGPA. Generally, contracts are awarded using one of the following methods (PCC 1998, 1999): (1) the lowest bidder within the government estimate; (2) the lowest bidder within the budget and with a reasonable price evaluated by a committee; and (3) the BV bidder evaluated by a committee.

Under BV approach, a bidder who provides the best value bid that meets tender requirements is awarded the contract. In the United States, the common BV award algorithms adopted in different States or public agencies consists of meets technical criteria-low bid; adjusted bid; adjusted score; weighted criteria; quantitative cost-technical tradeoff; qualitative cost-technical tradeoff; and fixed price-best proposal (Scott *et al.* 2006). In Taiwan, evaluation methodology in this approach uses the following three methods: the scoring method (contract awarded to the bidder with the highest score); ranking method (contract awarded to the bidder with the lowest ranking); and, unit-price evaluation method (contract awarded to the bidder with the lowest price divided by the score). In a final evaluation conference, the majority of an evaluation committee determines the contract winner regardless of the evaluation method utilized to rank or score bids.

1.2.2. Tendering procedure of BV approach

Different tendering procedures of BV approach are adopted in different public agencies or procurement projects. For example, Scott *et al.* (2006) proposed steps of BV approach for highway construction projects: select BV criteria; compose the evaluation plan and select BV scoring system; select BV award algorithm; publish BV RFP (request for proposal); form evaluation panel, if necessary, to perform formal evaluation of BV proposals; receive and evaluate proposals; and contract award. Minnesota Department of Transportation suggested a 10-step, general procedure for procurement of a BV contract (MNDOT 2012), including select project; coordinate with FHWA (Federal Highway Administration); coordinate with industry; determine BV criteria; prepare RFP and final design; advertise project; optional pre-bid conference; receive proposals and bids; opening of bids; and selection and award. Despite slightly different from one to another, these procedures indeed share some indispensable steps which are critical to the BV approach.

Figure 1 displays the supplier selection procedure based on the BV approach in Taiwan (PCC 1998, 1999; Yang, Wang 2003; Wang *et al.* 2013). The key steps of this procedure are described as follows:

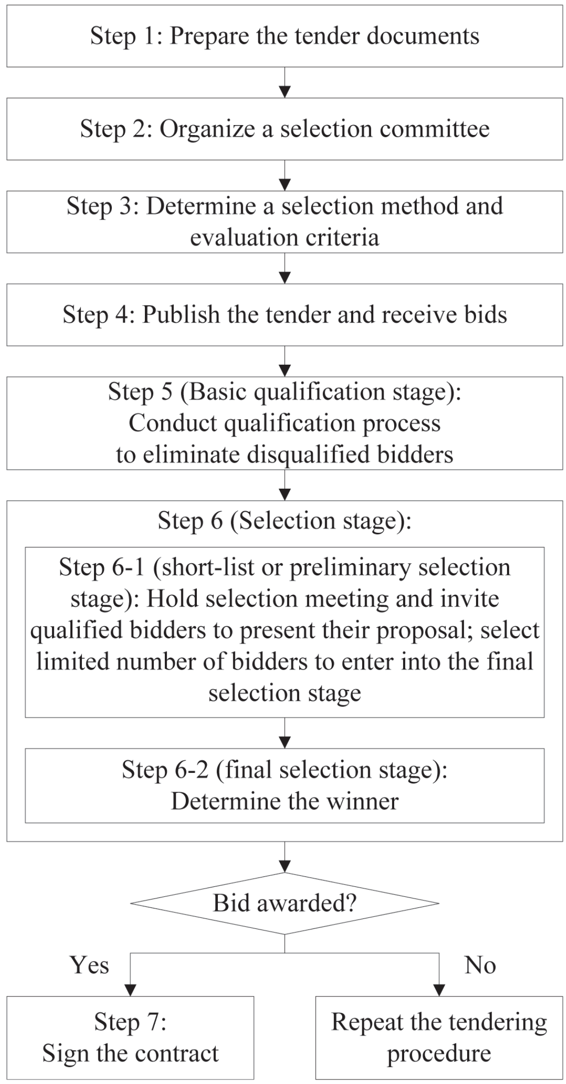

Fig. 1. Procedural steps of the BV approach

- Step 1: Prepare the tender documents – the project client prepares contract drafts and tendering documents that include a supplier evaluation methodology and a tendering notice.
- Step 2: Organize an evaluation/selection committee – the project client should establish an evaluation committee to review tender drafts. The committee typically comprises five to 17 professionals. In some cases, a task force is required to assist in examining bid documents in advance of a final evaluation conference. At least one-third of all committee members must be outside experts or scholars chosen from an on-line database maintained by the Public Construction Commission (PCC).
- Step 3: Determine a selection method and evaluation criteria – prior to publishing procurement documents, the evaluation committee must hold at least one meeting to determine evaluation rules. The committee must establish and weight evaluation criteria during this meeting. Detailed evaluation criteria are set by the project client, and then reviewed and determined by the committee based on the characteristics of each procurement project. If bid price is used as an evaluation criterion, the weight of the bid price must not exceed 50% of all criteria.
- Step 4: Publish the tender and receive bids – in Taiwan, the PCC has established a public web site (http://web.pcc.gov.tw/) to publish tendering information of government procurement projects. Moreover, the TGPA governs the tendering period. For open tendering, at least 14 tendering days are required.
- Step 5 (basic qualification stage) – if the number of bids does not exceed the minimum number of bidders (three bidders for the first tendering process), tendering documents will be revised and a new publishing procedure will be used. If the number of bidders is acceptable, then the procurement process proceeds to a basic qualification stage. In this stage, the aforementioned task force will review the bidders according to two types of qualification criteria, namely, basic qualifications (e.g. the supplier's licenses, business registration certificate, and recent tax payment certification) and specific qualifications (e.g. proof of financial resources, credit history, and record of experience). Following basic qualification, disqualified bidders are eliminated.
- Step 6 (Selection stage) – as indicated earlier, the selection stage consists of short-listing stage and final selection stage. Short-listing evaluation process may not be needed when only a few qualified bidders (say, less than four bidders) are involved in the bidding. If that is the case, the procurement process will go directly to the final selection stage. In the final selection stage, a final evaluation conference is

held to rank the qualified bidders; the most advantageous bidder wins the contract. During the evaluation conference, a prescribed evaluation method is applied to determine the best bidder or generate a list of order of the bidders who have earned a right to sign a contract with the project client.
- Step 7: Sign the contract – after the evaluation result is published, the project client conducts negotiations with the BV winning bidder or others bidders in descending order when the best bidder and the followers cannot agree on the contract and price. Although the contract is awarded to the most advantageous bidder, the price offered by the bidder cannot exceed the government estimate.

Among these steps, how to select bidders to enter into the final selection stage, i.e. determining the short-listing bidders, in practice is generally subjective and is easily accused of favoring specific bidders and even corruptions by the public. Therefore, this study aims at addressing this issue by proposing a novel approach that can help short-listing bidder selection in an objective manner.

1.2.3. Evaluation criteria

In the BV approach, the evaluation of bidders considers more than just bid price (Gransberg, Ellicott 1997). For example, the five aspects of evaluation criteria suggested for BV approach for highway construction projects in the U.S. consist of cost, time, performance and qualifications, quality management, and design alternates (Scott *et al.* 2006). The U.S. Federal Acquisition Regulation also indicates that "one or more non-cost evaluation factors such as past performance, compliance with solicitation requirements, technical excellence, management capability, personnel qualifications, and prior experience" need to be considered in "every source selection" in order to address the quality of products or services (FAR 2013). In addition, U.S. State governments have their own laws regulating the evaluation criteria. For instance, Minnesota's law states that evaluation criteria for BV procurements should at least include price, quality performance, timeliness of performance, customer satisfaction, on-budget performance, ability to minimize change orders, ability to prepare plans, technical capacity, qualifications, and ability to assess and minimize risks (Minnesota Statutes 2013).

In Taiwan, if a project client adopts the BV approach, the award will adhere to the following eight categories of criteria (PCC 1999):

1. Technology (e.g. technical specifications, professional or technical manpower and plan completeness);
2. Quality (e.g. quality control ability, testing methods and error detection rate);
3. Function (e.g. production capacity, compatibility and special effects);
4. Management (e.g. organizational structure, workforce qualifications and project management capability);
5. Commercial terms (e.g. contract period, terms of payment and supplier's remittance promise to an entity);
6. Past achievements in contract performance (e.g. record of contract performance, efficiency in contract performance and employee-employer relations);
7. Price (e.g. reasonability of the total bid price, cost control measures for contract performance and cost effectiveness); and
8. Financial plans (e.g. fund raising plan, annual cash flow and investment benefit analysis).

Each main criterion may consist of several sub-criteria accompanied by corresponding weights. Although criteria in each procurement project may differ, criteria are determined to assess supplier's capability to meet the project requirements. Details of criteria are established by the project client, and reviewed and determined by an evaluation committee of the project.

1.3. Data Envelopment Analysis

1.3.1. Methodology development and application

Based on the work of Farrell (1957), Data Envelopment Analysis (DEA) was initiated by Charnes *et al.* (1978) and developed as a method for assessing the comparative efficiency of organizational units (Thanassoulis 2001). The implementation of Farrell's idea did not really become popular until the work of Charnes *et al.* (1978) who coined the name "data envelopment analysis (DEA)" (Thanassoulis 2001).

DEA has two basic models – Charnes, Cooper and Rhode's model (CCR model) and Banker, Charnes, and Cooper's model (BCC model). Charnes *et al.* (1978) proposed an input orientation model that assumed constant returns to scale (CRS) using multiple inputs to produce multiple outputs. CRS assumed that a proportional change exists between input and output, and derives technical efficiency in DEA.

Banker (1984) assumed that a proportional change in input does not result in a proportional change in output. This concept forms another DEA model that addresses variable return to scale (VRS). The VRS derives the pure technical efficiency of DEA. Scale efficiency can be estimated by dividing technical efficiency by pure technical efficiency. Various extensions of basic DEA models can be found elsewhere (Cooper *et al.* 2000). However, examining which model is best suited to a pending problem is necessary prior to resolving a problem.

DEA has been utilized in many management-related domains such as healthcare (hospitals and doctors), education (schools and universities), banking, manufacturing, benchmarking, management evaluation, administration of retail stores, hotels and restaurants, production, logistics and accounting (Thanassoulis 2001; Easton *et al.* 2002; Gattoufi *et al.* 2004). For example, in a petroleum industry case, Easton *et al.* (2002) concluded that managers can obtain information to assist in the decision-making process in supply chain analysis based on DEA evaluation results. Integrated with case-based reasoning, Juan (2009) used DEA to evaluate the efficiencies of housing refurbishment contractors for determining an optimal contractor. Khodabakhshi *et al.* (2010) proposed an input-oriented super-efficiency stochastic DEA model for evaluating chief executive officers of US public banks and thrifts. To eliminate the problem of a so-called equal-weight effect for increasing evaluation accuracy, Hsiao *et al.* (2011) introduced entropy and illustrated their entropy-based Russell measure using data gathered from 24 of Taiwan's commercial banks to rank and compare it with the conventional Russell measure. Sadjadi *et al.* (2011) designed a robust super-efficiency DEA model for ranking different gas companies located in various parts of Iran. Their model was developed based on optimization technique which could be considered as a complementary alternative to sensitivity analysis and stochastic programming. Heidari *et al.* (2012) presented an application of DEA to quantify energy use efficiency for discriminating efficient greenhouse cucumber growers from inefficient ones.

1.3.2. Features of DEA

While a conventional statistical approach uses a central tendency theory to compare the performances of various DMUs or producers, which mean bidders in this study, by relating to an average DMU, DEA adopts an extreme point method to compare each DMU with only the best DMUs. A key feature which makes DMUs comparable in each case is that they perform the same function in terms of the kinds of resources they use and the types of output they produce. Inputs must capture all resources that impact output, and output must reflect all useful outcomes which are used to assess the performance of DMUs (Tsamboulas 2006). Therefore, if one can find input and output for a certain problem and the problem can be modeled using the input and output as described above, the problem then can be solved by using DEA. For example, for the issue of selecting short-listing bidders, the input and output to this issue are the preparation efforts made by all bidders and the evaluated scores given by committee respectively. That is, DEA is suitable for selecting short-listing bidders in BV-based procurement project and the detail is presented in Section 3.1.

In DEA, a curve on a graph that plots the minimum amount of input required to produce an output quantity is an isoquant or efficient frontier. All efficient DMUs form an efficient frontier and inefficient DMUs are inside the curve. When measuring the relative efficiencies of DMUs, a DEA measure can be defined as the ratio of total weighted output to total weighted input (Easton *et al.* 2002). Figure 2 depicts the DEA measures. In theory, an efficient DMU produces a maximum output using a given input. These efficient DMUs form a theoretical frontier that represents the absolute efficiency of a DMU. However, an empirical frontier exists because the production function (i.e. the function that relates outputs to inputs) is not well defined. Inside the empiri-

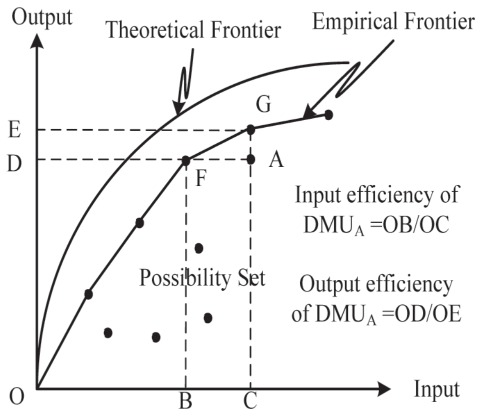

Fig. 2. DEA efficiency measures

cal frontier, namely, the possibility set, DEA provides an approach for improving inefficient DMUs to achieve efficiency. Figure 2 shows the input and output efficiencies of DMU A. Therefore, DMU G (on the frontier) is a peer DMU utilizing the same level of input and indicates how inefficient DMU A can improve its efficiency.

2. Proposed DEA-based approach

2.1. The approach description

In service procurement, evaluation criteria are set forth in the tendering documents prior to the evaluation conference. The criteria, varied in different procurement projects, are used for scoring bidders on the short-listing stage and are the indicators to rank bidders. As to DEA calculations, all inputs and outputs must be definitely known in order to portray the problem. In this study, a DMU is a bidder. This work defines the inputs of DEA as the preparation efforts made by all bidders. In other words, this study assumes that all bidders do their best according to tendering specifications to prepare their proposals for competition. Based on this assumption, the input values of DEA are equal to 1 from the perspective of a project client. Meanwhile, the results of various criteria evaluation conducted by each evaluation committee are the outputs of DEA evaluation. Therefore, the approach described herein is modeled by a single-input and multiple-output DEA model.

Additionally, the input or output orientation is determined by whether the decision-makers would rather change the inputs or outputs. In a BV-based procurement project, an evaluation committee cannot change any inputs of DMU. Thus, the study problem here is a pure output-oriented one.

2.2. DEA equations for bidder evaluation

Under the CCR model, the relative efficiency of a DMU equals to the ratio of its total weighted output to its total weighted input, subjective to lie between zero and unity (Charnes *et al.* 1978). Mathematically, the relative efficiency of a particular DMU (h_0) is calculated by Eqn (1):

$$\text{Maximize:} \qquad h_0 = \frac{\sum_{r=1}^{s} u_r y_{r0}}{\sum_{r=1}^{m} v_r x_{i0}}, \tag{1}$$

$$\text{subject to:} \quad \frac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{i=1}^{m} v_r x_{ij}} \leq 1' \ v_i, u_r \geq \varepsilon > 0;$$

$$r = 1, \ldots, s; \ i = 1, \ldots, m,$$

in which j is the j^{th} DMU (i.e. bidder; $j = 1, 2, \ldots, n$); y_{ij} is the r^{th} output of the j^{th} DMU; x_{ij} is the i^{th} input of the j^{th} DMU; u_r is the weight given to the r^{th} output; v_i is the weight given to i^{th} input i; and, ε is a non-Archimedean number.

Equation (1) yields infinite solutions, so it is necessary to reformulate it as a linear programming equation (as in Eqn (2)) (Charnes *et al.* 1978):

$$\text{Maximize:} \qquad h_0 = \sum_{r=1}^{s} u_r y_{r0}, \tag{2}$$

$$\text{subject to:} \quad \sum_{r=1}^{s} u_r y_{rj} - \sum_{i=1}^{m} v_r x_{ij} \leq 0;$$

$$\sum_{i=1}^{m} v_r x_{io} = 1,$$

in which if $h_0 = 1$ (or 100%) exists, a DMU is in a comparatively efficient state; otherwise, it is in a non-efficient state. All DMUs are calculated with the same attributes and the same scale. Therefore, Eqn (2) together with each bidder's input and output values are used to evaluate the bidder's relative efficiency (h_0). If a bidder's relative efficiency is calculated to be 1, then the bidder is considered efficient and is shortlisted as one of the potential BV winners; otherwise, the bidder is deemed disqualified and is ruled out of the final selection stage.

2.3. Steps of bidder evaluation with a DEA software

The calculations of the abovementioned DEA relative efficiency are facilitated in this study using a package of commercial software, called WARWICK DEA (Thanassoulis 2001). In this software, solving each problem (i.e. applying DEA to a case project) requires to conduct several steps, including building working space, determining analysis input and output, determining an application model and running efficiency calculations. Details of these steps are depicted as follows:

– Building working space – this step is to construct a sheet consisting of DMU, input and output data to run the following analyses.
– Determining analysis input and output – the software can deal with multiple inputs and multiple outputs for efficiency analysis. This study employs a single input (bidder investment for a contract award) and multiple outputs (average score on each criterion) to evaluate DEA efficiency.
– Determining an application model – both CCR and BCC models are available in this software. This study uses the CCR model with the "constant returns to scale" option to analyze the efficiency of different bidders.
– Running efficiency calculations – after setting the above options and using several defaults in the software, DEA calculations can be performed for various procurement projects.

3. Case studies to evaluate the efficiencies of BV bidders

3.1. Data collection and manipulation

The proposed model is applied to three case projects, the first and second of which are after-the-fact analyses while the third is an actual application to a real-world case project. Each bidder in a procurement project is treated as a DMU in the DEA evaluations. The preparation effort of bidding proposal (being the same for each bidder, namely 1) is the input of the DEA analysis whereas the average scores of criteria are the output for assessing the efficiency of each DMU. This study calculates an average of the scores, not the raw scores, given by committee members because this manipulation prevents the situation that the scores given by different committee members result in different DEA evaluation results for the same bidder. In addition, actual bidding evaluation results were collected from three case projects, which are discussed in the following sections.

3.2. Evaluations of case project 1

The case project 1 was to select a suitable software supplier to plan and develop a management information system (MIS). In this project, there were six bidders campaigning for only one contract award. In the final evaluation conference, there were four committee members who evaluated all bid proposals and presentations based on five decision criteria. The average values of the original scores for each bidder are shown in Table 1, where bidder 3 was the actual BV winner.

Table 2 presents the results of case project 1 by utilizing DEA. The results reveal that there are two bidders (i.e. bidders 3 and 5) with a DEA value of 100% (comparative efficiency), including the actual winner (bidder 3). Hence, applying the DEA would be helpful to support short-list contractor evaluation because it can identify the potential BV winners.

3.3. Evaluations of case project 2

The tendering content of case project 2 was to select two security companies providing services of security work for a science and industrial park. In this case project, there were seven bidders campaigning for two awards. In the final evaluation conference, six committee members evaluated

Table 1. Actual evaluation data of case project 1

Criteria (weight) bidder	C1 (10%)	C2 (30%)	C3 (30%)	C4 (20%)	C5 (10%)	Total Score	Actual winner
1	6.2	23.8	23.1	15.6	7.2	75.9	–
2	6.0	23.0	23.0	15.0	6.3	73.3	–
3	8.0	26.3	26.3	17.5	8.5	87.6	Yes
4	6.7	21.5	22.3	14.8	6.0	71.3	–
5	8.8	26.0	27.0	17.0	8.5	87	–
6	8.2	24.5	26.3	16.7	8.0	84.7	–

Notes: Criteria 1 (C1): understanding of the project; C2: system planning and design; C3: system coding capability; C4: project management capability; C5: experience and past achievement.

Table 2. DEA evaluation results of case project 1

DMU	Input	Output 1	Output 2	Output 3	Output 4	Output 5	DEA value (%)	Actual winner
1	1.000	6.200	23.800	23.100	15.600	7.200	90.67	–
2	1.000	6.000	23.000	23.000	15.000	6.300	87.62	–
3	1.000	8.000	26.300	26.300	17.500	8.500	100.00	Yes
4	1.000	6.700	21.500	22.300	14.800	6.000	84.32	–
5	1.000	8.800	26.000	27.000	17.000	8.500	100.00	–
6	1.000	8.200	24.500	26.300	16.700	8.000	97.73	–

all proposals and presentations based on five evaluation criteria. Table 3 shows the average values of the original scores for each bidder, where bidders 1 and 6 are the top-two ranking applicants and thus are the contract winners.

Table 4 shows the calculated results of case project 2 by deploying DEA. It reveals that there are five bidders (i.e. bidders 1, 2, 3, 6, and 7) with DEA values of 100%, including the contract winners, the bidders 1 and 6. Again, the DEA is capable of indicating a list of the potential BV winners with comparative efficiencies during the short-listing stage.

3.4. Evaluations of case project 3

This case project was to select a consultant company for developing an innovation-awarding operational guideline. The procurement involved a two-stage evaluation procedure: first, screening all bidders in the short-listing stage; second, choosing the best bidder by a final evaluation conference. A task force, primarily responsible for evaluating the tendering proposals in advance of the final evaluation conference, selected five bidders who campaigned for only one contract winner. In the first stage, the candidate should have an evaluation score of above 80 according to a traditional scoring methodology. Table 5 reveals the actual evaluation results by the task force of this case project. Bidders 1 to 5 are at the top-five rankings. The actual BV winner was bidder 1 after the final evaluation conference.

The DEA evaluations were conducted by the task force during the short-listing stage. All evaluation scores were transferred into the output of DEA. Additionally, the value of "1" was used as the input of DEA for each bidder. Table 6 presents the DEA calculation results. Since bidders 1 to 5 have DEA values of 100%, they have comparative efficiency compared to whom having a DEA value below 100%. Thus, these five bidders were

Table 3. Actual evaluation data of case project 2

Criteria (weight) bidder	C1 (20%)	C2 (25%)	C3 (25%)	C4 (20%)	C5 (10%)	Total score	Actual winner
1	18.0	20.5	20.2	17.5	7.8	84.0	Yes
2	13.0	22.0	21.0	17.0	8.0	81.0	–
3	18.3	19.7	18.8	16.8	7.8	81.5	–
4	12.5	18.5	17.3	17.2	7.2	72.7	–
5	12.7	21.3	20.1	16.1	7.7	78.0	–
6	17.4	20.1	19.1	17.0	8.0	81.7	Yes
7	16.9	19.9	18.9	17.0	8.0	80.6	–

Notes: Criteria 1 (C1): company organization; C2: feasibility of planning; C3: professional capability; C4: price; C5: presentation and question response.

Table 4. DEA evaluation results of case project 2

DMU	Input	Output 1	Output 2	Output 3	Output 4	Output 5	DEA value (%)	Actual winner
1	1.000	18.000	20.500	20.200	17.500	7.800	100.00	Yes
2	1.000	13.000	22.000	21.000	17.000	8.000	100.00	–
3	1.000	18.300	19.700	18.800	16.800	7.800	100.00	–
4	1.000	12.500	18.500	17.300	17.200	7.200	98.29	–
5	1.000	12.700	21.300	20.100	16.100	7.700	96.95	–
6	1.000	17.400	20.100	19.100	17.000	8.000	100.00	Yes
7	1.000	16.900	19.900	18.900	17.000	8.000	100.00	–

Table 5. Actual evaluation data of case project 3

Criteria (Weight) bidder	C1 (10%)	C2 (15%)	C3 (10%)	C4 (20%)	C5 (5%)	C6 (40%)	Total score	Ranking
1	9	13.3	9	18.5	4	35.3	89.0	1
2	8	12.5	8.5	17.5	3.75	34.3	84.5	3
3	4.75	14	9.25	18.3	4.25	32	82.5	4
4	9.25	10.8	8	16.3	5	31.5	80.8	5
5	9	12.8	9	18.8	3.25	36	88.8	2
6	4.25	10	6.25	18.3	3	32.8	74.5	7
7	6.5	11.5	7.75	16.8	2	33.8	78.3	6
8	4	10.3	7.5	15.5	1.75	31.8	70.8	8

Notes: Criteria 1 (C1): growth rate of R&D investment; C2: ratio of R&D investment to business sales; C3: ratio of R&D staff to total employees; C4: patent amount of current year; C5: growth rate of patent amount; C6: benefit generated by patent.

Table 6. DEA evaluation results of case project 3

DMU	Input	Output 1	Output 2	Output 3	Output 4	Output 5	DEA value (%)	Actual winner
1	1.000	9.00	12.80	9.00	18.80	3.25	100	Yes
2	1.000	8.00	13.00	8.50	18.00	3.80	100	–
3	1.000	4.80	14.00	9.30	18.00	4.30	100	–
4	1.000	9.25	10.80	8.00	16.30	5.00	100	–
5	1.000	9.00	12.80	9.00	18.80	3.25	100	–
6	1.000	4.25	10.00	6.25	18.30	3.00	97.34	–
7	1.000	6.50	12.00	7.80	7.00	2.00	94.44	–
8	1.000	4.00	10.00	7.50	16.00	1.80	88.89	–

recommended to enter into the find selection stage. Notably, the actual contract winner, bidder 1, was also in the list because of having a DEA value of 100%. Again, case study 3 shows that the DEA can facilitate the selection of the potential BV winner for services projects.

4. Discussions of case studies

4.1. Major findings

Based on the evaluations of the three case projects, major findings can be drawn as following:

- The BV winner has a DEA value of 100%, which means it has a comparative efficiency.
- A DEA value of 100% for a bidder means that the bidder is in the list of potential BV winners but not necessarily to be the final winner.
- Bidders who receive lowest scores from the committee evaluation are also ranked at the bottom of all the bidders in the DEA evaluation.
- Whatever the number of criteria or the weighting of criteria are, the DEA evaluation can distinguish the bidders with comparative efficiencies.

The first three findings together indicate that not only can DEA identify the bidder who is most eligible for winning the bid but DEA can also eliminate those bidders who are least appropriate for carrying out the project.

In addition, DEA generates a list of bidders without ranking whose relative efficiencies are all equal to 1. This result deals with the subjectivity issue encountered on the short-listing stage of traditional BV-based procurement projects since whether a bidder can be included in the short list depends on their evaluated relative efficiency.

Moreover, after the DEA evaluation, the committee has a chance to perform another evaluation on such fewer bidders to determine the final bid winner. The corresponding merits are twofold. First, when the number of bidders to be evaluated decreases, committee members can more concentrate on evaluating these short-listing bidders (i.e. without being affected by those excluded, less eligible bidders) and thereby, the members' consideration of evaluating the bidders may be slightly different. Reevaluation allows reflecting such consideration updates. Second, the possibility of erroneous evaluation can be lessened as committee members can revisit their earlier evaluation results during the re-evaluation and correct any mistake that is ignored.

4.2. Varied efficiency calculation

This work further examines whether DEA evaluation results being in a stable state with case project 1 by using varied efficiency calculation methodologies. That is, we calculate technical-efficiency by the constant returns to scale (CRS) CCR model, pure-technical-efficiency by the variable return to scale (VRS) BCC model and scale-efficiency by dividing the technical-efficiency by the pure-technical-efficiency. Table 7 displays the results of varied efficiency analysis for case project 1. The results show that the pure technical efficiency causes all DMUs to be the same. Moreover, the results also indicate that the values of scale efficiency and technical efficiency for all DMUs are the same because the values of pure technical efficiency are 100%. Therefore, the model adopted for DEA analysis in the previous section is appropriate.

4.3. Sensitivity analysis on evaluation criteria

Selecting suitable evaluation criteria can lead to success in finding a qualified or best bidder. This study employs a sensitivity analysis on case project 2 to test the impact of various criteria on the results of contract awarding. Table 8 displays the results of sensitivity analysis of criteria. The second column of Table 8 lists the original DEA value for each DMU, which is the same as the results showed in Table 4. Meanwhile, the third-to-seventh columns present the DEA values after removing criteria 1 to 5, respectively. When criterion 5 is removed (see column 7), the DEA values are significantly changed and are unable to suggest bidder 6 to be potential winner. The finding here is that the criteria used (the output of a DEA analysis) affect the DEA evaluation results. Therefore, it should be careful to select appropriate criteria in the BV-based procurement projects.

Conclusions

Differing from the traditional lowest-bid tendering method, the BV method determines contract award based on a prescribed evaluation criteria. This study supports the short-listing stage of the BV method by proposing a novel DEA-based, single-input and multiple-output approach. Unlike other existing models which produce rankings of bidders, the proposed approach integrates the evaluation results of individual criteria to generate a list of potential BV winners. The three case studies have demonstrated that DEA is a reliable method that can provide an objective way to locate the potential BV winners with comparative efficiencies into the short list. Restated,

Table 7. Results of varied efficiency analysis for case project 1

DMU	Total Score	Technical efficiency (%)	Pure technical efficiency (%)	Scale efficiency (%)	Actual winner
1	75.9	90.67	100.00	90.67	–
2	73.3	87.62	100.00	87.62	–
3	87.6	100.00	100.00	100.00	Yes
4	71.3	84.32	100.00	84.32	–
5	87.0	100.00	100.00	100.00	–
6	84.7	97.73	100.00	97.73	–

Table 8. Results of sensitivity analysis of criteria for case project 2

DMU	Original DEA value (%)	DEA value by removing C1	DEA value by removing C2	DEA value by removing C 3	DEA value by removing C4	DEA value by removing C5	Actual winner
1	100.00	100.00	100.00	100.00	100.00	100.00	Yes
2	100.00	100.00	100.00	100.00	100.00	100.00	–
3	100.00	98.27	100.00	100.00	100.00	100.00	–
4	98.29	98.29	98.29	98.29	89.62	98.29	–
5	96.95	96.82	93.38	96.95	96.95	96.96	–
6	100.00	100.00	100.00	100.00	100.00	97.76	Yes
7	100.00	100.00	100.00	100.00	100.00	97.14	–

in the three case projects, the actual BV winners selected by the committee members were all fallen into the list of potential winners suggested by the DEA model.

Further research can be conducted in the following directions. First, this study uses a one-input and multiple-output model of DEA to investigate the supplier selection problem. Other types of DEA models may be analyzed for their applicability. Second, the input values of DEA here are equal to 1.0 by simplifying that all bidders will do their best to prepare their proposals for competition. A new model should be explored to overcome this simplification. Third, the case studies here are related to only the service projects. Additional research may be performed to applying DEA to other types of procurement projects, such as construction work, property and consultant service. Finally, lessons learned here should be helpful in applying the DEA to facilitate other supplier selection problems when a multi-criteria evaluation method is used.

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