

A Construction Subcontractor Selection Model

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ABSTRACT

In today's construction market, subcontractors execute significant portions of construction work. Subcontractors lessen resource requirements faced by general contractors and provide specialized expertise to construction projects. The reliance of general contractors on subcontractors to execute major portions of construction work makes the success of construction projects highly susceptible to the performance of these subcontracting organizations. As a result, subcontractors' selection decisions are of crucial importance to general contractors bearing in mind that such decisions are exercised by general contractors multiple times in every single project. Existing models of subcontractors' selection do not result in one holistic view for subcontractor evaluation. This paper contributes a Data Envelopment Analysis (DEA) model to guide general contractors in their subcontractor selection decisions. The proposed DEA approach addresses the limitation associated with existing models and results in one holistic view for subcontractor evaluation.

KEYWORDS: Subcontractor selection, Decision support system, Performance measurement, Benchmarking, Data envelopment analysis.

INTRODUCTION

For almost the past two decades, subcontracting has been utilized extensively in the construction industry. Hinze and Tracey (1994) and Kumaraswamy and Matthews (2000) state that it is common to subcontract 80% to 90% of the construction work to subcontractors. Shash (1998) indicates that many general contractors act as construction management agents only and subcontract a large volume of their work to subcontractors. Wang (2000) argues that it is usual for a semiconductor facility construction project to involve over 50 subcontractors working on the jobsite. More recently, Ng et al. (2008 a, 2008 b), Arditi and Chotibhongs (2005) and Wang and Liu (2005) indicate that subcontractors continue to play a vital role in executing significant portions of construction work.

Subcontractors help general contractors to overcome problems related to the need for special expertise, shortage in resources and limitation in finances (Elazouni and Metwally, 2000). The operations of the average general contractor are not sufficiently extensive to afford full-time employment of skilled craftsmen in each of the several trade classifications needed in the field (Arditi and Chotibhongs, 2005). Subcontracting allows general contractors to employ a minimum workforce in construction projects and promotes specialization. It capitalizes on the skills of trade specialists and copes with the fluctuating construction demand (Ng et al., 2003). Arditi and Chotibhongs (2005) advocate that the use of subcontracting has proved to be efficient and economical in the use of available resources. Subcontracting might improve quality and reduce project time and costs (Ng et al., 2003). Qualified subcontractors are usually able to perform their work specialty more quickly and at a lesser cost than the general contractor can (Arditi and

Chotibhongs, 2005).

The reliance of general contractors on subcontractors to execute major portions of construction work makes the success of construction projects highly susceptible to the performance of the subcontracting organizations. As a result, researchers emphasize the importance of selecting appropriate subcontractors (Kumaraswamy and Matthews, 2000; Ng et al., 2008 a&b; Arditi and Chotibhongs, 2005; Arslan et al., 2008; Tserng and Lin, 2002). As Palaneeswaran and Kumaraswamy (2000) phrase it: "the success level of projects may depend on the philosophy of selecting **the right person for the right job.**"

Despite this almost two-decade practice of subcontracting significant portions of construction work and the realization of the vital impact of subcontractors' work on overall project success, little research has been conducted to aid general contractors in their selection of subcontractors. Literature review reveals only few models that address this important decision-making issue that is exercised by general contractors multiple times on every single project.

Mainly, existing models of subcontractor selection (Arslan et al., 2008; Tserng and Lin, 2002; Albino and Gravelli, 1998; Okoroh and Torrance, 1999; Luu and Sher, 2006; Ko et al., 2007) evaluate subcontractors based on a set of subjective criteria that are deemed important by the decision maker. Such subjective criteria include performance on previous projects, financial strength, completion on time, safety record, timely payment to labor and suppliers... etc. However, none of these models combines subcontractors' bid price along with the subjective criteria resulting in one holistic subcontractor evaluation. This is crucial to practitioners. General contractors rely heavily on subcontractors' bid proposal to make selection decisions. The lowest bid price is usually the key determinant factor for selecting subcontractors by general contractors (Arslan et al., 2008; Tserng and Lin, 2002; Luu and Sher, 2006).

To fill this gap, this paper contributes a Data Envelopment Analysis (DEA) model to guide general contractors in their subcontractor selection decisions. The

DEA approach combines both subcontractors' bid price along with any related subjective criteria that is deemed important by the decision maker resulting in one holistic subcontractor evaluation.

The proposed DEA model is highly flexible. It can be easily tailored to reflect a general contractor's criteria for subcontractor selection. This flexibility includes number and type of factors considered in the analysis. More importantly, the proposed approach provides a framework for selection decisions at large. The DEA model is well-suited to guide organizations that are exercising selection decisions.

PREVIOUS WORK

Few researchers investigated the issue of subcontractor selection. Albino and Gravelli (1998) proposed a neural network approach for subcontractor selection. The authors investigated the neural network implementation and the related managerial and technical innovations by an application case related to an assembly operation in a construction site. Ko et al. (2007) critiqued the approach proposed by Albino and Gravelli (1998) because of the difficulties associated with identifying network topology and membership functions. Okoroh and Torrance (1999) developed a knowledge-based expert system using fuzzy logic. Lin and Chen (2004) argued that limitations of fuzzy logic include the fact that the membership function of natural language expression depends on the managerial perspective of the decision-maker. Lin and Chen (2004) added that another limitation is that the computations of a fuzzy-weighted average is still complicated and not easily appreciated by managers.

Tserng and Lin (2002) proposed an Accelerated Subcontracting And Procuring (ASAP) model that is based on eXtensible Markup Language (XML) and portfolio theory in financial management. ASAP helps general contractors to select subcontractors by deciding on an appropriate tradeoff between risk (i.e., cash flow) and profit for different combinations of subcontractors. ASAP is based on the assumption that all considered subcontractors are recognized as qualified subcontractors.

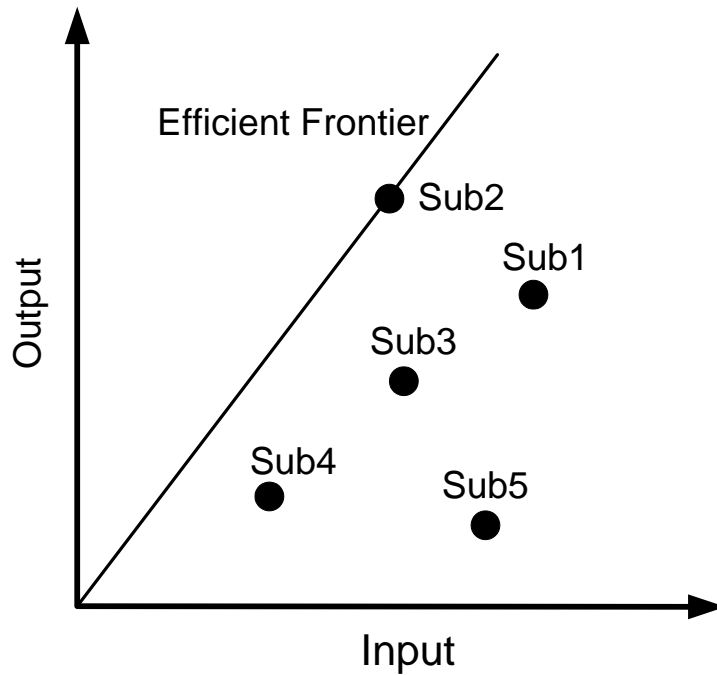


Figure (1): Efficient Frontier.

Luu and Sher (2006) developed a case based reasoning procurement advisory system for subcontractor selection. In this system, subcontractor selection cases are represented by a set of attributes elicited from experienced construction estimators. Ko et al. (2007) developed a Subcontractor Performance Evaluation Model (SPEM) based on an Evolutionary Fuzzy Neural Inference Model (EFNIM). EFNIM is a synergism of generic algorithms, fuzzy logic and neural network. Factors considered by Ko et al. (2007) in subcontractor selection include construction technique, duration control ability, corporative manner, material wastage, services after work completion, collaboration with other subcontractors... etc. Ko et al. (2007) indicated that a limitation of their model is that both quality and accuracy of training data are crucial to its performance.

Arslan et al. (2008) proposed a web-based subcontractor evaluation system called WEBSSES. WEBSSES determines a weighted average score for

considered subcontractors based on 25 evaluation criteria that are grouped under 4 headings: cost, quality, time and adequacy. Criteria under the cost heading are financial capacity, timely payment to labor and completion of job within budget. All 25 criteria are assumed of identical importance. Generally, it is well-accepted that weighted average scores have an inherent weakness due to the biases introduced in the development of the weights and the additive assumptions utilized in the computations of the weighted score average.

Briefly stated, there are few models in the construction literature that addressed subcontractors' selection decisions. Existing models made clear contributions in tackling this important decision-making issue. These models improved our understanding of the criteria involved in subcontractor selection decisions. However, existing models do not combine subcontractors' bid proposal along with other subjective criteria resulting in one holistic subcontractor evaluation.

Table (1): Variables Considered in the DEA Model for Subcontractor Selection.

Variable	Method of measurement	Input/Output
Amount of bid proposal	Dollar amount	I
Performance of relevant previous projects		O1
Financial capacity		O2
Completion of job within time		O3
Prompt payment to labor		O4
Quality of production	Scale of 1 (lowest) to 10	O5
Standard of workmanship	(highest)	O6
Quality of materials used		O7
Compliance with contract		O8
Compliance with site safety requirements		O9
Collaboration with other subcontractors		O10

DATA ENVELOPMENT ANALYSIS MODEL FOR SUBCONTRACTOR SELECTION

The following subsections discuss selection criteria for subcontractors, elaborate on DEA background, methodology and mathematical form and provide an example to illustrate the proposed DEA model for subcontractor selection.

Identifying the Selection Criteria

In their subcontractor selection practice, general contractors rely heavily on subcontractors' bid proposal to make selection decisions. The lowest bid price is usually the key determinant factor for selecting subcontractors (Arslan et al., 2008; Tserng and Lin, 2002; Luu and Sher, 2006). This sole reliance on subcontractors' bid proposal to make selection decisions is critiqued by researchers. Arslan et al. (2008) argued that it may result in problems in quality of work, delay in project duration, create additional costs in construction projects and lead to serious money losses for construction companies in the long run.

To avoid the negative consequences of solely basing the selection decision on subcontractors' bid proposal, researchers call for an evaluation that is based on a set of criteria. Several researchers have isolated factors that are important for subcontractor evaluation (Ng et al., 2008

a&b; Arslan et al., 2008; Ko et al., 2007). Examples on these factors include: performance of relevant previous projects, financial capacity, completion of job within time, prompt payment to labor, quality of production, standard of workmanship, quality of materials used, compliance with site safety requirements, compliance with contract and collaboration with other subcontractors (Ng et al., 2008 a&b; Arslan et al., 2008; Ko et al., 2007).

In summary, practitioners rely heavily on subcontractors' bid proposal to make selection decisions. Researchers, on the other hand, call for an assessment that includes multiple criteria to make selection decisions. As a result, this paper combines subcontractors' bid proposal along with multiple subjective criteria to aid in the selection decision. Table (1) shows variables that are considered in the proposed DEA model for subcontractor selection along with their method of measurement. Bid proposals are measured in monetary terms. The rest of the variables are evaluated by management for the subcontractor in question based on a scale of 1 (lowest) to 10 (highest).

Data Envelopment Analysis (DEA)

DEA was developed by Charnes et al. (1978, 1979, 1981). Nowadays, DEA is well-deployed in other industries with many papers published on its utilization

for performance measurement and decision making. DEA deployment in construction is still limited. Examples on construction-DEA research include the work of El-Mashaleh (2003), El-Mashaleh et al. (2001, 2005, 2007, 2009), McCabe et al. (2005), Pilateris and McCabe (2003), Vinter et al. (2006), Cheng et al. (2007), Chiang et al. (2006) and Xue et al. (2008).

DEA is a non-parametric linear programming approach that is designed to compare and evaluate the relative efficiency of a number of Decision Making Units (DMUs) (Charnes et al., 1978). These DMUs can be organizations, business units, universities,... etc. For the purposes of this research, DMU refers to a subcontractor.

Thamassoulis (2001) explains that DEA is non-parametric because it allows efficiency to be measured without any assumptions regarding the functional form of the production function or the weights for the different inputs and outputs. Charnes et al. (1978) realized the difficulty in seeking a common set of weights to determine relative efficiency. As a result, DEA allows each DMU to adopt a set of weights to determine its relative efficiency compared to other DMUs. Each DMU is allowed to adopt a set of weights, which shows it in the most favorable light in comparison to the other DMUs. Consequently, McCabe et al. (2005) argued that a DMU that is inefficient with even the most favorable weights cannot argue that the weights are unfair.

DEA is based on an input-output framework, where inputs are minimized and/or outputs are maximized. Cooper et al. (2000) provided the following data selection criteria for inputs and outputs:

- Numerical data are available for each input and output;
- The items (inputs, outputs and choice of DMUs) should reflect an analyst's or a manager's interest in the components that will enter into the relative efficiency evaluations of the DMUs; and
- The measurement units of the different inputs and outputs need not be congruent. Some may involve number of persons, areas of floor space, money expended,... etc.

Bearing in mind the above input/output selection

criteria and the fact that inputs are minimized and outputs are maximized, we categorize "amount of bid proposal" in Table (1) as input (I). Clearly, the rest of the variables are considered outputs (O1-O10).

DEA makes use of linear programming to determine which of the set of DMUs under study form an envelopment surface. This envelopment surface is called the efficient frontier. The efficient frontier is "made up" of efficient DMUs. Figure (1) shows an example of an efficient frontier for a simple one input-one output case with only 5 subcontractors under consideration. The slope of the line connecting each point to the origin corresponds to the output per input. The highest slope is for the line connecting the origin through Sub2. This line is called the efficient frontier. Note that the efficient frontier touches at least one point and all points are therefore on or below this line. The frontier "envelops" all the data points suggesting the name data envelopment analysis.

DEA provides a comprehensive analysis of relative efficiency by evaluating each DMU and measuring its performance relative to the efficient frontier. DMUs that lie below the efficient frontier are considered inefficient compared to the DMUs that "determine" that frontier. As such, Sub1, Sub3, Sub4 and Sub5 in Figure (1) are considered inefficient compared to Sub2.

A limitation of DEA is the fact that its discriminatory power depends on the number of DMUs in comparison to the number of variables (inputs + outputs). A rule of thumb indicates that the minimum number of DMUs should be 3 times the number of variables (Charnes and Cooper, 1990). However, Ellis (2003), Wang (2002) and Cheng et al. (2007) relaxed this requirement by creating an "Ideal" DMU. An Ideal DMU has the lowest values of inputs and the highest values of outputs (Cheng et al., 2007).

The Mathematical Form of DEA

The mathematical form of DEA is shown in Equations (1-4). For a detailed discussion, readers are referred to Thamassoulis (2001), Cooper et al. (2000) and Coelli et al. (1998).

Table (2): Example Data.

Subcontractor	I (\$)	O1	O2	O3	O4	O5	O6	O7	O8	O9	O10
Sub1	219,501	7	5	2	1	4	4	6	9	2	9
Sub2	217,622	4	2	5	7	9	6	5	8	9	8
Sub3	225,688	6	5	8	9	2	9	5	8	3	2
Sub4	239,461	4	6	9	2	1	4	6	7	8	3
Sub5	232,589	2	9	8	6	2	4	6	9	2	1
Sub6	212,398	3	2	4	3	5	7	5	2	1	4
Sub7	213,333	1	4	3	5	2	4	4	1	3	2
Sub8	241,576	2	6	7	9	4	4	6	7	8	3
Sub9	209,244	3	5	1	3	2	4	5	4	3	2
Sub10	215,815	4	6	7	8	3	7	5	2	1	4
Ideal Sub	209,244	10	10	10	10	10	10	10	10	10	10

Assume that we have n DMUs ($j=1, \dots, n$) with m input items and s output items. Let the input and output data for DMU _{j} be $(x_{1j}, x_{2j}, \dots, x_{mj})$ and $(y_{1j}, y_{2j}, \dots, y_{sj})$, respectively. Note that we measure the efficiency of each DMU once. As a result, we need n optimizations, one for each DMU _{j} to be evaluated.

$$\max \theta_0 = \frac{\sum_{r=1}^s u_r y_{r0}}{\sum_{i=1}^m v_i x_{i0}} \tag{1}$$

$$\text{subject to } \frac{\sum_{r=1}^s u_r y_{rj}}{\sum_{i=1}^m v_i x_{ij}} \leq 1 \tag{2}$$

$$i=1, \dots, m; \quad j = 1, \dots, n; \quad r=1, \dots, s \tag{3}$$

$$u_r, v_i \geq 0 \tag{4}$$

where:

θ_0 = the measure of efficiency for DMU₀ (the DMU under evaluation), which is a member of the set $j = 1, \dots, n$ DMUs.

u_r = the output weight, which is determined by the solution.

v_i = the input weight, which is determined by the solution.

y_{r0} = the known amount of the r^{th} output of DMU₀.

x_{i0} = the known amount of the i^{th} input of DMU₀.

y_{rj} = the known amount of the r^{th} output of DMU _{j} .

x_{ij} = the known amount of the i^{th} input of DMU _{j} .

The objective function is to maximize the efficiency of DMU₀ (the DMU under evaluation). This is done by maximizing the sum of DMU₀'s outputs divided by the sum of its inputs (Equation 1). Equation 2 means that the efficiency of all DMUs is ≤ 1.0 . This implies that all DMUs are either on the efficient frontier or below it and that the efficiency scores range between 0 and 1.0.

Therefore, in DEA terminology, efficient DMUs are given an efficiency score of 1.0. Inefficient DMUs have an efficiency score that falls in the following range: $0 \leq \text{efficiency} < 1.0$.

Illustrative Example

To illustrate the proposed DEA model for subcontractor selection, let's consider the data shown in Table (2). Ten subcontractors are considered for selection with 1 input (I) and 10 outputs (O1-O10). The input and outputs refers to the ones shown in Table (1). For the sake of demonstration, we limited the number of DMUs to 10 and the number of variables to 11. However, note that DEA can handle tens of variables and thousands of DMUs.

Given the fact that we have 11 variables, this means that at least 33 DMUs are needed to keep the discriminatory power of DEA. Since we only have 10

DMUs, we need to create an Ideal Sub. As indicated earlier, an Ideal DMU has the most favorable inputs and outputs. So, let's consider the least bid proposal submitted by subcontractors as the input for the Ideal Sub. An examination of all bid proposals in Table (2) indicates that the least bid proposal is submitted by Sub9 for an amount of \$209,244. Consequently, the input value for the Ideal Sub as shown in Table (2) is \$209,244. On the other hand, the value for every output for the Ideal Sub is 10, since this is the most favorable value.

Table (3): DEA Results.

Rank	DMU	Efficiency Score
1	Ideal Sub	1.0
2	Sub2	0.87
3	Sub1	0.86
4	Sub3	0.83
5	Sub5	0.81
6	Sub4	0.79
7	Sub8	0.78
8	Sub10	0.77
9	Sub6	0.69
10	Sub9	0.5
11	Sub7	0.49

The DEA solver software of Cooper et al. (2000) is used to run the DEA model. Table (3) ranks all considered Subs (Sub1-Sub10) and shows their efficiency scores. Note that Sub1-Sub10 are rated in comparison to Ideal Sub, which has an efficiency score of 1.0. The rest of the Subs have efficiency scores that are less than 1.0.

Since Sub2 has the highest efficiency score (0.87) among all considered subcontractors, we consider this subcontractor our first choice in executing relevant construction work.

The above example demonstrates how the proposed DEA model is utilized to select one subcontractor out of 10 potential subcontractors. The proposed DEA approach combines subcontractors' bid proposals along with 10 subjective criteria to aid in the selection process. The

model results in efficiency scores rating every subcontractor in relation to the efficient frontier. The subcontractor with the highest efficiency score is selected to execute the relevant construction work. Consequently, and based on DEA results, general contractors can exercise more informed decisions when considering subcontractors for executing construction work.

Even though this example is based on 10 subcontractors and 11 variables, it is worth noting that the proposed DEA model is highly flexible. It can be easily tailored to incorporate any general contractor's criteria for subcontractor selection. This flexibility includes number of DMUs and number and type of factors that are considered in the analysis.

CONCLUSIONS

Subcontractors' selection decisions are of prime importance to general contractors. These decisions are exercised by general contractors multiple times on every single project. Existing models of subcontractors' selection evaluate subcontractors based on a set of subjective criteria that are deemed important by the decision maker. However, none of these models combines subcontractors' bid price along with the subjective criteria resulting in one holistic subcontractor evaluation. This is crucial to practitioners. Contractors rely heavily on subcontractors' bid proposal to make selection decisions. As such, this paper contributes a DEA model for subcontractors' selection that addresses the limitation associated with existing models and results in one holistic view for subcontractor evaluation.

The proposed DEA model is highly flexible. It can be easily tailored to reflect any general contractor's criteria for subcontractor selection. This flexibility includes number of DMUs and number and type of factors that are considered in the analysis. More importantly, the proposed approach provides a framework for selection decisions at large. It is well-suited to guide organizations that are exercising selection decisions.

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