PRACTICAL FRONTIER
IN CONSTRUCTION PREQUALIFICATION
USING DATA ENVELOPMENT ANALYSIS

by

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A thesis submitted in conformity with the requirements
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ABSTRACT

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Contractor prequalification is essential in most construction projects. Data Envelopment Analysis (DEA) had been recognized as a useful technique to prequalify contractors by assigning relative efficiency scores. DEA is capable of identifying improvement targets for inefficient contractors but not for the efficient ones, however. This thesis presents an enhanced contractor prequalification model using DEA and a methodology for improving the efficiency of empirically efficient contractors by defining a new "Practical Frontier" and utilizing management input. The established Practical Frontier can be used as a regional performance standard for the owner in prequalification and as improvement guidelines for contractors.

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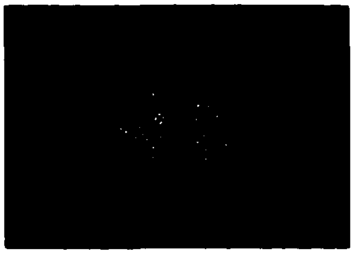
LIST OF NOMENCLATURE

BCC	Banker, Charnes and Cooper (DEA Model)
CCDC	Canadian Construction Document Committee
CCR	Charnes, Cooper and Rhodes (DEA Model)
CPP	Contractor Prequalification Process
CRS	Constant Return to Scale
DEA	Data Envelopment Analysis
DMU	Decision Making Unit
DRS	Decreasing Return to Scale
EMS	Efficiency Measurement System (Computer software)
FPI	Firm Performance Index
IRS	Increasing Return to Scale
PMF	Project Management Firm
UTCPM	University of Toronto Contractor Prequalification Model
VRS	Variable Returns to Scale
WSIB	Workplace Safety and Insurance Board



1.0 INTRODUCTION

This chapter presents an overview of the research. The background of construction prequalification and the application of Data Envelopment Analysis in contractor prequalification are presented. The issues that trigger the research are then discussed and the objectives of the thesis are defined. The proposed solution approach for the determined goals is introduced. Finally, the structural organization of the thesis is shown at the end of this chapter.

1.1 Background

For the owner of any construction project, to be able to select the best available contractor is vital. The demand for such a contractor selection system is tremendous since construction is one of the oldest and largest industries in our society. Prequalification, a screening process applied to potential contractors before tendering, has been used commonly and under many different forms.

Currently, a standard prequalification model that can be used widely in the construction industry is not yet available. Most of the companies/public agencies that perform prequalification have their own prequalification model. The following are some prequalification models that are found in the literature:

- Qualifier-1, Contractor Prequalification Model (Russell and Skibniewski, 1990)
- Qualifier-2, Knowledge-based system for Contractor Prequalification (Russell et al., 1990)
- Fuzzy Set Prequalification Model (Elton et al., 1994)
- Hypertext Decision Support Prequalification Model (AbouRizk and Chehayeb, 1995)
- Cluster Analysis in Contractor Classification (Holt, 1996)
- Neural Network Prequalification Model (Hanna et al., 1997)
- Contractor Prequalification Process – CPP (Gong, 1999)
- University of Toronto Contractor Prequalification Model – UTCPM (Ramani, 2000)

1. Qualifier-1 – Contractor Prequalification Model

Qualifier-1 is a prequalification model developed by Russell and Skibniewski (1990), which employs a dimensional weighting procedure. The model produces aggregate weighted ratings of candidate contractors calculated based on analysis results obtained from questionnaires. Equation 2-1 presents the linear formulation used in the model.

$$AR_k = \sum_{i=1}^{n} W_i \left[\sum_{j=1}^{m_i} (w_{ij})(R_{ijk}) \right] \qquad i=1,\ldots,n \qquad j=1,\ldots,m_i \qquad \text{(EQ 2-1)}$$

where:

AR_k = Aggregate weighted rating of candidate contractor k

n = Number of composite decision factors (CDF)

W_i = Weight of CDF i (ranges from 0 to 1.0, sum of all W_i = 1)

m = Number of decision factors (DF) describing the CDF

w_{ij} = Weight of the DF j, describing CDF i (ranges from 0 to 1.0, sum of all $w_{ij}=1$)

R_{ijk} = Rating of DF j describing CDF i (ranges from 1 to 10) for candidate contractor k

The composite decision factors (CDFs) are the prequalification categories that consist of a number of decision factors (DFs) which are the prequalification criteria. Weights are assigned to both the CDFs and DFs. The authors also developed different sets of weights of the CDFs for public owners and private owners. The advantage of the model is the ability to reduce the effort require to perform the prequalification and the subjectivity involved in the decision making process. Russell and Skibniewski (1990) also state a few shortcomings of this model:

- The model is dependent of the user's ability to process the contractor data.
- A low score in one section can be offset with a high score in another section.
- Model's inability to represent the risk profile of the decision maker and the uncertainty associated with the data collected on candidate contractors.
- Difficulty in handling the combined criteria with dissimilar units of measure.

2. Qualifier-2, Knowledge-based system for Contractor Prequalification

Russell et al. (1990) developed Qualifier-2 as an attempt to overcome the disadvantages of Qualifier-1. Qualifier-2 is a knowledge-based system in which the decision of prequalification is made by the model user using the decision rules, not the calculated scores. The prequalification criteria are also categorized into five Composite Decision Factors (CDFs) that make the top level and further divided into various relevant Decision Factors (DFs) that make the sub levels. A set of heuristic Decision Rules (DRs) presented in "if...then" format was developed for all levels of decision factors to support to the decision making process. The evaluation of a candidate contractor is performed from the lowest DF level up to the top CDF level of the hierarchy. Contractors must meet the decision criteria to proceed to the next step of the model. Qualifier-2, although is capable of overcoming the disadvantages of the weighted scoring systems such as Qualifier-1, still has a limitation since there is no explicit treatment of the uncertainties associated with the heuristic knowledge contained in the knowledge base (Russell et al., 1990).

3. Fuzzy Set Prequalification Model

Fuzzy Set Prequalification, developed by Elton et al. (1994), was a prequalification model that utilizes fuzzy set theory to include the uncertainties in the contractor evaluation process that Qualifier-1 and Qualifier-2can not address. The uncertainties involve in the prequalification systems may be the qualitative nature of the information from the contractor, the reliability of data, and the uncertainty associated with the decision makers. The fuzzy logic, which includes a certain degree of uncertainty in the evaluation and distributes the criteria weights accordingly, is therefore appropriate to apply into the contractor prequalification system to handle ambiguous qualitative information. The disadvantages of the fuzzy set prequalification model, however, are the number of parameters and the complexity of the framework. The user of the model is required to have a mathematical background to understand and run the analysis.

4. Hypertext Decision Support Prequalification Model

AbouRizk and Chehayeb (1995) developed this model to assist decision makers who use weighted scoring systems in the weight assigning process for different criteria. The model uses pair-wise comparison between two factors rather than gives importance weights to a larger number of factors. An $n \times n$ square matrix is used to compare the criteria. Factor i is compared to factor j, its adjacent factor, and a value is assigned to reflect the importance of one to the other. Eigenvectors are then used to calculate the weight of each factor against all the other factors in the system. The aggregate weight of a contractor is developed from the initial $n \times n$ matrix and the importance of the individual factors in the whole system. The total score of a candidate contractor is determined as percentage of all the possible factors.

Computer software that is capable of converting existing text into hypertext was developed to perform the calculations in the process. This model, although presents a structured approach for determining relative weights of importance, still retains a certain degree of bias that can be associated with the weight assignments when comparing the factors pair-wise.

5. Cluster Analysis

Holt (1996) applied cluster analysis (CA) methodology into the process of classifying construction contractors. The set of candidate contractors is evaluated by predetermined selection criteria (Holt et al., 1994). CA analyses the raw data and divides the original set of data into a series of smaller sub-sets of contractors that have similar attributes (contractor characteristics). CA then identifies the sub-sets as good, not-so-good and bad; the best sub-sets of contractor established is considered qualified for tender. The method considers contractor attribute scores for the entire original set and uses an algorithm to group them (Holt et al., 1994). The output of this analysis is a tree diagram (a dendrogram) that graphically shows contractors with similar characteristics in the hierarchical tree as distinct branches. Distances between the nodes of the dendrogram are proportional to the difference between contractors. The advantages of CA include the ability to handle a large number of contractors in the analysis, easy (graphical) interpretation of sub-sets to highlight particular strong or weak points, and the power to identify the most discriminating criteria (Holt, 1996). The author also highlighted the future development of this model in the incorporation of a weighting regime to recognize the most significant criteria or best performance indicators.

6. Neural Network Prequalification Model

Hanna et al. (1997) created a neural network prequalification model and prototype software. Neural networks can learn from historical data and update their knowledge with the input of additional data, a process referred to as training or learning. The major disadvantage of neural networks is the requirement of a large historical information database. It is often difficult to obtain sufficient data to train the system due to the reluctance of many contractors to give up data.

7. Contractor Prequalification Process

Gong (1999) developed the Contractor Prequalification Process (CPP) computer program based on fuzzy logic. The CPP is a 3-stage model that employs the hierarchical framework discussed in Qualifier-2 (Russell et al., 1990) and uses fuzzy logic as the basis for its mathematical calculations. The advantage is this model is its user-friendly procedure of entering and storing information. One limitation of this model is the use of an external equation solver to calculate eigenvectors and eigenvalues.

8. University of Toronto Contractor Prequalification Model – UTCPM

One recent method of comparing contractors by considering their efficiency measures had been introduced by Ramani (2000). The model, named UTCPM, employed the Data Envelopment Analysis (DEA) methodology that calculates efficiency scores for each contractor. The UTCPM model consists of three stages: bonding capacity, DEA, and rank & short-listing. Figure 1-1 presents a graphical representation of the model.

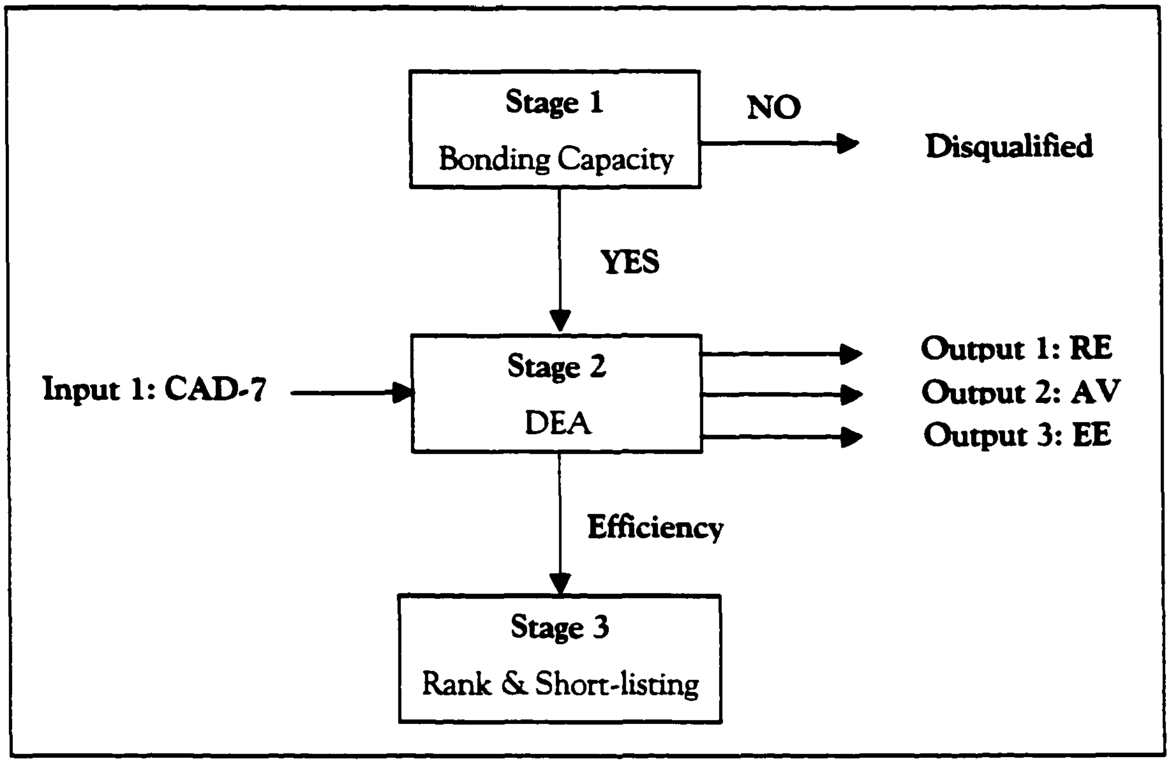


Figure 1-1: Graphical Presentation of UTCPM (Ramani, 2000)

where:

- RE: Relevant Experience
- AV: Average Annual Value of Construction
- EE: Employee Experience
- CAD-7: WSIB Safety Index

Stage 1 of the model is as a screening stage; any contractor that is unable to obtain the appropriate bonding for the project is eliminated from the process. The bonding capacity has been used by many owners as a single measure of evaluating prequalification packages submitted by contractors as they rely on the surety's judgements (Ramani, 2000).

Stage 2 of the model is where Data Envelopment Analysis (DEA) is applied. DEA is a linear programming methodology used to evaluate the relative performance or efficiency of organizational units in a system. Each contractor is one unit under evaluation in the system. The four criteria selected to be the variables of the analysis are CAD-7 Safety Index, Relevant Experience, Average Annual Value of Construction and Employee Experience. The DEA is done on all contractors and the results of the analysis provide the efficiency score for each contractor.

In Stage 3 of the UTCPM, the obtained efficiency scores are used to rank the contractors. The number of qualified contractor is then short-listed (or reduced) to determine the desired number of prequalified contractor. The decision on the final number of contractor to bid on the project will be made by the owner.

The eight prequalification models described above employ frameworks that vary from simple weighted scoring system to complex mathematical methodologies. All prequalification systems, however, have the same basic steps (Russell and Skibniewski, 1988):

- Development of criteria
- Gather contractor data
- Evaluate contractor data
- Apply contractor data to criteria
- Make decision to prequalify contractor

Most of the models have the advantages and disadvantages in their applications. The last model, the UTCPM, is discussed in this section due to the significance of its Data Envelopment Analysis (DEA) framework to this research. DEA is a powerful technique for measuring the relative efficiency of organizational units that have multiple inputs and outputs. DEA has been developed for 24 years and applied in over 50 industries (Charnes et al., 1994). The application of DEA in the contractor prequalification process provides an evaluating method that is computationally advanced and capable of reducing human bias in the process. Besides assigning efficiency scores, DEA also determines improvement target for inefficient contractors.

1.2 Problem Definition

Contractor prequalification using Data Envelopment Analysis (DEA) has been recognized for its potential of eliminating the complexities in the prequalification process. DEA is a linear programming framework which produces a single measure of efficiency for each unit under evaluation from the available values of inputs and outputs. In the contractor prequalification context, DEA establishes a best practice (or efficient) frontier among the contractors and considers the contractors that lie below the frontier as inefficient.

In the UTCPM model (Ramani, 2000), when evaluating contractors, DEA has the ability to simultaneously handle multiple inputs and outputs in the analysis but does not differentiate the relative importance of these variables. This means the "weights" of the prequalification criteria in the analysis are allowed to fluctuate freely and the contractors will appear at their best efficiency, not their actual efficiency. The use of weight restrictions, therefore, can enhance the accuracy of the prequalification process using DEA.

The variables (inputs, outputs) used in the DEA are selected from the wide selection of contractor prequalification criteria. This variable selection can always be modified to improve the accuracy of the model.

DEA can provide valuable information about unit's efficiency, improvement sources and targets for inefficient units. The limitation of DEA, however, is that it cannot determine the possible improvement for the units that are already evaluated as efficient. In the construction context, improvement is always an essential issue as the market is becoming more competitive. If it is possible to identify the efficient contractors, it is also desirable to determine the targets for these contractors to improve.

P-DEA, a methodology capable of determining targets for efficient units in DEA was developed by Sowlati (2001). The P-DEA model is a linear programming model that utilizes management inputs to establish "artificial" improved units and a new efficient frontier, and therefore identifies the possible improvement for the "real" efficient units. The model had been tested with the data from the banking industry and obtained convincing results. The potential of the adaptation of the P-DEA model in the contractor prequalification situation, therefore, can be considered.

1.3 Research Objectives

The objectives of this research are:

- To improve the existing contractor prequalification model using DEA, the UTCPM model.
- To adapt the P-DEA framework into the contractor prequalification situation.
- To develop a methodology that can be used to create best-practice benchmarks for comparing contractors for a specific project type.

1.4 Solution Approach

The objectives of this research can be achieved by utilizing a contractor's prequalification information together with the mathematical frameworks of DEA and P-DEA. The methodology to develop the practical frontier of contractors consists of three stages. In Stage-I, DEA with weight restrictions obtained from management opinion is run on the data of ten construction contracts to identify the efficient contractors. In Stage-II, management opinions about contractors' practical improvement is integrated in an adaptation of the P-DEA model to create the new improved "artificial" contractors. In the last stage, DEA is run again on all the contractors, both real and artificial to establish the new frontier of efficient contractors, the practical frontier.

1.5 Thesis Organization

The structure of this thesis is presented in seven chapters as described below:

- Chapter II presents an overview of the contractor prequalification process. The focus of this chapter is the examination of contractor prequalification criteria as this is an important issue in establishing the practical frontier. The advantages and disadvantages of using prequalification are discussed from both the contractor and owner's point of view.
- Chapter III is dedicated to the topic of Data Envelopment Analysis (DEA). General introduction, concepts, evolution, basic terminologies, and methodology of DEA are presented. Two basic DEA models, the CCR and BCC models, are explained. These models will be utilized throughout the three stages of the proposed methodology. The UTCPM model is further discussed in the DEA context.
- Chapter IV reviews the P-DEA linear programming model which provides a method for establishing the practical frontier using DEA. Methodology and limitation of the model are discussed together with its potential application in the contractor prequalification situation.
- Chapter V presents the solution approach of the proposed methodology and data preparation procedure. The processes of prequalification data and management opinion collection, and variable selection for the DEA are described.

- Chapter VI shows the analysis and results of the three stages of the proposed methodology. The modification of the UTCPM model for the DEA is introduced in Stage-I. The adaptation of the P-DEA model and incorporation of management opinion is presented in Stage-II, and Stage-III demonstrates the development of practical frontier. The results are discussed at the end of each stage.
- Chapter VII provides the conclusions of the research and the recommendations for future development of the proposed methodology.

2.0 CONTRACTOR PREQUALIFICATION

This chapter presents an overview of the contractor prequalification process. An examination of the contractor prequalification criteria described in literature is executed. The advantages and disadvantages of using prequalification from both the contractor and owner's point of view are discussed. The existing prequalification models in literature are looked at and the UTCPM model is reviewed in details due to the significance of its DEA framework.

2.1 What is Prequalification?

In the construction context, prequalification is a screening procedure used by an owner or project manager to determine whether interested contractors are competent to perform the project with respect to a given set of criteria (Russell and Skibniewski, 1990). After being qualified, the contractors will be allowed to enter the bidding stage. The prequalification process is believed to be an "art" more than a science because of the qualitative and subjective nature of the evaluation procedure. Prequalification is usually performed by a senior project manager (or a group of individuals) using a specific evaluation system together with personal judgements to assess contractors' information.

In this thesis, the term "owner" will be used to represent the party that performs the prequalification process for the project and may include the project owner, its representative, the consultants or the designers. The term "contractor" will be used for the party that is being prequalified. In most cases, the prequalification process does not give any advantages to the contractors in the bidding stage since no ranking is considered after they are qualified (Nicholls, 2002). The process, however, still plays an important role in view of the fact that the contractors have to be qualified to be in the later stage of the competition.

2.2 Prequalification Criteria

Prequalification criteria are determined by the owner or project managers and usually specific to a particular project. There are several prequalification models utilizing different frameworks currently used in the industry and found in literature. Most of these models, however, employ similar key criteria that deal with all aspects of the contractor's qualification. These criteria may be judged at different level of significance (weights) depend on the project objectives or the model's assumption. This section presents a selection of major prequalification criteria that are suggested by two major researches (Holt et al., 1994 and Russell, 1996) and the Canadian Construction Document Committee (CCDC, 1996). The criteria are categorized into five groups:

- Contractor's Organization
- Financial Consideration
- Contractor's Resource
- Past Experience
- Past Performance

2.2.1 Contractor's Organization

This prequalification category consists of eight evaluating criteria:

- *Size*
- *Age*
- *Image*
- *Legal structure*
- *Labour type*
- *Health & safety policy*
- *Work expertise*
- *Management procedures*

Size of the contractor is considered as its in-house resource capacity to undertake the construction works. The value of annual construction value can be a good indicator of the contractor's size. Holt et al. (1994) introduced a formula that measures the contractor's size using current/non-current assets and liabilities as variables:

$$MFC = M * (CA - CL + 0.5 * NCA - NCL)$$

where:

MFC: Maximum value of work contractor can be committed to without payment at one time

M: Modifying coefficient

CL: Current liabilities

NCL: Noncurrent liabilities

CA: Current assets

NCA: Noncurrent assets

Age of a construction company may present a good sign of stability, reliability and experience. In the current construction market, however, this may not hold true because a company with a long history can also experience a great impact from the current recession; at the other end, a new company can be established purposely for a particular project (Ramani, 2000). A duration of three years was recommended as a testing period of the company in the market environment by Holt et al. (1994).

Image is a subjective variable where the contractor's public reputation and impression with the owner will have significant influences on the prequalification decision. The owners can usually visualize a number of contractors that they believe to be qualified for the job based on the reputation or previous working experiences with the owner (Nicholls, 2000). Membership of trade/specialist associations is one of the factors that can enhance the contractor's image (Holt et al., 1994).

Legal structure of the contractor can make an impression to the owner about its legal capacity and responsibility. The CCDC-11 document issued by the Canadian Construction Document Committee (CCDC, 1996) asks the contractors for information on their legal type of company (joint venture, corporation, registered), year established (age of company), and names and titles of major stakeholders (officers, partners, principal).

Labour determines the type of labour (union/non-union) that the contractor will be using for the project. The owner should have a good understanding of the constructor's labour structure as union issues can impact the project costs and schedule positively and negatively. Local labour agreements and labour contract issues should be inspected (Russell, 1996).

Health & safety is one important issue that an owner may want to consider to avoid any accidents and reputation damage to the project if dealing with a contractor that has a poor safety records. In Ontario, it is standard practice for contractors to obtain a CAD-7 safety rating from the Workplace Safety and Insurance Board (WSIB) to demonstrate their safety performance to the owner. This rating, however, had been reviewed for its reliability and fairness by the construction industry. Starting in 2000, the WSIB had moved all small employers in any of the construction groups from the CAD-7 program to the new Merit Adjusted Premium Plan (MAP) (WSIB, 2001).

Work experience. The owner should identify the type of work that is usually performed by the contractor's own work force and consider only the experience gained by the contractor's own work force, not from its subcontractors. The contractor's ability to deal with unexpected circumstances and the familiarity with specific materials/equipment required for the project (Russell, 1996).

Management procedures include the administration and project control procedures employed by the contractor that needed to execute the project properly. Company procedures such as the company's business development plan, estimating/bidding practices, subcontractor administration and management, management training system, equipment maintenance program, purchasing system and capabilities, and union agreements should be well examined to understand the organizational procedures and how they are performing. Project control procedures employed by the contractor can indicate the level of quality with which the proposed project will be executed. These procedures include scheduling techniques, cost reporting and control systems, quality control system, material tracking system, and safety program (Russell, 1996). A quality control policy is generally voluntary and therefore the implementation of such a system may show the intention of achieving a high-quality project by the contractor. Quality control system can also be implemented at the request of the owner or from a "third-party" such as government agencies (Holt et al., 1994).

2.2.2 Financial Consideration

This prequalification category consists of six evaluating criteria:

- *Ratio analysis*
- *Bank references*
- *Credit references*
- *Sales history*
- *Bonding capacity*
- *Financial capacity*

Ratio analysis indicates contractor's financial condition and it can be used to predict possible failure in future project (Holt et al., 1994). Financial ratios that can be used for the evaluation include the current ratio (current assets/current liabilities), net assets and pre-tax profit/interest ratio.

Bank reference shows the credit history that the contractor has built up with its financial institution. A period of three years with the same banks can be considered a minimum time for a contractor to develop a financially reliable status (Holt et al., 1994). The references can be highly subjective if no standard format for evaluation is available. Financial stability can significantly affect the performance of the contractor.

Trade creditor references provided by suppliers and manufacturers show the stability of the contractor in paying for the supplies. It is beneficial to the owner if the contractor has established good coordination with its suppliers to acquire the necessary materials in a timely manner. References from suppliers with minimum three years trading history are considered reliable (Holt et al., 1994).

Sales history. The annual value of construction work shows the contractor's size, capacity and the growth. An increase in annual sales of a company can give a sign of growth in capacity and profitability. Growth, however, may imply underlying reduction in effectiveness of management and/or overtrading (Holt et al., 1994). Three years of consistent growth is recommended as an appropriate period for evaluation. The CCDC-11 (1996) document, however, asks for five years of annual sales information. Further checks on liquidity, profitability and equity/debt capital can be done in addition to sales (Holt et al., 1994).

Bonding capacity investigates the contractor's ability to obtain the required bonds for the project and the cost incurred by the contractor to secure such bonds. Using this factor, the owner relies on the judgement made by the surety institutions about the financial and operational stability of the contractor (Russell, 1996).

Financial Stability is used to evaluate contractor's financial condition and capability. A secure and stable cash flow is vital to any construction project. Russell (1990) suggested that besides credit and bank reference, items related to the available financial statement should be investigated.

- Items related the preparation of the financial statement such as the number of accounting partners that the contractor has dealt with in last 5 years, the accounting method used in the statement, and the contractor's in-house capacity for producing timely and accurate financial statements.
- Items impacting the evaluation of the financial statement such as union dues pay date if the contractor is unionized, sufficient insurance coverage and payment balance of the contractor, and familiarity about the construction industry of the contractor's insurance company.

2.2.3 Contractor's Resource

This prequalification category consists of three evaluating criteria:

- *Qualification of owners*
- *Qualification of key personnel*
- *Current capacity*

Qualification of owners. Evaluation should focus on the degree of involvement of the owners of the construction company on management activities. In small private firms, the owner usually plays a major roll in making daily management decisions while in a public corporate, the shareholders do not have much influence on the day-by-day operations (Holt et al., 1994).

Qualification of key personnel will have direct effect on project quality and profit. Key personnel may include project managers, estimators, site superintendents, and foremen. Name, current position, resume of qualification and experience, and other references (e.g. academic qualification, membership of professional institutes, age range, experience overseas, etc.) of key office personnel that are proposed by the contractor to the project should be provided to the owner to evaluate the offered management power. The owner should carefully consider their resume to identify the related experience required for the project (Nicholls, 2000). Qualifications and experience of key personnel in charge of site work are equally important to the project as management staff's quality. Quality of detail planning and execution of the project is largely dependent on the performance of the site personnel. Key personnel with adequate amount of experience (12-22 years) gained from the same company are more desirable as this continuous experience assures familiarity of organizational structure and optimum efficiency (Holt et al., 1994).

Current Capacity concerns the contractor's ability to undertake additional work by examining the amount of uncompleted work the contractor is committed to and compare to its capacity in the past. This factor evaluates the contractor's current workload and identifies any problems that the contractor may be facing in the ongoing projects that can have a potential impact on its performance of the proposed project. Russell (1990) reveals two issues that should be examined when considering the contractor's current workload.

- **Work under contract.** The owner should inspect the amount of work the contractor is currently obligated to, whether the contractor is gaining profit, experiencing any delays or disputes on these current projects, and how the contractor handles change orders.

- **Bid backlog.** The number of projects for which the contractor has submitted a bid but not yet awarded and the number projects that the contractor plans to bid in the near future may be investigated to assess the potential impact on the contractor's expected performance.

2.2.4 Past Experience

This prequalification category consists of four evaluating criteria:

- *Types of project completed*
- *Size of project completed*
- *National or local experience*
- *Experience on project specific maters*

Types of project completed. Construction experience from a contractor based on previous projects should be examined to identify any correlation with the characteristics and scope of the proposed project. Details about previous projects such as description, value, location, owner, consultant, completion date, and available references can assist the owner in understanding the contractor's size, related construction experience and previous performance. Familiarity of the particular project type improves the likelihood of achieving the required project quality and completion time by the contractor. A substantial amount of road construction experience from a contractor may not have much relevance to a bridge building project, therefore, only related experience should be considered. Similar projects in the last two years can be considered as relevant recent experience (Holt et al., 1994).

Size of projects completed provides an indication of the magnitude of work that the contractor is familiar with. A contractor bidding on a project that is too large or too small compared to its normal experience may not deliver the best performance to the owner's interest (Holt et al., 1994).

National or local experience. It is preferable to have a contractor with experience of the local conditions, understanding of local authorities and registration, and familiarity with trade and labour sources in the area. A minimum working period of two months in the project region in the last two years can be considered acceptable local experience (Holt et al., 1994).

Project-specific criteria. All the project-specific items should be outlined and clearly understood by both the project owner (to be able to question the contractor), and by the contractor (to be able to carry out the project properly). Russell (1990) pointed out a number of specific items that can be confronted in a construction project:

- Location consideration, in the case of an overseas project
- Special equipment required and how to obtain them
- Long lead items such as special HVAC equipment
- Construction with a new industrial process
- Constraints from the working environment (e.g. traffic, access and disposal limits, existing operating facilities, weather, etc.)
- Labour or material intensive project
- Union labour agreement peculiarities
- Existence of hazardous materials and required treatments

2.2.5 Past Performance

This prequalification category consists of six evaluating criteria:

- *Contract failure*
- *Time overruns*
- *Cost overruns*
- *Actual quality achieved*
- *Litigation tendency*
- *Debarment & fraud*

Contract failure. Contractors with a history of non-complete projects obviously would not receive a favourable impression from the owner. The owner, however, should investigate the failure to identify whether it was the result of the contractor's poor performance or something beyond its control (e.g. termination by frustration) (Holt et al., 1994).

Time overruns (delays) should also be examined to find any link to the contractor's performance. Delays can be caused by the owner, the designers, or unexpected circumstances such as unusual weather or ground conditions (Holt et al., 1994).

Cost overruns usually go hand in hand with delays because of resulting additional labour and administrative costs. Cost overruns can be the result of either unexpected reasons (price fluctuations, variation in the works, etc.) or contractor's claims (Holt et al., 1994). It is, therefore, necessary to understand the justification of those claims to avoid contractors that seek benefits from contractual claims.

Actual quality achieved by contractors can be collected through references from previous clients. The degree of satisfaction from previous owners can be transferred into a quality score to evaluate the contractors (Holt et al., 1994).

Litigation tendency. Litigation during the project will lead to significant cost overruns and delays. The owner, therefore, should examine the contractor's history of litigation and disputes to avoid contractors that give low bid and try to make up by claims and change orders later in the construction process. The assessment, however, can be difficult since the litigation can also result from a troublesome owner (Holt et al., 1994).

Debarment. The owner should question if the contractor was barred in a certain jurisdiction area by a governmental agency in the past, also when and why. *Fraudulent Activity* is a search for contractor's history for any illegal activities such as providing false financial data, or performing substandard quality work (Russell, 1996).

Table 2.1 summarizes 27 prequalification criteria that were discussed.

Table 2-1: Prequalification Criteria

CONTRACTOR'S ORGANIZATION	1. Size
	2. Age
	3. Image
	4. Legal structure
	5. Labour type
	6. Health & safety policy
	7. Work expertise
	8. Management procedures
FINANCIAL CONSIDERATION	9. Ratio analysis accounts
	10. Bank references
	11. Credit references
	12. Sales history
	13. Bonding capacity
	14. Financial capacity
CONTRACTOR'S RESOURCE	15. Qualification of owners
	16. Qualification of personnel
	17. Current capacity
PAST EXPERIENCE	18. Type of projects completed
	19. Size of projects completed
	20. National or local experience
	21. Experience on project-specific matters
PAST PERFORMANCE	22. Contract failure
	23. Overruns: time
	24. Overruns: cost
	25. Actual quality achieved
	26. Litigation tendency
	27. Debarment & fraud

2.3 Advantages & Disadvantages of Prequalification

Prequalification has been recognized as a useful tool for the owner to ensure the project will be completed by a qualified contractor. The process, however, can also cause some minor negative effects to both parties in the contract, the owner and contractor. This section presents the advantages and disadvantages of the prequalification process identified by Russell (1994).

2.3.1 Advantages to the Owner

The fundamental benefit to the owner from the prequalification process is to be able to eliminate the contractors that are deemed incompetent to complete the project to the industry's and owner's standards. Prequalification can help to prevent any potential losses incurred by the owner such as delays, cost overruns, low-quality construction, disputes, accidents, etc., if an unqualified contractor wins the bid. As the quality of construction cannot be guaranteed by the bonding or financial references, an assessment of the technical qualification should be carefully done by the owner. This gives the owner the benefit of using its professional construction knowledge to evaluate the contractor instead of using quantitative financial analysis from the surety company, which is evaluated differently.

Compared to the post-qualification process, where all contractors enter the bid first and the one with lowest bid is evaluated for qualifications, prequalification saves the owner time and effort to evaluate all tenders and allows the construction of the project to begin earlier. It also helps the owner avoid the complications associated with post-qualification when the lowest bidder is found incompetent. Prequalification gives the owner more time for the qualification analysis and the power to control the number of contractors that can enter the bidding stage.

2.3.2 Advantages to the Contractor

With prequalification, fewer contractors enter the bidding stage and therefore the qualified contractors have the benefit of facing a reduced but consistent level of competition. It can also save the contractor a significant amount of time and money in preparing the cost estimate or proposal if the contractor is not deemed qualified by the owner.

The contractors face less reputation damage or exposure if they are disqualified in the prequalification stage as oppose to the same in postqualification. When the owner disqualifies a contractor in prequalification process with the reason of capacity, it could be a benefit to the contractor because the project may actually be too large for the contractor to handle.

2.3.3 Disadvantages to the Owner

It is obvious that the implementation of a prequalification system will require the owner to absorb an expense additional to the tendering process. The cost and effort of developing, updating and implementing a prequalification system can be significant. Still, it is believed that this expense is justified as the system can efficiently help the owner to avoid much greater costs resulted from the failures of an unqualified contractor (Russell, 1996).

There is a perception in the construction industry that the number of bidders and the bidding price have an inverse relationship (Ramani, 2000); when there are fewer bidders in the competition, higher mark-ups in project price are expected. As a result, the owner may incur a higher project cost when there is less price competition.

2.3.4 Disadvantages to the Contractor

The greatest disadvantage to the contractor may be the subjectivity that may exist in the prequalification process. As most practical prequalification models are established using some form of weighted scoring system, biases from the person who developed the weights and from the person who performs the evaluation are introduced into the decision making procedure. The contractors may not be treated fairly due to the effects of their images or reputation towards the owner. One other minor disadvantage to the contractors is the extra effort to produce the prequalification package to the owner; however, this is only a one-time effort since after the first prequalification package, the contractor only has to update the information.

2.4 Summary

This chapter is an introduction and overview of the contractor prequalification procedure. The characteristics, benefits and shortcomings of prequalification are discussed with the emphasis on the prequalification criteria, as this will be the essential element in a later stage of this thesis.

In the next chapter, the subject of Data Envelopment Analysis and its application in construction prequalification will be discussed in further details as they set the foundation for the investigation of contractor practical frontier using DEA.

3.0 DATA ENVELOPMENT ANALYSIS

This chapter gives an overview of Data Envelopment Analysis (DEA). General introduction, concepts, evolution, basic terminologies, and methodology of DEA are presented to provide a background of the framework. Two basic DEA models, the CCR and BCC models, in their input/output-oriented configurations are explained. The advantages and disadvantages of DEA are also discussed. In the last section of this chapter, the UTCPM model is further discussed in the DEA context. This chapter is dedicated to the subject of DEA to explain the technical theory behind the application of DEA in construction prequalification and set the foundation for the investigation on practical frontier in the later chapter.

3.1 Introduction of DEA

Data Envelopment Analysis (DEA) is a mathematical technique that utilizes linear programming to evaluate the relative performance or efficiency of organizational units in a system that converts multiple inputs into multiple outputs. The units under study are called decision making units (DMUs). DEA can provide valuable information about a unit's efficiency and improvement sources and targets for inefficient units. An enormous range of applications involving DEA have been found including education (public schools and universities), health care (hospital clinics, physicians), banking, armed forces (recruiting, aircraft maintenance), auditing, sports, market research, mining, agriculture, sitting and spatial studies, retail outlets, organization effectiveness, transportation (highway maintenance), public housing, index number construction, and benchmarking (Charnes et al., 1994).

3.2 Concepts

In parametric analyses, the objective is to optimize a single regression plane through the data; a single optimized regression equation is assumed to apply to each unit creating an average unit for the entire population of observations. DEA, in the other hand, generates an efficient frontier or envelopment surface to the data population, and calculates a maximal performance measure using piecewise optimization on each individual observation with respect to the closest observation on the frontier (Charnes et al., 1994).

Figure 3-1 illustrates the difference between DEA and regression, where DEA identifies the best performers, i.e. those that have maximized their output for a given input; regression shows an average line derived by minimizing error (least squares).

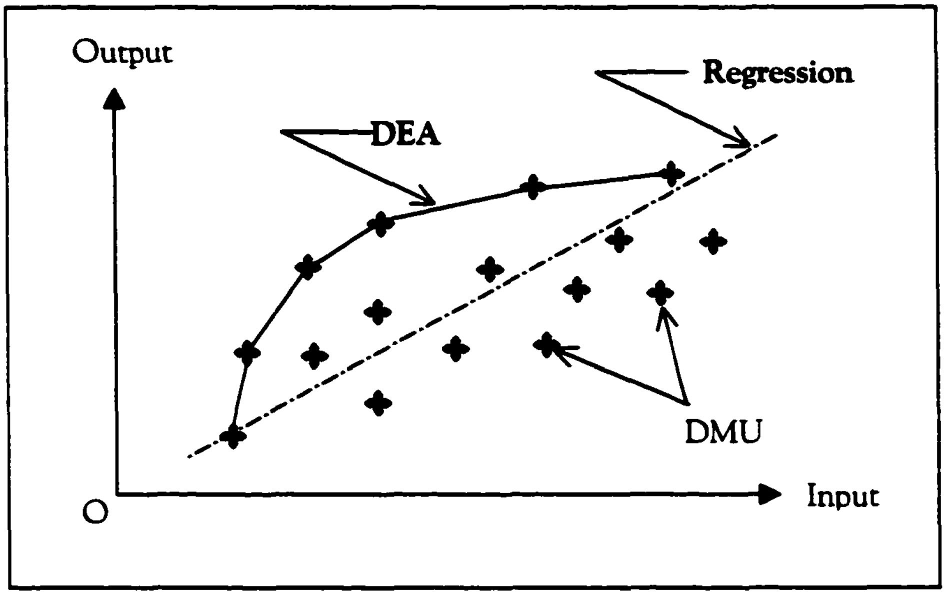


Figure 3-1: Comparison of DEA and regression (Charnes et al., 1994)

3.3 Evolution of DEA

Since 1978, a great volume of literature has been published on the field of DEA along with its rapid development, acceptance and application. This section summarizes some of the major milestones in the evolution of DEA including basic models that form the foundation for a wide range of applications.

1957. Farrell's idea of estimating the technical efficiency for a single single-output/input was introduced (Farrell, 1957). This has been considered the ignition for the establishment of DEA.

1978. Charnes et al. (1978) generalized Farrell's model to overcome the challenges of multiple inputs/outputs situation by creating a single "virtual" output to a single "virtual" input relative-efficiency measure. The CCR model, named after the authors, linked the estimation of technical efficiency and production frontiers, and became the first paper written on DEA.

1983. The Multiplicative models were introduced by Charnes et al. (1983). The models, in contrast to most of other DEA models, allow a piecewise log-linear or a piecewise Cobb-Douglas envelopment.

1984. Banker et al. (1984) presented the BCC model. Similar to the CCR model, the BCC model can either be used as an input or output-oriented model; however, it employs variable-returns-to-scale envelopment surface (as shown in Figure 3-1) while the CCR model uses the constant-returns-to-scale surface.

1985. The Additive models were introduced by Charnes et al. (1985). This model integrates both the output and input orientation in approaching a variable-returns-to-scale envelopment surface.

3.4 Terminologies

This section provides a brief definition of some of the technical terminologies that are frequently used in the subject of DEA.

DMU. A DMU is a decision-making-unit, an organizational unit from which its inputs and outputs are optimized to determine a efficient working model. A DMU can be an entity, process or operation. In the construction context, a DMU represents a contractor in the prequalification process.

Efficiency. Efficiency of a DMU is a comparison of the observed and optimal values of its output and input. DEA produces *relative* efficiency because the measurement made is with reference only to other units in the comparative group.

Pareto-Efficient. A DMU is Pareto-efficient when it is not possible to increase any output level (or decrease any input level) without lowering at least another one of its output levels and /or without raising at least one of its input levels.

Technical Efficiency. Technical efficiency of a DMU is the ability to produce a maximal amount of outputs from a given set of inputs or to use minimal inputs for a designated amount of outputs.

Envelopment Surface. The surface partially formed by a set of efficient DMUs when comparing the performance of all units using DEA. The envelopment surface is also referred to as the empirical production function or the empirical frontier. The empirical frontier is illustrated in Figure 3-2.

3.5 DEA Theory and Methodology

This section presents the efficiency theory of DEA and its application in the contractor prequalification context. The characteristics of DEA such as orientation and invariance are also discussed.

3.5.1 Production Frontier: Theoretical and Empirical

Figure 3-2 illustrates the concepts of the empirical and theoretical production frontiers. For simplification, this figure presents the DMUs with multiple inputs and outputs in a two-dimensional surface to generalize the case of multi-dimensional surface. The output/ input values are considered as weighted inputs/outputs.

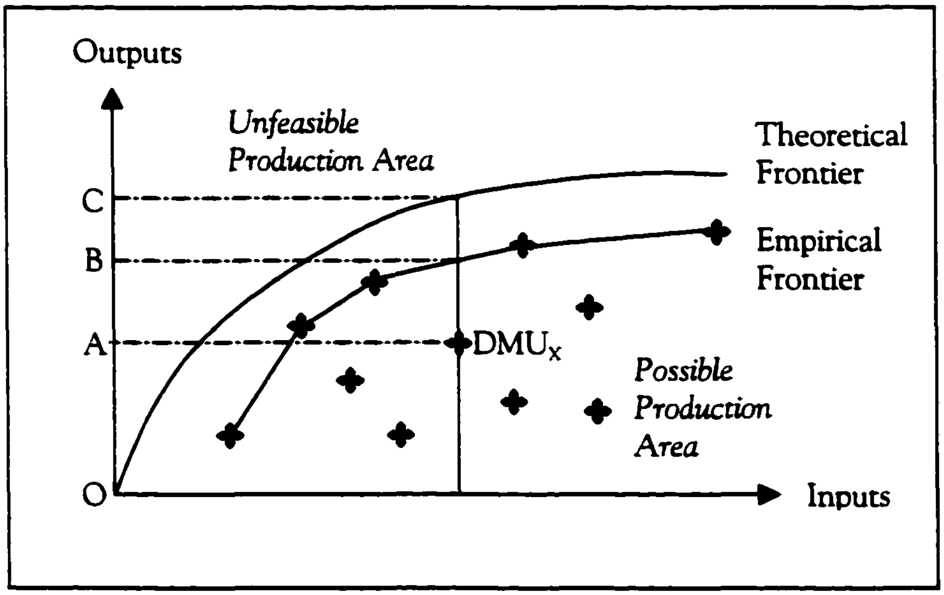


Figure 3-2: Empirical Frontier & Theoretical Frontier (Sowlati, 2001)

The relationship between the consumption of inputs and production of outputs within a DMU is described by the production function, represented by a cross mark in the graph. The empirical frontier is formed by the perimeter that connects all the "relatively best" DMUs in the observed population (highest level of outputs for a certain amount of inputs, or lowest amount of inputs for a certain level of outputs). The theoretical frontier represents the maximum possible production that a DMU can achieve in any level of inputs and outputs. These theoretical relationships, however, cannot be easily identified. The relative efficiency measurement, which bases upon the observational data, is therefore more readily used than the absolute efficiency, which needs the theoretical values.

Two efficiency values can be defined for DMU_X according to Figure 3-2:

- Absolute Efficiency = OA / OC
- Relative Efficiency = OA / OB

In DEA, the DMUs that lie on the empirical frontier are relatively efficient and have an efficiency score of 1.0. Those that lie under this frontier are deemed to be inefficient and will have the efficiency score of less than 1.0.

In the context of application of DEA on construction prequalification, the DMUs can represent the candidate contractors that are subjected to the prequalification process. The prequalification criteria will be the inputs and outputs for each DMU (contractor). The DEA will then be able to identify the efficient contractors on the frontier and assign the efficiency score for all contractors under evaluation. These efficiency score can be used to compare the contractors and eventually decide which ones are qualified.

3.5.2 Envelopment Surface, Orientation & Variable Invariance

The concepts and methodologies of DEA, in the last 25 years, had been developed into a collection of mathematical models such as CCR, BCC, Additive, Multiplicative, etc. These models can be distinguished by the characteristics of the two essential components that comprise the evaluation of efficiency, the envelopment surface and orientation.

Figure 3-3 illustrates the envelopment surfaces and orientation in DEA.

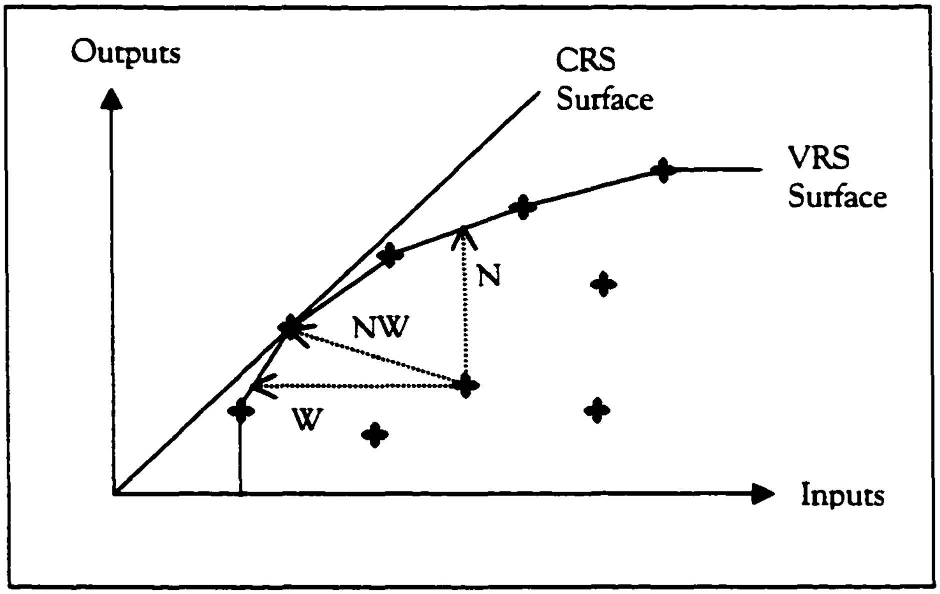


Figure 3-3: Envelopment Surfaces & Orientation (Sowlati, 2001)

The envelopment surface in DEA can take the form of constant-return-to-scale (CRS) or variable-return-to-scale (VRS). The CRS surface is represented by a straight line that starts at the origin and passes through the first DMU that it meets as it approaches the observed population (See Figure 3-3). The models with CRS envelopment surface, therefore, assume that an increase in inputs will result in a proportionate increase in the output levels. The CCR model, one of the basic DEA models, employs a CRS envelopment surface.

The VRS surface, on the other hand, envelops the population by connecting the outermost DMUs, including the one approached by the CRS surface (See Figure 3-3). The VRS surface, therefore, has relaxed the assumption of constant-return-to-scale by allowing an increase in inputs to result in a non-proportionate increase of output levels. Decreasing-return-to-scale (DRS) and increasing-return-to-scale (IRS) are defined to demonstrate the two characteristics of the VRS envelopment surface when an increase in inputs results in an increase of output level at a lower and higher rate, respectively (Thanassoulis, 2001). BCC, Additive and Multiplicative are the DEA models that produce a VRS envelopment surface.

The other essential characteristic of DEA models is orientation. Orientation indicates the direction an inefficient DMU uses to approach the envelopment surface (efficient frontier). A DMU can approach efficiency by either an increase its output levels while maintaining the same level of input (*output-oriented*), or a decrease its input amount while keeping the same output level (*input-oriented*). In DEA calculations, for input orientation, the efficiency scores are in the range of 0 to 1.0 and DMUs with score of 1.0 are considered efficient. For output orientation, the efficiency scores are equal or greater than 1.0 with 1.0 as the score of efficient DMUs. Figure 3-3 illustrates the output-oriented movement by the "N" arrow (heading North) and the input-oriented movement by the "W" arrow (heading West).

The CCR and BCC models both utilize the input-oriented and output-oriented movements. The Additive model uses the combination of the two movements; it reduces the input levels and at the same time increases the outputs. The Additive model, however, only moves towards the efficient point on the envelopment surface that gives the maximum distance in a "north-westerly" direction (Charnes et al., 1994). The "NW" arrow in Figure 3-3 illustrates this movement.

Original value and/or format of observed variables (inputs, outputs) can occasionally create difficulties in the analysis of DEA (e.g. negative numbers, large difference in numerical value). It is, therefore, sometimes beneficial to multiply or add a certain factor to transform the variables into the desirable form. This manipulation of variables does not affect the efficiency score of the DMUs due to the invariance characteristics of most DEA models (Ali and Seiford, 1993). *Scale invariance* allows the variables to be measured in any units and to be scaled to any factor since only the relative scores of the DMUs are calculated. *Translation invariance* allows the variables to be added by a value (e.g. to make the values positive) without disturbing the outcome of the analysis. The BCC model exhibits both scale invariance and translation invariance characteristics while CCR model is only Scale Invariant.

3.6 Basic DEA Models

The four basic DEA models recognized by Charnes et al. (1994) are the CCR ratio model, the BCC model, the Multiplicative model and the Additive model. This section presents the mathematical notation and the underlying framework of the first two models, the CCR and BCC, due to their relevance in this research.

3.6.1 CCR Ratio Model

The CCR Ratio Model is the fundamental DEA model. The linear programming characterizations presented in later sections for the CCR and BCC model were originally derived from the ratio forms (Charnes et al., 1994).

The essential characteristic of the CCR ratio construction is the transformation of the multiple inputs/outputs situation for each DMU to that of a single virtual input and output. The efficiency of a DMU is defined as the maximum of a ratio of weighted outputs to weighted inputs.

$$\max \quad h_o = \frac{\sum_{r=1}^{s} u_r y_{ro}}{\sum_{i=1}^{m} v_i x_{io}} \qquad \text{(EQ 3-1)}$$

s.t.

$$\frac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}} \leq 1 \qquad j = 1,\ldots,n$$

$$u_r, v_i \geq 0 \qquad r = 1,\ldots,s \qquad i = 1,\ldots,m$$

where:

- h_o: Efficiency of DMU_o (DMU under investigation)
- n: Number of DMUs
- m: Number of inputs

- s: Number of outputs
- x_{ij}: Value of input from input i to DMU j
- y_{rj}: Value of output from output r to DMU j
- v_i: Weight (or multiplier) assigned to input i
- u_r: Weight assigned to output r

Equation 3-1 is a fractional programming model that can be solved to calculate the efficiency score of DMU_o and its input and output weights. The objective of the model is to determine the weights (v_i, u_r) that maximize the efficiency ratio of DMUo. The first constraint of the model is used to assure all DMU will obtain an efficiency score of less than or equal to one with this set of weights. The second constraint is used to restrict the weights to be non-negative.

3.6.1.1 CCR Input Oriented Model (CCR-I)

Equation 3-2 is a linear programming problem that had been transformed from the fractional programming model (EQ 3-1) (Charnes et al., 1994).

$$\max \quad h_o = \sum_{r=1}^{s} u_r y_{ro} \qquad \text{(EQ 3-2)}$$

s.t.

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

$$\sum_{r=1}^{s} u_r y_{rj} - \sum_{i=1}^{m} v_i x_{ij} \le 0 \qquad j = 1,\ldots,n$$

$$u_r, v_i \ge 0 \qquad r = 1,\ldots,s \qquad i = 1,\ldots,m$$

The optimal objective value of equation 3-2 is h_o. DMU_o is considered to be CCR-*inefficient* if $h_o > 1$, and *CCR-efficient* if $h_o = 1$. Figure 3-4 shows the efficient frontier (envelopment surface) that is formed by the set of efficient DMUs and the production possibility set in the single input/output case.

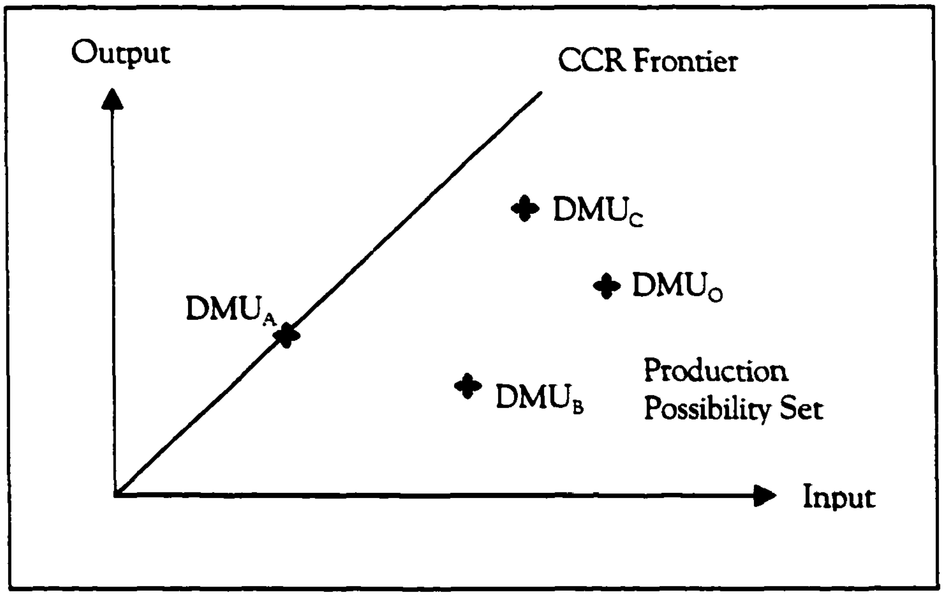


Figure 3-4: CCR Efficient Frontier and Production Possibility Set (Sowlati, 2001)

Accordingly, the dual problem of the linear programming model EQ 3-2 can be determined:

$$\min \quad \theta \qquad \text{(EQ 3-3)}$$

s.t.

$$\theta x_{io} - \sum_{j=1}^{n} \lambda_j x_{ij} \geq 0 \quad i = 1,\ldots,m$$

$$\sum_{j=1}^{n} \lambda_j y_{rj} \geq y_{ro} \qquad r = 1,\ldots,s$$

$$\lambda_j \geq 0 \qquad j = 1,\ldots,n$$

In EQ 3-3, θ and λ_j are the dual variables of the primal model EQ 3-2. The scalar variable θ is defined as the proportional reduction that should be applied to all inputs of DMU_o to make DMU_o efficient. This is where the model exhibits the input-oriented characteristic by reducing the amount of input to achieve efficiency while holding the output level unchanged. This efficiency is call radial efficiency since the input reductions cause a radial movement toward the efficient frontier. The primal problem (EQ 3-2) is also referred to as the *multiplier* form, and the dual problem (EQ 3-3) is the *envelopment* form; these two linear programming problems are equivalent.

To obtain a standard form of linear programming, the inequality constraints in EQ 3-3 can be converted to equality constraint by using additional slack variables s^- and s^+. In DEA, the slack variables are also understood as additional improvements in inputs or outputs. The standard linear program of EQ 3-3 is (Cooper et al., 2000):

$$\min \quad \theta \qquad \text{(EQ 3-4)}$$

s.t.

$$\theta x_{io} - \sum_{j=1}^{n} \lambda_j x_{ij} - s_i^- = 0 \qquad i = 1,\ldots,m$$

$$\sum_{j=1}^{n} \lambda_j y_{rj} - s_r^{+} = y_{ro} \qquad r = 1,\ldots,s$$

$$\lambda_j, s_r^{+}, s_i^{-} \geq 0 \qquad j = 1,\ldots,n \quad r = 1,\ldots,s \quad i = 1,\ldots,m$$

When θ for a DMU is 1.0 (no proportional input reduction) but the slack variables are not zero, it means there are still additional improvements in efficiency of this DMU can be achieved by reducing (or increasing) specific inputs (or outputs) (Charnes et al., 1994). To eliminate the ambiguity of input reductions by θ and the slack variable s^-, EQ 3-4 was modified to allow the minimization over θ to pre-empt the optimization involving the slacks (Charnes et al., 1978).

$$\min \quad z_o = \theta - \varepsilon \sum_{i=1}^{m} s_i^{-} - \varepsilon \sum_{r=1}^{s} s_r^{+} \qquad \text{(EQ 3-5)}$$

s.t.

$$\theta x_{io} - \sum_{j=1}^{n} \lambda_j x_{ij} - s_i^{-} = 0 \qquad i = 1,\ldots,m$$

$$\sum_{j=1}^{n} \lambda_j y_{rj} - s_r^{+} = y_{ro} \qquad r = 1,\ldots,s$$

$$\lambda_j, s_r^{+}, s_i^{-} \geq 0 \qquad j = 1,\ldots,n \quad r = 1,\ldots,s \quad i = 1,\ldots,m$$

In the modified model (EQ 3-5), ε is a very small constant called an Archimedean (infinitesimal) constant, which usually is chosen as 10^{-6} (Sowlati, 2001). The optimization process is therefore executed in two steps: the maximal reduction of inputs (optimal θ^*) will be completed first, and then movement onto the efficient frontier will be achieved using the slack variables (s^- and s^+). A DMU is therefore considered efficient if and only if $\theta^*=1$ and all slacks are zero (Charnes et al., 1994). Figure 3-5 illustrates the efficient frontier and projections of inefficient units in the input oriented CCR model.

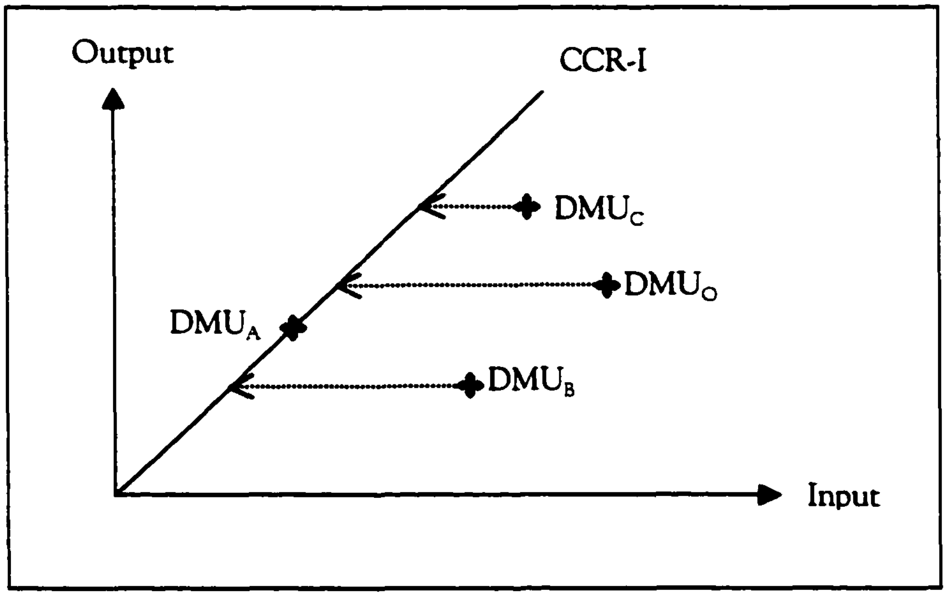


Figure 3-5: Envelopment surface and Projections in the CCR-I model (Charnes et al., 1994).

For the two-dimensional case shown in Figure 3-5, the value of the slack variable will always be zero. In higher-dimensional cases (multiple inputs/outputs), however, positive input and output slacks are usually required to reach the envelopment surface and achieve full efficiency (Charnes et al., 1994).

3.6.1.2 CCR Output Oriented Model (CCR-O)

In the CCR output oriented model, the optimization process is achieved through the maximization of output levels while not using additional amount of inputs. Similar to the CCR-I model, the primal form of the CCR-O is established as follows:

$$\min \quad q_o = \sum_{i=1}^{m} v_i x_{io} \qquad \text{(EQ 3-6)}$$

s.t.

$$\sum_{r=1}^{m} u_r y_{ro} = 1$$

$$\sum_{i=1}^{m} v_i x_{ij} - \sum_{r=1}^{s} u_r y_{rj} \geq 0 \qquad j = 1,\ldots,n$$

$$u_i, v_r \geq \varepsilon \qquad r = 1,\ldots,s \qquad i = 1,\ldots,m$$

and accordingly, the dual form:

$$\max \quad z_o = \phi + \varepsilon \sum_{i=1}^{m} s_i^{-} + \varepsilon \sum_{r=1}^{s} s_r^{+} \qquad \text{(EQ 3-7)}$$

s.t.

$$\phi . y_{ro} - \sum_{j=1}^{n} \lambda_j y_{rj} + s_r^{+} = 0 \qquad r = 1,\ldots,s$$

$$\sum_{j=1}^{n} \lambda_j x_{ij} + s_i^{-} = x_{io} \qquad i = 1,\ldots,m$$

$$\lambda_j, s_r^{+}, s_i^{-} \geq 0 \qquad j = 1,\ldots,n \qquad r = 1,\ldots,s \qquad i = 1,\ldots,m$$

In the CCR-O dual model (EQ 3-7), the ϕ variable is introduced as the increase in output to make the DMU efficient. The optimization process in the CCR-O model is similar as that of the CCR-I model; the difference, however, is in the projection of the DMU towards the efficient frontier as shown in Figure 3-6.

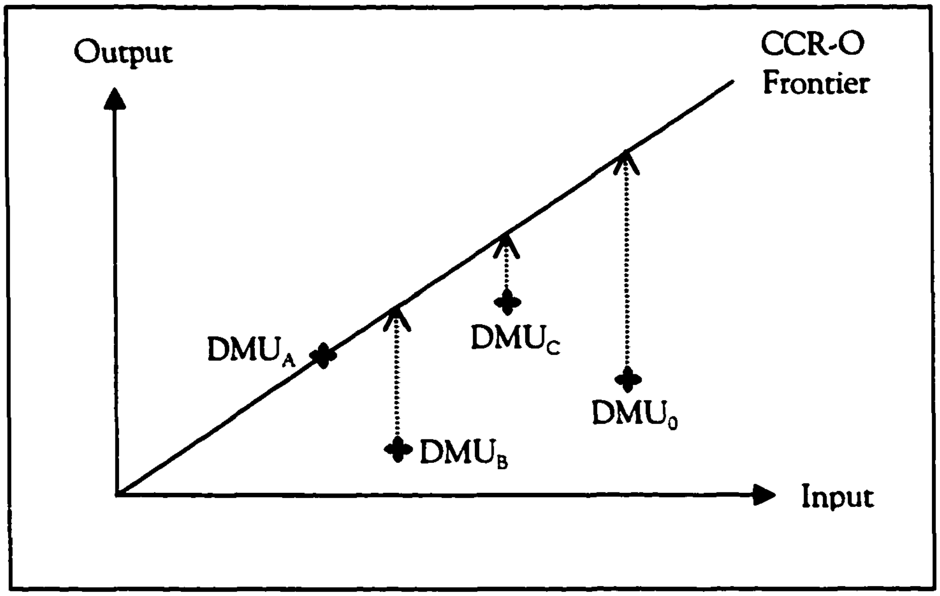


Figure 3-6: Envelopment surface and projections in the CCR-O model (Charnes et al., 1994).

A DMU is considered efficient in a CCR input oriented model if and only if it is also characterized efficient in the corresponding CCR output oriented model.

3.6.2 BCC Model

In 1984, Banker, Charnes and Cooper presented the BCC model. Similar to the CCR model, the BCC model has both input and output-oriented optimization; however, it employs variable-returns-to-scale envelopment surface while the CCR model uses the constant-returns-to-scale surface.

3.6.2.1 BCC Input Oriented Model (BCC-I)

The linear programming for the BCC model with an input orientation are given in EQ 3-8:

$$\max \quad h_o = \sum_{r=1}^{s} u_r y_{ro} + u_o \qquad \text{(EQ 3-8)}$$

s.t.

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

$$\sum_{r=1}^{s} u_r y_{rj} - \sum_{i=1}^{m} v_i x_{ij} + u_o \leq 0 \qquad j = 1,\ldots,n$$

$$u_r, v_i \geq \varepsilon \qquad r = 1,\ldots,s \qquad i = 1,\ldots,m$$

$$u_o \text{ free}$$

The dual form of the above model is expressed as:

$$\min \quad z_o = \theta - \varepsilon\sum_{i=1}^{m} s_i^- - \varepsilon\sum_{r=1}^{s} s_r^+ \qquad \text{(EQ 3-9)}$$

s.t.

$$\theta x_{io} - \sum_{j=1}^{n} \lambda_j x_{ij} - s_i^- = 0 \qquad i = 1,\dots,m$$

$$\sum_{j=1}^{n} \lambda_j y_{rj} - s_r^+ = y_{ro} \qquad r = 1,\dots,s$$

$$\sum_{j=1}^{n} \lambda_j = 1 \qquad j = 1,\dots,n$$

$$\lambda_j, s_r^+, s_i^- \geq 0 \qquad j = 1,\dots,n \quad r = 1,\dots,s \quad i = 1,\dots,m$$

The formulations of the BCC input oriented model are similar to that of the CCR model except the presence of the convexity constraint ($\Sigma\ \lambda_j = 1$) in the dual and equivalently, the presence of u_o, which is an unconstrained variable, in the primal problem. This constraint demonstrates the variable-returns-to-scale characteristic of the BBC model. Figure 3-7 shows the envelopment surface and projections of inefficient DMUs to the efficient frontier in a two-dimensional case. The inefficient DMUs first approach the frontier by reducing their input and then by using the slack variables if any.

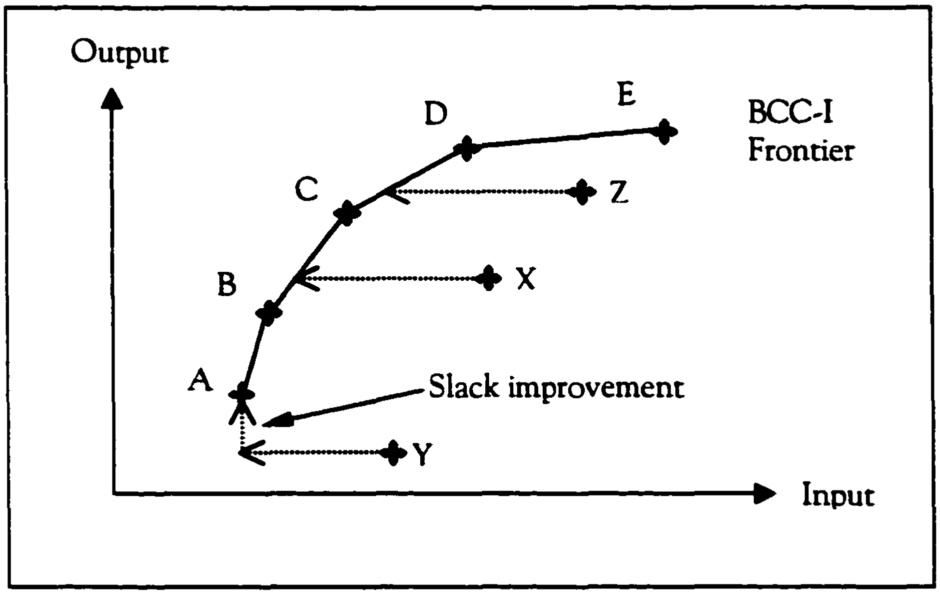


Figure 3-7: Envelopment surface and projections in the BCC-I model (Charnes et al., 1994).

In Figure 3-7, DMU$_Y$ is inefficient and therefore a reduction in input is needed. Additional improvement by the slack variable, however, should be utilized so DMU$_Y$ can reach the efficient frontier at DMU$_A$. Similar to the CCR model, a DMU is therefore considered BCC-efficient if and only if $\theta^*=1$ **and** all slacks are zero. A DMU that is characterized as efficient in the CCR model will also be characterized as efficient in the BBC model but the converse does not necessarily hold true.

3.6.2.2 BCC Output Oriented Model (BCC-O)

The essential difference between the input oriented BCC model and the output oriented BCC model is that the linear programming BBC model tries to achieve proportional output augmentation by maximizing on ϕ. The multiplier form of the problem is as follows:

$$\min \quad q_o = \sum_{i=1}^{m} v_i x_{io} + v_o \qquad \text{(EQ 3-10)}$$

s.t.

$$\sum_{r=1}^{m} u_r y_{ro} = 1$$

$$\sum_{i=1}^{m} v_i x_{ij} - \sum_{r=1}^{s} u_r y_{rj} + v_o \geq 0 \qquad j = 1,\ldots,n$$

$$u_i, v_r \geq \varepsilon \qquad r = 1,\ldots,s \qquad i = 1,\ldots,m$$

$$u_o \text{ free}$$

Accordingly, the envelopment form:

$$\max \quad z_o = \phi + \varepsilon.\sum_{i=1}^{m} s_i^{-} + \varepsilon.\sum_{r=1}^{s} s_r^{+} \qquad \text{(EQ 3-11)}$$

s.t.

$$\phi.y_{ro} - \sum_{j=1}^{n} \lambda_j y_{rj} + s_r^{+} = 0 \qquad r = 1,\ldots,s$$

$$\sum_{j=1}^{n} \lambda_j x_{ij} + s_i^{-} = x_{io} \qquad i = 1,\ldots,m$$

$$\sum_{j=1}^{n} \lambda_j = 1 \qquad j = 1,\ldots,n$$

$$\lambda_j, s_r^{+}, s_i^{-} \geq 0 \qquad j = 1,\ldots,n \qquad r = 1,\ldots,s \qquad i = 1,\ldots,m$$

In the BCC output oriented model, a DMU is efficient if and only if the maximal output augmentation $\phi^* = 1$ and all slacks are zero. Figure 3-8 illustrates the projection of inefficient DMUs towards the envelopment surface in the BCC-I models.

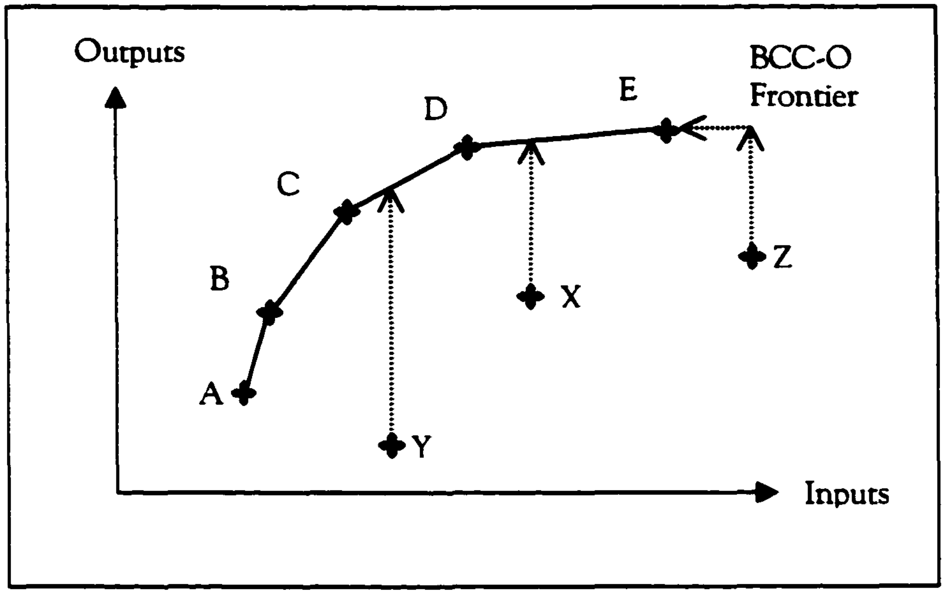


Figure 3-8: Envelopment surface and projections in the BCC-O model (Charnes et al., 1994).

3.7 DEA Benefits and Limitations

Data Envelopment Analysis has been proven a useful analytical tool in comparing organizational units with multiple inputs and outputs. DEA not only compares the performance of the units by assigning efficiency scores but also provides indication on the sources and magnitude of improvement for inefficient units. DEA does not require any assumption about the functional form (regression equation, production function, etc.) as in parametric approach (Charnes et al., 1994). DEA calculations are also value free and do not require specification or knowledge of the weights for the inputs or outputs; however, judgements can be included when desired.

DEA, however, still has some disadvantages. To provide reliable results, the variables (inputs and outputs) used for the analysis should not be correlated. DEA also requires a minimum number of units under evaluation to maintain its discriminating power (Banker et al., 1984). Data accuracy and verification should be given careful consideration since DEA solutions are sensitive to error in the data. Finally, the use of DEA requires knowledge about formulation of models, choice of variables, underlying assumptions, data representation, interpretation of results, and model's limitations.

3.8 Applications of DEA in Construction Prequalification

As previously introduced in Chapter I, an application of DEA in construction prequalification was developed by Ramani (2000). This section reviews the UTCPM model and especially its DEA framework. The UTCPM model consists of three stages: bonding capacity, DEA, and rank & short-listing.

Stage 1 of the model is a screening stage; any contractor that is unable to obtain the appropriate bonding amount for the project will be eliminated from the process. Stage 2 of the model employs data envelopment analysis as an evaluation tool to compare the efficiency of all candidate contractors. Each contractor is one DMU in the DEA model. The four prequalification criteria selected to represent a contractor's input and outputs are CAD-7 Safety Index (input), Relevant Experience, Average Annual Value of Construction and Employee Experience (outputs). The selection of criteria was made based on a developed prequalification system that used by a project management firm. The data of inputs and outputs used to test the model was collected from actual prequalification packages submitted by contractors for seven contracts.

The DEA model used for the prequalification process is a BCC model (both input-oriented and output-oriented cases) since it is believed that the variable-returns-to-scale is more indicative of the construction industry (Ramani, 2000). The DEA was run on all contractors using a computer program called ProDEA. The efficiency score calculated from the analysis was used to rank the contractors.

In Stage 3 of the UTCPM, the contractors were ranked by their efficiency scores. The decision on the final number of contractor to bid on the project was predetermined by the owner. The list of ranked contractor was then cut off at this desired number and the top contractors were considered qualified for the bidding stage.

3.9 Summary

This chapter presented an overview of the data envelopment analysis concepts and models together with the application of DEA in construction prequalification. The use of DEA in construction prequalification is believed to help eliminate the bias that is often present in the process (Ramani, 2000). The efficiency evaluation produced by DEA, however, is only valid relative within the particular group under investigation. A contractor that is judged by DEA as efficient in this group may not be actually efficient when compared to the best practice standard in the construction industry. It is, therefore, desirable to identify the industrial best practice standard to be used as a benchmark in construction prequalification, i.e. to identify the practical frontier. The next chapter will present an approach that can be used to develop such a benchmark.

4.0 PRACTICAL FRONTIER IN DEA

This chapter reviews the P-DEA model developed by Sowlati (2001). P-DEA is a linear programming model which provides a method for establishing the practical frontier in DEA. The model as originally developed was not suitable for this approach; another constraint was therefore added. Methodology and limitation of the model are discussed together with its potential application in the contractor prequalification situation.

Data Envelopment Analysis (DEA) has been widely accepted as a useful tool in assessing efficiency of production units. DEA distinguishes efficient units and identifies possible improvements for inefficient units. Because of its local relativity in evaluation, however, DEA is unable to indicate the possible improvements that can be achieved by efficient units. It is always important for management to realize and determine improvement targets for relatively efficient units to promote improvement of the organization as a whole. In construction prequalification context, it is desirable for both the owner and contractors to realize the performance of the "best practice" contractors in the industry and their targets for improvement.

Sowlati (2001) asserted that if the inputs and outputs of efficient units can be varied within specified ranges, then it is possible to determine other combinations of inputs and outputs from which new, "artificial" DMUs can be created. These new artificial DMUs will be constrained to be more efficient than the DEA efficient unit from which they were created. A linear programming model called P-DEA and a methodology for improving the efficiency of empirically efficient units by defining a new practical frontier and utilizing management inputs were developed by Sowlati (2001). The practical frontier, which formed mostly by the artificial DMUs, allows the analyst to identify the new adjusted efficiency scores for the old real DMUs and therefore indicate the area for possible improvements. Figure 4-1 illustrates the development of the practical frontier based on the DEA empirical frontier.

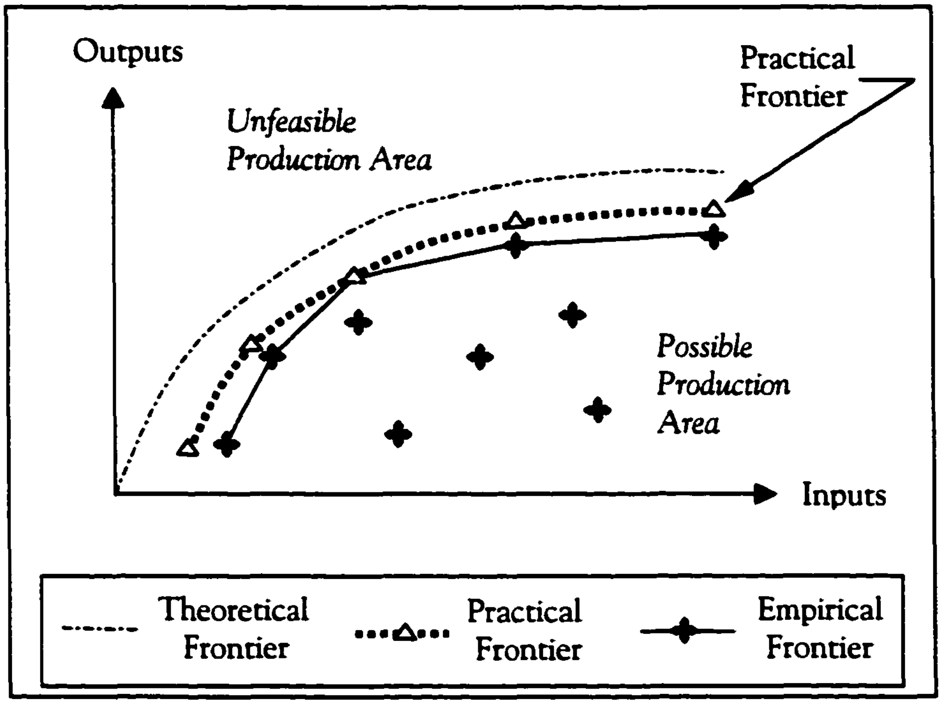


Figure 4-1: The Theoretical, Practical and Empirical Frontiers (Sowlati, 2001)

4.1 P-DEA Linear Programming Model

P-DEA is a linear programming model developed by Sowlati (2001). The model combines the DEA framework and management inputs to define the Practical Frontier. The development of the model starts with the BCC ratio model (EQ 4-1):

$$\text{Max} \quad h_o = \frac{\sum_{r=1}^{s} u_r y_{ro} + u_o}{\sum_{i=1}^{m} v_i x_{io}} \qquad \text{(EQ 4-1)}$$

s.t.

$$\frac{\sum_{r=1}^{s} u_r y_{rj} + u_o}{\sum_{i=1}^{m} v_i x_{ij}} \le 1, \qquad \forall j,$$

$$u_r, v_i \ge \varepsilon \qquad r = 1,\ldots,s \qquad i = 1,\ldots,m$$

$$u_o \text{ free}$$

where:

x_{ij} and y_{rj} are the inputs and outputs of the jth DMU

u_r and v_i are the output and input weight, respectively.

The objective of the EQ 4-1 is to obtained the weights that maximize the efficiency of the unit under evaluation, DMU$_{o..}$ while limiting the efficiency of all DMUs to less than or equal to 1.0. Variables of this model are the efficiency score and the input/output weights; the inputs and outputs of DMU$_o$ are known.

In reality, some of the factors (inputs, outputs) are fixed and no change or improvement can be made to their values (e.g. store area). Other factors, however, can vary in certain ranges. Information about these possible changes can be obtained from management opinions. In this P-DEA model, the upper and lower bounds for some or all inputs and outputs for a DMU$_o$ are defined as follows:

$$L_{xio} \le x_{io} \le U_{xio} \quad \text{and} \quad L_{yro} \le y_{ro} \le U_{yro}$$

In the next step, taking a DMU_o that has efficiency score of 1.0, the model attempts to establish a new DMU that has an efficiency score greater than that of DMU_o (>1.0) and has the input and output values within the specified ranges. EQ 4-1 is then modified to:

$$\text{Max} \quad h_o = \frac{\sum_{r=1}^{s} u_r \tilde{y}_{ro} + u_o}{\sum_{i=1}^{m} v_i \tilde{x}_{io}} \qquad \text{(EQ 4-2)}$$

s.t.

$$\frac{\sum_{r=1}^{s} u_r y_{rj} + u_o}{\sum_{i=1}^{m} v_i x_{ij}} \le 1, \qquad \forall j,$$

$$1 \le \frac{\sum_{r=1}^{s} u_r \tilde{y}_{ro} + u_o}{\sum_{i=1}^{m} v_i \tilde{x}_{io}} \le 1 + \delta$$

$$L_{xio} \le \tilde{x}_{io} \le U_{xio}, \qquad \forall i,$$

$$L_{yro} \le \tilde{y}_{ro} \le U_{yro}, \qquad \forall r,$$

$$u_r, v_i \ge \varepsilon \qquad r = 1,\ldots,s \qquad i = 1,\ldots,m$$

u_o free

In EQ 4-2, the efficiency score, the weights (u_r, v_i), and $\tilde{x}_{io}$ (outputs of new DMU), $\tilde{y}_{ro}$ (inputs of new DMU) are now the variables; only the lower and upper bounds are known from management opinions. The model allows the inputs and outputs to vary within the limits to achieve higher efficiency (>1.0) and therefore create a new DMU. While the objective function is trying to maximize the efficiency of the new DMU, the weights must be feasible for all other units (efficiency score not greater than 1.0).

A new constraint on the efficiency score is also added in EQ 4-2. The upper limit of (1+δ) for the efficiency of the new unit is needed to keep the model bounded, and the lower limit of 1.0 to constraint the new DMU at least as efficient than the one from which it was created. δ, the amount of possible increase in the efficiency of an empirically efficient unit, can be specified by management (for example: 4%). This is only a general estimate and not applicable to all efficient units. For some units, it will be more or less than 4% or have no improvements on efficiency at all. That is the reason for the practical frontier "touching the empirical frontier (Sowlati, 2001).

Next, EQ 4-2 can be transformed into a linear fractional programming model by substituting:

the variables:	$\tilde{x}_{io}.v_i$	by	p_r	
	$\tilde{y}_{ro}.u_r$	by	q_i	and
the constraints:	$L_{xio} \le \tilde{x}_{io} \le U_{xio}$	by	$v_i.L_{xio} \le q_i \le v_i.U_{xio}$,	
	$L_{yro} \le \tilde{y}_{ro} \le U_{yro}$	by	$u_r.L_{yro} \le p_r \le u_r.U_{yro}$	

Equation 4-3 is the linear program transformed from the fractional program (EQ 4-2). The fractional objective function is maximized by setting the denominator equal to a constant (1 in this case) and maximizing only the numerator (Charnes et al., 1962).

$$\text{Max} \quad \sum_{r=1}^{s} p_r + u_o \qquad \text{(EQ 4-3)}$$

s.t.

$$\sum_{i=1}^{m} q_i = 1,$$

$$\sum_{r=1}^{s} u_r y_{rj} + u_o - \sum_{i=1}^{m} v_i x_{ij} \le 0, \qquad \forall j,$$

$$\sum_{r=1}^{s} p_r + u_o - \sum_{i=1}^{m} q_i \ge 0,$$

$$\sum_{r=1}^{s} p_r + u_o - \sum_{i=1}^{m} q_i (1+\delta) \ge 0,$$

$$v_i . L_{xio} \le q_i \le v_i . U_{xio}, \qquad \forall i,$$

$$u_r . L_{yro} \le p_r \le u_r . U_{yro}, \qquad \forall r,$$

$$u_r, v_i \ge \varepsilon \qquad r = 1,\dots,s \qquad i = 1,\dots,m$$

$$u_o \text{ free}$$

EQ 4-3 can be solved using linear programming method to find the variables q_i, v_i, p_r, u_r. The values of the inputs and outputs of the new unit can then be calculated as:

$$\tilde{x}_{io}^{*} = \frac{q_i^{*}}{v_i^{*}} \qquad \text{and} \qquad \tilde{y}_{ro}^{*} = \frac{p_r^{*}}{u_r^{*}}$$

The P-DEA model can be run on every efficient unit to obtain a set of new DMUs that have efficiency score of equal or greater than one. These new DMUs will form the practical frontier that envelops the empirical one.

4.2 Methodology

The procedure of using P-DEA for improving the efficient unit and establishing the practical frontier has three stages. Figure 4-2 graphically presents the methodology proposed by Sowlati (2001).

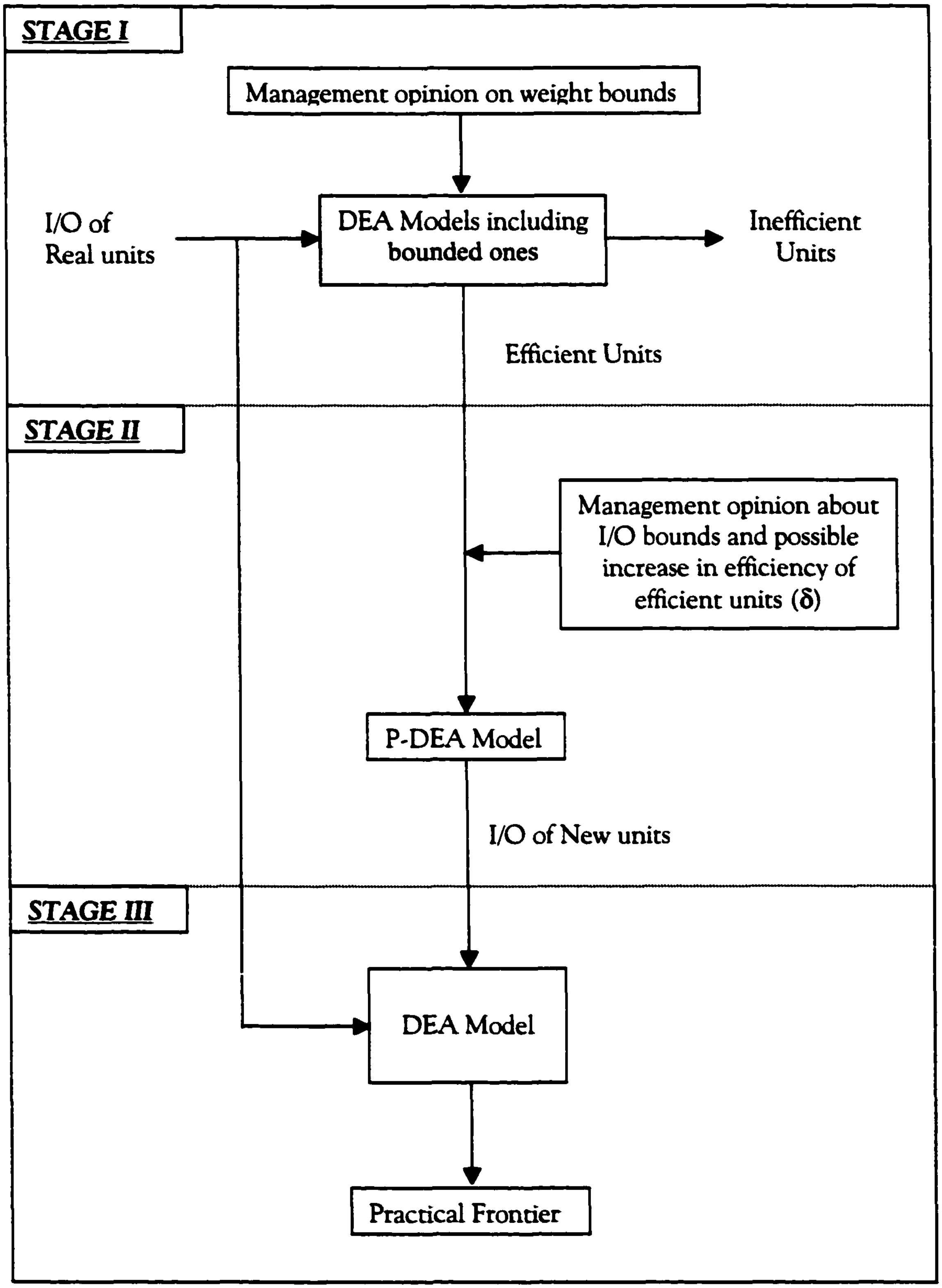


Figure 4-2: P-DEA Methodology (Sowlati, 2001)

In Stage-I, conventional DEA methodology is used to evaluate the efficiency of all units and identify efficient units. An unrestricted DEA will be run first, and then restrictions on the weights from management opinions can be applied into the model to increase the discrimination power.

In Stage-II, the obtained management opinions on possible efficiency improvement and allowable input/output ranges of efficient DMUs is incorporated into the P-DEA model (EQ 4-3) to solve for inputs and outputs of the new "improved" DMUs. These new units, together with some units on the empirical frontier, will form the practical frontier.

In the last stage, established DEA model is run again with all the real and new "improved" DMUs and a new set of efficient units will be defined. This new set may include the new improved units and the real ones. The practical frontier formed by this new set of efficient units will envelop or touch the empirical frontier but will not cross it.

The methodology has been tested on sales data from Canadian bank branches to evaluate the performance (or efficiency) of each branch with respect to the chosen population of 79 bank branches (Sowlati, 2001). The factors used in the analysis were personnel resources (Sales, Support and Other employees) as the inputs, and sale products (Loans, Mortgages, RRSPs, and Letter of credits) as the outputs of the model. It was found that after stage III of the model, the number of real efficient units was reduced from eight units (evaluated by DEA in stage I) to two units.

4.3 Limitation of P-DEA

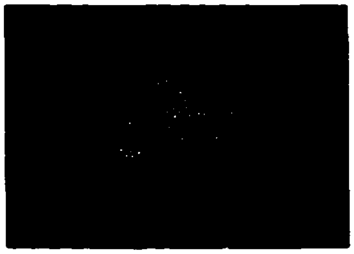
The greatest limitation of the P-DEA model is believed to be the process of obtaining management opinions (Sowlati, 2001). The process is usually time-consuming and difficult to develop an appropriate method to collect the right information. The selection of experts is critical due to the demand of accuracy and validity of information, and also recognition of opinions by those being evaluated. It is also desirable to have more than one expert, but this can lead to variance and disagreement between opinions.

The method of information gathering can be collecting surveys or interviews; the later procedure is believed to be more efficient since the expert can have an exact understanding of the issues through explanations rather than just questions. It is ideal to have a panel of respectable experts (from both the owner and contractor sides) that will discuss the issues and arrive at a compromise conclusion.

4.4 Summary

This chapter presents the methodology and the linear programming P-DEA model that can be used to establish the Practical Frontier. Details of the mathematical development of the model and its limitation in implementation are demonstrated. The model is recognized with its potential application in the contractor prequalification situation.

This chapter also concludes the literature review and background development portion of this research. The next chapter will present procedure of comprising prequalification information, data envelopment analysis and practical frontier development to achieve the specified objectives of the research.



5.0 DATA & SOLUTION APPROACH

This chapter presents the solution approach of the proposed methodology and the procedure of data preparation. The processes of prequalification data gathering and management opinion collection are described. The definition and selection procedure of the variables used for the DEA analysis are discussed. A brief introduction of the CCDC-11 document and the prequalification model used by the consulted experts are provided.

5.1 Approach

The primary objective of this research is to establish a practical frontier of contractors. This can be achieved by utilizing contractor's prequalification information together with mathematical frameworks of DEA and P-DEA. In the procedure of defining the practical frontier, other goals of this research are to improve the existing DEA Contractor Prequalification model (Ramani, 2000) and adapt the Practical DEA model (Sowlati, 2001) into the contractor prequalification context. The process of developing the practical frontier of contractors presented in this research can be summarized in the following steps:

1. Data collection, transformation of data and statistical analysis.
2. Selection of contractor prequalification criteria.
3. DEA with consideration on weights restriction and model orientation.
4. Incorporating management opinion.
5. P-DEA adaptation and analysis.
6. Establishment of practical frontier using DEA.

The methodology used in developing the practical frontier for contractors are adapted from the P-DEA model (Sowlati, 2001) with some modifications. The proposed model is named P-DEA+ for its construction application and the modifications from the P-DEA model will be discussed in later sections. Figure 5-1 graphically summarizes the proposed methodology for establishing the practical frontier, which consisted of three stages and two models, the DEA Prequalification model and the P-DEA+ model.

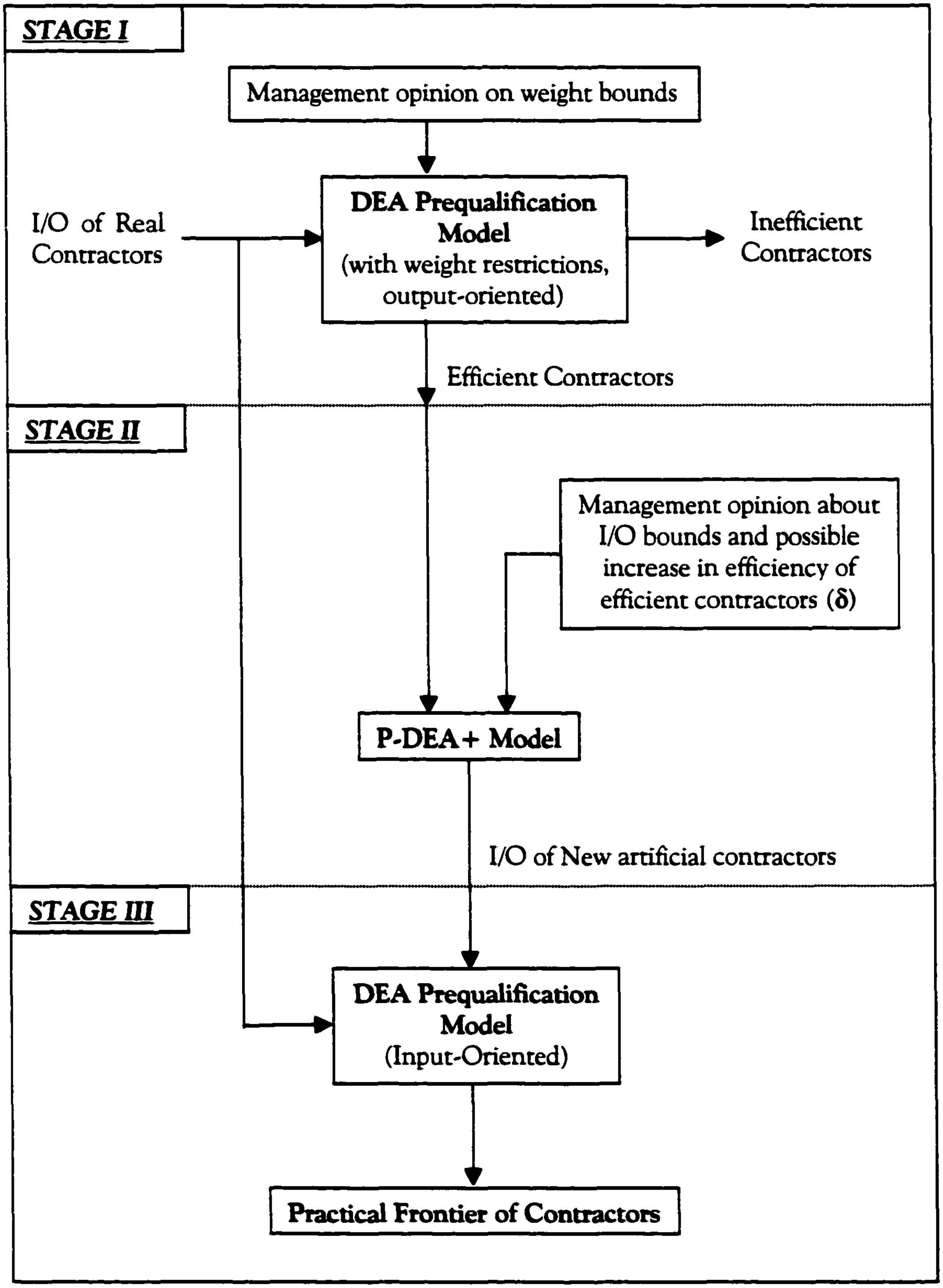


Figure 5-1: Methodology

5.2 Data Collection

The prequalification data used in this research was obtained from a project management firm in Southern Ontario (referred to as "PMF"). PMF is a joint venture of three large construction management companies and it has the capacity of undertaking one of the most sizeable projects in the region. Prequalification packages for 10 contracts submitted by contractors to the PMF were selected and information that is relevant to the analysis was extracted. Prequalification data for seven contracts were the same data set used by Ramani (2000); additional data for three new contracts were also included in this study. These ten contracts have values ranging from 3 to 12 millions dollars and were prequalified in the period of 1998-2000. The structure types in these contracts vary from roadwork to major bridges and all projects were located in the Greater Toronto Area. Appendix B presents the complete data of the contracts. Table 5-1 presents the values and construction types of the ten contracts.

Table 5-1: Contract Values and Construction Types.

Contract Name	Value ($Millions)	Construction Type	Prequalification Time	Number of Contractors
A	3	Bulk Excavation	June	16
B	4	Buried Water Lines	August	18
C	1.5	Building Demolition	January	15
D	4	Utility Duct Bank	May	15
E	5	Sanitary Sewage Pumping Station	September	19
F	15	Major Bridge Projects	November	15
G	12	Road Construction	March	20
H	5	Building Modification	October	19
I	5	Caissons	June	17
J	5	Road & Bridge Works	May	20

The prequalification package required by PMF includes a completed CCDC-11 form, resumes of supervisory personnel to be assigned to the project, a letter from bonding company stating the contractor's bonding capacity, a certificate of Clearance from the Workplace Safety and Insurance Board (WSIB) and a current CAD-7 Calculations Safety Records also from WSIB.

The CCDC-11 (1996) document, "Contractor's Qualification Statement", developed and issued by the Canadian Construction Document Committee (CCDC), is a standard form for obtaining information on capacity, skill and experience of contractors bidding on building construction project. This document was drafted based on years of expert inputs from various sectors of the construction industry; the latest version of CCDC-11 document is the 1996. It is a common practice in Canada to use the CCDC-11 document as one of the information collection methods for the prequalification process. The CCDC-11 document contains eight information questions: Legal structure of contractor, Financial references, Annual value of construction, Principal projects completed, Similar or related project completed, Major construction projects underway, Key office personnel resume, and Key site personnel resume (See Appendix-A for a copy of the CCDC-11 document).

The prequalification model used by PMF is a weighted scoring system with ten criteria. The system can award a maximum of 50 points and each criterion has different possible maximum score. Some scoring benchmarks in the system can be changed to adapt with the characteristics of the project (e.g. the value of the Average Annual Construction to obtain maximum score). Table 5-2 presents the PMF's prequalification scoring system. The brackets contain the maximum score allotted to each criterion.

Table 5-2: PMF's Prequalification Scoring System

EVALUATION CRITERIA
Type of Company
Corporation (4), Partnership (3), Individual (2)
Average Annual Value of Construction
Over 5 M (6), 3 - 5 (4), 2 - 3 (1), less than 2 (0)
Financial References
Bank (4), Bonding Co. (3), None (0)
Completed Projects in Last Five Years
4 or more (3), 1 to 3 (1), or NIL (-4)
Related Projects (with references)
Good Experience (10), some experience (5),
NIL experience or no info provided (-10)
Key Personnel Assigned to Projects
(5 Max)
Personnel Resumes
Resumes (2), None (0)
Letter of Required Bonding
Yes (10), Not Sufficient (0), None (-5)
WCB Clearance Certificate
Yes (2), No Information (0)
CAD - 7 Report
Good Standing(4), Average (2), Poor or no info. (0)

5.3 Selection of Criteria (Variables)

In this stage, the available information was selected and transformed to develop an appropriate data set to enter into the DEA model. The selection of the prequalification criteria to be DEA variables will determine the categories of the data set. The DEA framework used in this research was a modification of the UTCPM developed by Ramani (2000). A new selection of variables was used in this research and a set of weight constraints was incorporated later on.

After considerations of the availability of data, the degree of importance and relevance of the prequalification factors, the existing prequalification criteria exercised by PMF, and the DEA variables used in the UTCPM model, five contractor prequalification criteria were selected to form the set of DEA variables in this research. These five variables were *Safety Records*, *Current Capacity*, *Sales History*, *Related Work Experience*, *and Employee Experience*. These variables were selected from a variety of criteria based on their prominent significance in the prequalification process recognized by both researchers and industrial practitioners (Holt et al., 1994; Russell, 1996; CCDC, 1996 and PMF). Availability of data is also a decisive factor in the selection of variables; contractor information representing the selected variables can be obtained from the submitted CCDC-11 standard document.

Current Capacity is introduced as the new variable in this model and will be explained later. *Bonding Capacity* is one of the most important criteria in the prequalification process; however, because it is not considered a quantitative variable, contractors without bonding capacity are simply not included in the analysis; bonding capacity was used only as a screening variable and not in the DEA.

Table 5-3 shows the source information extracted from the prequalification packages and the corresponding DEA variables.

Table 5-3: Source information and corresponding DEA variables.

Source Prequalification Information	DEA Variables
1. CAD-7 Firm Performance Index (FPI)	1. Safety Records (SR)
2. Current Work Load.	2. Current Capacity (CC)
3. Annual Construction Value in the last 5 years	3. Sale History (SH)
4. Value of Related Works (last 5 years)	4. Related Work Experience (RE)
5. Employee Resumes	5. Employee Experience (EE)

These five sets of available information are raw information, extracted directly from the source. To transform the available information into the data that correctly represents the selected prequalification criteria and suitable for the DEA afterwards, transformations and conversions were applied on the collected information.

In the DEA framework, the contractor information (or performance indicator), which is represented by the five selected variables, is the input to the system, and the efficiency is the output. In the proposed prequalification model using DEA, however, these five variables were further categorized as two inputs (Safety Records and Current Capacity) and three outputs (Sale History, Related work Experience). Figure 5-2 illustrates the difference between the input/output of the framework and inputs/outputs of the DEA prequalification model. The double meaning of terminology "input" and "output" can be confusing but because it is standard terminology in DEA, the terms were kept.

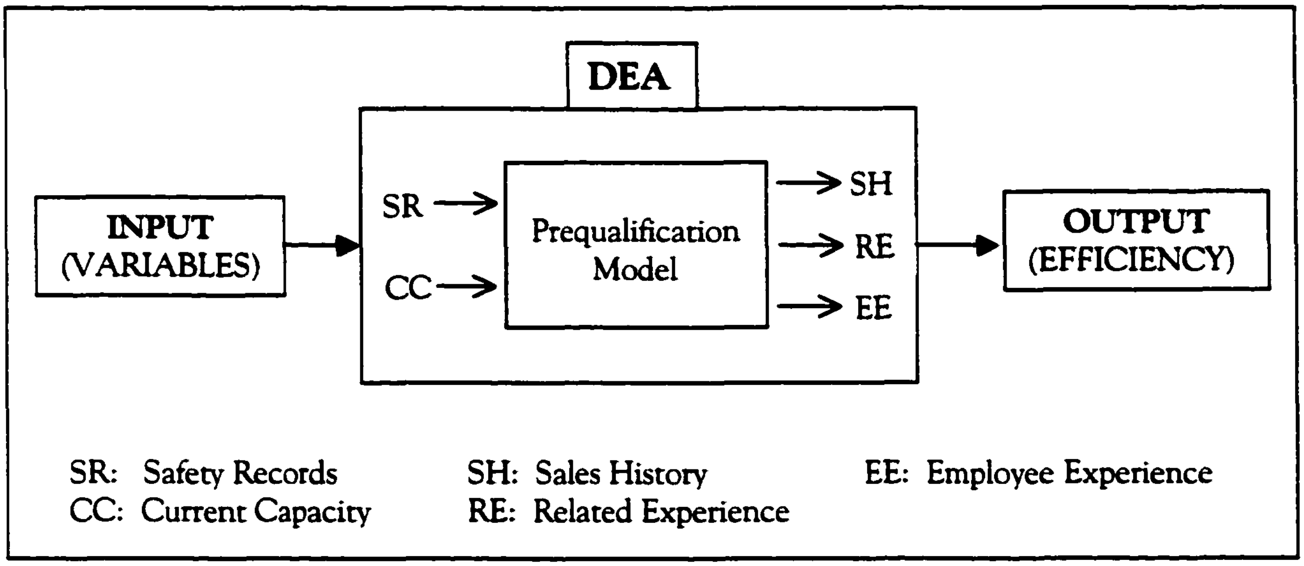


Figure 5-2: DEA Input/Output and Variables

In DEA, there is a rule of thumb on the maximum number of inputs and outputs that can be used in the model to obtain reliable results. Banker et al. (1984) proposed that the number of DMUs should be at least three times more than the sum of the number of inputs and outputs. The "discrimination power" of DEA increases as the number of DMUs included in the analysis increases (Sowlati, 2001). In the data set selected for this research, each of the ten contracts has a minimum number of 15 contractors (DMUs), which is three times the total number of 2 inputs and 3 outputs. The minimum number of DMUs, however, is not necessary if the practical frontier is set and used consistently. In fact, the analysis does not have to be a batch process; it can be run with one new DMU and the practical frontier.

5.3.1 Safety Records

Safety is always one of the key issues in any construction project, especially in Canada. A contractor with a poor safety record is more likely to have accidents and damage to project reputation. The Firm Performance Index (FPI) evaluated in the CAD-7 Calculation sheet by the WSIB was used as the indication of the contractor's safety records. The original values of the FPI are in the range of –2.0 (worst) to 1.0 (best) with 0 representing the average acceptable score. To accommodate the constraints of DEA, the FPI values were transformed into the range of 4.0 (worst) to 1.0 (best) by subtracting the value by 2 and then multiplying by –1. The subtraction was done since DEA cannot handle negative number due to its ratio analysis, and the scale was inverted to make the *Safety Records* variable an input in DEA (factor being minimized to improve).

5.3.2 Current Capacity

Resource capacity of a contractor is always vital to the success of the project. It is desirable for the owner to understand if the contractors will be overloaded when they undertake the project. It is, however, a complex task to determine a numerical value that can represent the capacity of the contractor. Public organizations such as State Departments of Transportation (DOTs) in the US define and calculate the "Maximum Capacity" of a contractor's operation in their annual evaluations. This variable is a measure of the number and size of the projects a contractor can theoretically take on and complete successfully. This variable can be compared with the total amount of work-on-hand plus the cost of any pending project to determine if the contractor is within his capacity (Russell, 1996).

The *Current Capacity* is a variable that was not previously considered in both the prequalification system of PMF and the UTCPM model. Management opinion had been consulted about the potential application and development of this variable. The variable received positive attention and a formula that estimates the *Current Capacity* value was agreed on. Since the "maximum capacity" values for the contractors used in this research are not available, the information about the contractor's current work load submitted in the CCDC-11 document and the average annual construction value were used to determine the *Current Capacity* variable. In this research, *Current Capacity* is defined as the ratio of a contractor's current workload, including the proposed project, over the aggregate maximum amount of work that the contractor had taken at any time in the last five years. The suggested formula to estimate the *Current Capacity* variable is shown below:

$$\boxed{CC = \frac{CWL + PV}{AACV} \times c \times 100\%}$$

where:

CC:	Current Capacity (in percentage)
CWL:	Current Work Load
PV:	Project Value of the project in question
AACV:	Average Annual Construction Value in the last 5 years
c:	Constant

The value of the Current Work Load (CWL) variable can be extracted from Appendix C of the CCDC-11document (under "Major construction projects underway as of the date of submission"). The monetary values of the undergoing projects are multiplied by the complete percentages and then summed to get the CWL value. The Average Annual Construction Value (AACV) in the last five years of the contractor can also be obtained from the CCDC-11document; this variable will be explained in detail later.

The only unknown parameter in this formula is the constant "c". This constant is included in the formula to take into account the discrepancy in using the AACV to approximate the Maximum Capacity value. The AACV and Maximum Capacity values are believed to have a proportionate relationship, but finding the correct value of this "c" factor is a complicated task which is beyond the scope of this research. It is certainly desirable to be able to determine its true value; however, for the purpose of DEA, this value is not necessary. As mentioned earlier in Chapter III, the DEA BCC model employs the "*Scale Invariance*" property that allows the variables to be measured in any units and to be scaled to any factor since only the relative scores of the DMUs are calculated. The suggested formula for the *Current Capacity* value is therefore satisfactory to be used for this research. For the analysis, *Current Capacity* is considered as an input since a contractor should minimize this value to be more efficient.

5.3.3 Related Work Experience

Related Work Experience is considered the most important factor in prequalifying a contractor. The submitted Contractor's Qualification Statement form (CCDC-11) provides information on the projects previously executed by the contractors that have the similar nature to the project in question. The monetary values of all these related projects were summed to represent the *Related Work Experience* variable for the DEA. This factor was used as an output variable since it should be maximized.

5.3.4 Sales History (Average Annual Value of Construction)

The submitted CCDC-11 provides annual construction value achieved by the contractor in the last 5 years. These values were averaged to obtain a number that can represent the sales history of the contractor. The actual monetary values were used for the *Sales History* variable in the DEA and this was used as an output variable since it should be maximized.

5.3.5 Employee Experience

Beside the company's work experience, it is the human expertise that really makes the contractor qualified. Resumes of key supervisory personnel assigned to the project by the contractor are provided in the submitted prequalification packages. The number of years of experience of these personnel was totalled to produce a quantitative value that can indicate the management resource of the contractor. *Employee Experience* is the third output variable used in the analysis.

5.4 Initial Analysis of the Data

After transforming the available information into the appropriate data format, the data were analyzed to evaluate the impact of the data value on the analysis. Table 5-4 shows the statistical characteristics of the data and Table 5-5 presents the results of the correlation analysis performed on the data.

Table 5-4: Data Statistics

STATISTICS	S.R. {I}	C.C. {I}	R.E. {O}	S.H. {O}	E.E. {O}
Minimum	1	4.497378	0.024	1.2778	10
Maximum	4	454.1635	507.52	1546.446	327
Mean	1.599351	113.9795	35.83602	60.77078	78.86207
Standard Deviation	0.723265	89.32416	79.93374	147.6315	47.7288

Table 5-5: Correlation Analysis of Data (All contracts)

CORRELATION	S.R. {I}	C.C. {I}	R.E. {O}	S.H. {O}	E.E. {O}
S.R. {I}	1				
C.C. {I}	0.071618	1			
R.E. {O}	0.017412	-0.03374	1		
S.H. {O}	0.002924	-0.21739	0.358187	1	
E.E. {O}	0.040904	-0.12843	0.172937	0.162232	1

where:

- S.R.: Safety Records (Input)
- C.C.: Current Capacity (Input)
- R.E.: Related Experience (Output)
- S.H.: Sales History (Output)
- E.E.: Employee Experience (Output)

Figure 5-2 shows the scatter plot between the two input variables *Safety Records* and *Current Capacity*. The scatter plots for other variables are presented in Appendix C.

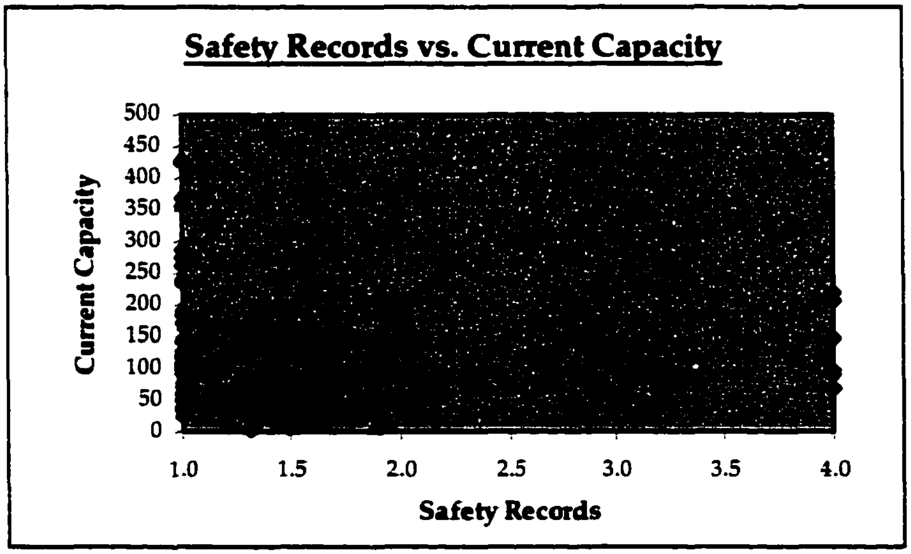


Figure 5-3: Scatter plot of Safety Records and Current Capacity

Correlation between inputs and outputs is an important issue in DEA. A strong correlation between inputs (or outputs) could indicate that the two variables represent the same characteristic and this will decrease the discriminating power of DEA. In the case of high correlation, one of the variables can be omitted from the model; however, this should be done with caution since a mathematical correlation could imply logical or causal correlation (Sowlati, 2001).

Correlation analysis was done separately on every contract, and one with the combination of data from all 10 contracts. Similar results found in the 10 single correlation analyses and result of the overall analysis was shown in Table 5-4. It was observed that all the variables have low correlation. The highest correlation was found to be 0.358 between *Related Experience* and *Sales History*. The five selected variables and the data were considered appropriate.

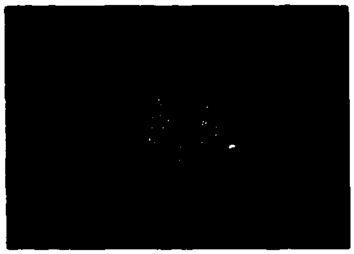
5.5 Collection of Management Opinion

The collection of management opinion was done to gather information that can be used in improving the DEA contractor prequalification model and in developing the practical frontier. The process of collecting management opinion was performed via both interviews and surveys. The experts involved in the investigation included two senior project managers at PMF and a senior project manger from a large construction corporation.

Issues about the selection of variables (inputs & outputs), the perceived importance of these variables, the range of allowable changes of the variables, and the prospect of improvement of efficient units were discussed. After discussions, the following conclusions were drawn:

- The selection of prequalification criteria was reasonable and practical. The introduction of the Current Capacity variable was encouragingly agreed upon.
- The relative importance (weights) of the variables were suggested as follow:
    - Safety Records: 4
    - Current Capacity: 3
    - Related Experience: 20
    - Sales History: 6
    - Employee Experience: 7
- The ranges of allowable change of variables of efficient units were estimated as:
    - Safety Records: +20% to -20%(≥1)
    - Current Capacity: +30% to -20%
    - Related Experience: +3% to -5%
    - Sales History: +5% to -10%
    - Employee Experience: +20% to -20%
- The possible increase in efficiency score (δ) of best practice contractors was expected to be about 6% on an annual basis.

With the data, DEA variables and management opinion available, these parameters could be substituted into the proposed framework to perform the analysis.



6.0 ANALYSIS & RESULTS

This chapter shows the analysis and results of the three stages of the proposed methodology. The modification of the UTCPM model for the DEA is introduced in Stage-I. The adaptation of the P-DEA model and incorporation of management opinion is presented in Stage-II, and Stage-III demonstrates the development of practical frontier. The results are discussed at the end of each stage.

6.1 Stage I - DEA Analysis

The Data Envelopment Analysis software used in this research was the Efficiency Measurement System (EMS) developed at University of Dortmund, Germany. EMS is capable of handling DEA problems with over 5000 DMUs and about 40 inputs and outputs. In this stage, BCC variable returns-to-scale (VRS) DEA with no weight restriction were run on all 10 contracts, both input and output-orientation were investigated.

The DEA was performed with the BCC model since this model is believed to be more representative of the construction industry due to its VRS character. In Stage-I, the analysis was first performed with no restriction imposed on the input and output weights. The analysis was then run again with the weight restrictions suggested by management to identify any improvement of the model. With no restrictions, the weights were allowed to vary freely so the DMUs exhibited their best efficiency. These optimum weights, however, may not be reasonable under management's opinion since they may not correctly reflect the degree of importance of the variables.

Table 6-1 and 6-2 show sample result sheets of DEA analysis produced by the "EMS" software for contract A with input orientation and output orientation, respectively.

Table 6-1: EMS Results – Contract A – Input Orientation – No weight restriction

DMU No.	DMU Name	Efficiency Score	Variable Weights					Benchmarks	Variable Slacks				
			SR	CC	RE	SH	EE		SR	CC	RE	SH	EE
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
1	A1	0.6176	0	0.016	0.014	0.017	0.009	7 (1.000)	0.371	0	35.599	58.28	31
2	A2	0.9943	0.994	0	0	0	0.015	6 (0.947), 8 (0.053)	0	36.64	3.405	1.177	0
3	A3	0.9999	1	0	0.002	0.019	0.025	6 (1.000)	0	46.904	4.16	1.077	20
4	A4	0.3995	0	0.01	0	0.002	0.011	7 (1.000)	0.177	0	26.568	55.8	37
5	A5	0.6536	0.418	0.002	0	0	0.01	7 (0.680), 16 (0.320)	0	0	34.158	39.318	16.261
6	**A6**	**1.0000**	1	0	0.144	0.117	0	[2]					
7	**A7**	**1.0000**	0	0.026	0	0.015	0	[6]					
8	**A8**	**1.0000**	0.995	0	0	0	0.005	[3]					
9	A9	0.3296	0.212	0.001	0	0	0.008	7 (0.689), 8 (0.136), 16 (0.176)	0	0	34.645	40.287	0
10	**A10**	**1.0000**	0.405	0.005	0.002	0.004	0	[1]					
11	A11	0.8557	0	0.019	0	0	0.006	7 (0.589), 12 (0.411)	0.325	0	25.487	24.303	0
12	**A12**	**1.0000**	0.005	0.018	0	0.003	0.005	[1]					
13	**A13**	**1.0000**	0.995	0	0	0.253	0	[0]					
14	A14	0.9879	0.776	0	0.012	0	0	8 (0.616), 10 (0.384)	0	12.205	0	18.619	59.561
15	A15	0.3249	0.208	0.001	0.005	0.014	0.027	7 (0.537), 16 (0.463)	0	0	40.652	32.392	73.075
16	**A16**	**1.0000**	0.679	0.002	0.021	0	0	[3]					

Table 6-2: EMS Results – Contract A – Output Orientation – No weight restriction

DMU No.	DMU Name	Efficiency Score	Variable Weights					Benchmarks	Variable Slacks				
			SR	CC	RE	SH	EE		SR	CC	RE	SH	EE
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
1	A1	2.0833	0.006	0.016	0	0	0.01	12 (1.000)	1.488	7.693	5.664	11.938	0
2	A2	2.4872	0.994	0	0	0.414	0.004	8 (0.663), 10 (0.003), 13(0.334)	0	105.166	4.161	0	0
3	A3	1.5263	1	0	0	0	0.026	6 (1.000)	0	46.904	3.924	0.138	0
4	A4	2.1380	0.073	0.007	0.006	0	0.01	10 (0.072), 12 (0.928)	2.566	40.933	0	16.304	0
5	A5	2.0407	0.248	0.005	0.005	0	0.01	10 (0.020), 12 (0.980)	0.627	38.881	0	17.111	0
6	**A6**	**1.0000**	0.995	0	0.209	0.006	0	[1]					
7	**A7**	**1.0000**	0.07	0.023	0.003	0.009	0.002	[1]					
8	**A8**	**1.0000**	0.756	0.001	0.001	0.017	0.005	[2]					
9	A9	1.5625	0.1	0.003	0	0	0.008	12 (1.000)	2.587	150.603	8.957	18.074	0
10	**A10**	**1.0000**	0	0.016	0.005	0	0	[5]					
11	A11	1.2197	0	0.019	0	0	0.006	7 (0.117), 12 (0.883)	0.622	0	12.355	0.594	0
12	**A12**	**1.0000**	0.416	0.008	0	0	0.005	[6]					
13	**A13**	**1.0000**	0.986	0	0	0.252	0	[1]					
14	A14	1.0520	0.776	0	0.012	0	0	8 (0.594), 10 (0.406)	0	16.098	0	19.804	52.544
15	A15	5.8445	0.13	0.002	0.016	0	0.028	10 (0.012), 12 (0.988)	2.583	164.897	0	3.602	0
16	**A16**	**1.0000**	0.655	0.002	0.021	0	0	[0]					

In Table 6-1 and 6-2, the first column shows the reference number of the DMU in this analysis, and the second column shows the code for the DMUs (contractors) under evaluation. Column (3) shows the DEA efficiency score calculated by EMS. As mentioned, for input orientation, the efficiency scores are in the range of 0 to 1.0 and DMUs with score of 1.0 are considered efficient. For output orientation, the efficiency scores are equal or greater than 1.0 with 1.0 as the score of efficient DMUs.

The next five columns (4-8) show the weights assigned to the inputs and outputs by EMS in the analysis. In this stage, the weights are optimized by the DEA mechanism to maximize the efficiency scores of each DMU. In column (9), for inefficient DMUs, it shows the "benchmarks" or reference DMUs (by contractor reference number – column 1) with corresponding intensities (the lambdas - λ) in brackets; for efficient DMUs, it shows the number of inefficient DMUs that have chosen this DMU as "benchmark" in square bracket. Columns (10) to (14) show the slacks variables applied to the inputs and outputs.

With the obtained results of the efficiency scores and slacks, it is now possible to identify the sources and amount of any inefficiency that may be present. The target values of inputs and outputs for inefficient DMUs to approach the efficient frontier can be determined as follow:

- For Input Orientation:

$$X_i * \theta - s_i^- = \hat{X}_i \qquad\qquad Y_r + s_i^+ = \hat{Y}_r$$

- For Output Orientation:

$$X_i - s_i^- = \hat{X}_i \qquad\qquad Y_r * \phi + s_i^+ = \hat{Y}_r$$

where:

X_i: Value of input i of inefficient DMU

$\hat{X}_i$: Value of input i to make DMU efficient

s_i^- : Slack value on input i

θ : Input-oriented Efficiency score

Y_r : Value of output r of inefficient DMU

$\hat{Y}_r$: Value of output r to make DMU efficient

s_i^+ : Slack value on output r

ϕ : Output-oriented Efficiency score

The analysis was done on all 10 contracts and the results are summarized in Table 6-3 and 6-4 for input-oriented and output-oriented cases, respectively.

Table 6-3: Efficiency Scores – DEA Stage I (No weight restriction) – Input Oriented

Number of Contractor	Contracts									
	A	B	C	D	E	F	G	H	I	J
1	0.618	0.880	0.348	1.000	1.000	1.000	1.000	0.999	0.864	0.886
2	0.994	0.994	0.999	1.000	1.000	1.000	1.000	1.000	1.000	0.276
3	0.999	1.000	0.999	1.000	1.000	0.588	0.940	0.999	0.619	1.000
4	0.399	0.559	0.406	1.000	0.495	0.758	0.995	0.999	0.655	1.000
5	0.654	1.000	1.000	0.650	0.752	1.000	1.000	0.438	1.000	1.000
6	1.000	0.752	1.000	0.370	1.000	1.000	0.657	0.999	0.722	0.826
7	1.000	0.363	1.000	1.000	0.999	0.410	1.000	0.999	1.000	0.489
8	1.000	0.704	1.000	1.000	1.000	0.932	0.470	1.000	0.756	0.686
9	0.330	1.000	1.000	0.849	0.999	0.951	0.290	0.546	0.757	1.000
10	1.000	0.999	0.526	0.759	0.751	1.000	0.936	1.000	1.000	0.797
11	0.856	0.489	0.657	0.550	1.000	0.693	1.000	0.551	0.889	1.000
12	1.000	0.983	1.000	1.000	0.683	0.434	0.999	0.390	0.921	1.000
13	1.000	0.525	1.000	1.000	0.677	0.760	1.000	0.999	1.000	0.252
14	0.988	0.734	1.000	0.999	0.809	0.779	0.459	0.999	1.000	0.741
15	0.325	1.000	0.251	1.000	0.772	0.747	0.824	0.816	0.939	1.000
16	1.000	0.781			0.811		0.689	1.000	1.000	0.675
17		1.000			0.705		1.000	0.943	0.872	0.508
18		1.000			0.497		0.999	0.999		0.378
19					0.863		0.651	0.841		1.000
20							0.627			0.642
Mean	0.82	0.82	0.81	0.88	0.83	0.80	0.83	0.87	0.88	0.78
S.D.	0.265	0.215	0.287	0.204	0.172	0.205	0.228	0.215	0.132	0.248
Max	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Min	0.32	0.36	0.25	0.37	0.50	0.41	0.29	0.39	0.62	0.23
# of Eff.	7	6	8	9	6	5	7	4	7	8
% Eff.	0.438	0.333	0.533	0.600	0.316	0.333	0.350	0.211	0.412	0.400

Table 6-4: Efficiency Scores – DEA Stage I (No weight restriction) – Output Oriented

Number of Contractor	Contracts									
	A	B	C	D	E	F	G	H	I	J
1	2.08	1.06	4.75	**1.00**	**1.00**	**1.00**	**1.00**	1.61	1.61	1.23
2	2.49	2.04	1.51	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	2.95
3	1.53	**1.00**	2.01	**1.00**	**1.00**	4.10	1.68	4.43	4.99	**1.00**
4	2.14	1.85	3.92	**1.00**	2.00	2.09	1.37	1.21	2.03	**1.00**
5	2.04	**1.00**	**1.00**	2.27	1.91	**1.00**	**1.00**	2.61	**1.00**	**1.00**
6	**1.00**	1.79	**1.00**	2.66	**1.00**	**1.00**	1.27	2.95	5.03	2.00
7	**1.00**	1.28	**1.00**	**1.00**	2.26	1.68	**1.00**	3.26	**1.00**	4.04
8	**1.00**	1.50	**1.00**	**1.00**	**1.00**	1.29	2.77	**1.00**	3.03	5.48
9	1.56	**1.00**	**1.00**	1.31	1.51	1.18	2.29	2.23	2.06	**1.00**
10	**1.00**	1.43	3.54	1.84	1.96	**1.00**	1.22	**1.00**	**1.00**	1.46
11	1.22	1.20	2.53	2.76	**1.00**	3.78	**1.00**	1.49	1.63	**1.00**
12	**1.00**	1.05	**1.00**	**1.00**	1.36	2.11	1.11	2.56	1.56	**1.00**
13	**1.00**	1.03	**1.00**	**1.00**	1.48	47.44	**1.00**	4.21	**1.00**	2.42
14	1.05	1.41	**1.00**	1.02	2.43	16.84	2.12	3.82	**1.00**	3.50
15	5.84	**1.00**	8.78	**1.00**	1.71	2.10	1.08	1.43	1.33	**1.00**
16	**1.00**	2.79			1.78		5.05	**1.00**	**1.00**	5.62
17		**1.00**			1.58		**1.00**	1.23	1.65	2.16
18		**1.00**			2.62		1.62	4.96		2.25
19					1.30		2.50	1.04		**1.00**
20							1.70			4.59
Mean	1.68	1.36	2.34	1.39	1.57	5.84	1.64	2.27	1.88	2.28
S.D.	0.536	0.488	2.178	0.654	0.522	12.182	0.978	1.326	1.298	1.569
Max	5.84	2.79	8.78	2.76	2.62	47.44	5.05	4.96	5.03	5.62
Min	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
# of Eff.	7	6	8	9	6	5	7	4	7	8
% Eff.	0.438	0.333	0.533	0.600	0.316	0.333	0.350	0.211	0.412	0.400

From the results, it is observed that the percent of efficient DMUs is in the range of 0.33-0.66 for the input-oriented case and 0.21 to 0.60 in the output-oriented cases. In one contract, the number of efficient DMUs with output-oriented analysis is always equal to that number with input-oriented analysis. This is because a DMU is characterized as efficient with an output orientation if and only if it is also efficient with an input orientation applied to the same data set and vice versa (Charnes et al., 1994).

With input-oriented analysis, the efficiency scores in all the contracts are relatively high (0.78-0.88). An efficiency score of 0.80 implies that it is possible for the contractor to become efficient by reducing the level of input by 20% and still keeping the existing level of outputs.

In the output orientation case, the efficiency scores are in the range of 1.36 to 5.84. Two significantly low efficiency scores were found in contractor F13 (47.44) and F14 (16.84). These are considered as outliners since contractors F13 and F14 both have zero values for the *Employee Experience* output due to failure to provide information of key supervisory personnel assigned to project.

6.2 Stage I - DEA with Weight Constraints

In the last section, the contractors were evaluated by DEA without any weight restrictions. As mentioned earlier, the flexibility of freeing the weights may not produce a "fair" comparison as it allows the contractors to appear their best without controlling of what is most important. The model can be more realistic considering the relative importance of the weights.

The analysis was rerun with a set of weight restrictions recommended by management in this section; variable-returns-to-scale was used. The relative importance of the weights assessed by management was converted into constraints as ratios and added to the basic DEA model to get a refined measure of efficiency. The results were then examined to determine whether the model with weight restrictions improves the accuracy of the evaluation procedure. The mathematical forms of the weight constraints are:

- $\dfrac{v_1(Safety\,Records)}{v_2(CurrentCapacity)} = \dfrac{4}{3}$
- $\dfrac{u_1(RelatedExperience)}{u_2(SalesHistory)} = \dfrac{20}{6}$
- $\dfrac{u_1(RelatedExperience)}{u_3(EmployeeExperience)} = \dfrac{20}{7}$

The vector form of the weight restrictions prepared for the DEA by the EMS software is shown in Table 6-5.

Table 6-5: DEA Weight Restrictions

	SR {I}	CC {I}	RE {I}	SH {O}	EE {O}
SR-CC	1	-1.33333	0	0	0
CC-SR	-1	1.333333	0	0	0
RE-SH	0	0	1	-3.333333	0
SH-RE	0	0	-1	3.333333	0
RE-EE	0	0	1	0	-2.857143
EE-RE	0	0	-1	0	2.8571429

Table 6-6 and 6-7 show the sample result sheet produced by EMS software of DEA with weight restrictions on Contract A for input and output orientation cases.

Table 6-6: EMS Results – Contract A – Input Orientation – With Weight Restrictions

DMU No.	DMU Name	Efficiency Score	Variable Weights					Benchmarks	Variable Slacks		
			SR	CC	RE	SH	EE		RE	SH	EE
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
1	A1	0.6119	0.015	0.015	0.029	0.019	0.008	7 (1.000)	29.937	43.947	46.676
2	A2	0.1458	0.005	0.004	0.039	0.019	0.014	7 (1.000)	33.789	54.968	66.456
3	A3	0.1393	0.005	0.003	0.077	0.069	0.022	7 (1.000)	35.19	44.563	99.756
4	A4	0.3977	0.01	0.01	0.012	0.014	0.008	7 (1.000)	24.4	35.108	49.589
5	A5	0.4193	0.016	0.01	0.025	0.006	0.008	7 (1.000)	18.504	39.876	67.209
6	A6	0.1661	0.006	0.004	0.035	0.02	0.013	7 (1.000)	30.493	53.946	74.445
7	**A7**	**1.0000**	0.025	0.025	0.01	0.003	0.003	[14]			
8	A8	0.2476	0.009	0.006	0.012	0.004	0.005	7 (1.000)	8.069	27.335	5.9
9	A9	0.1917	0.007	0.005	0.063	0.052	0.005	7 (1.000)	27.656	43.666	27.054
10	**A10**	**1.0000**	0.019	0.015	0.003	0.001	0.001	[1]			
11	A11	0.7290	0.018	0.018	0.015	0.005	0.005	7 (1.000)	22.505	20.382	11.741
12	A12	0.7164	0.027	0.018	0.01	0.003	0.004	7 (1.000)	0.26	15.296	2.258
13	A13	0.2119	0.008	0.005	0.022	0.006	0.009	7 (1.000)	34.107	48.133	27.805
14	A14	0.3180	0.011	0.007	0.008	0.002	0.003	7 (0.841), 10 (0.159)	0	0	0
15	A15	0.1794	0.007	0.004	0.061	0.02	0.023	7 (1.000)	31.307	50.002	103.264
16	A16	0.3637	0.013	0.009	0.013	0.004	0.004	7 (1.000)	3.59	25.15	16.947

Table 6-7: EMS Results – Contract A – Output Orientation – With Weight Restrictions

DMU No.	DMU Name	Efficiency Score	Variable Weights					Benchmarks	Variable Slacks	
			SR	CC	RE	SH	EE		SR	CC
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
1	A1	7.407	0.02	0.015	0.026	0.008	0.009	10 (1.000)	0.001	0.672
2	A2	11.55	0.134	0.003	0.04	0.012	0.014	10 (1.000)	1.615	209.83
3	A3	20.00	0.04	0.003	0.07	0.021	0.025	10 (1.000)	2.546	221.52
4	A4	6.177	0.023	0.009	0.022	0.006	0.008	10 (1.000)	8.451	24.732
5	A5	6.602	0.015	0.01	0.023	0.007	0.008	10 (1.000)	0.105	30.75
6	A6	11.08	0.035	0.004	0.039	0.012	0.014	10 (1.000)	2.792	174.289
7	**A7**	**1.000**	0.033	0.025	0.01	0.003	0.003	[2]		
8	A8	3.709	0.019	0.006	0.013	0.004	0.005	10 (1.000)	2.637	94.371
9	A9	5.934	0.041	0.004	0.021	0.006	0.007	10 (1.000)	7.692	134.793
10	**A10**	**1.000**	0.02	0.015	0.003	0.001	0.001	[14]		
11	A11	3.293	0.024	0.018	0.016	0.005	0.005	7 (0.402), 10 (0.598)	0	0
12	A12	2.452	0.024	0.018	0.011	0.003	0.004	7 (0.360), 10 (0.640)	0	0
13	A13	6.936	0.209	0.004	0.024	0.007	0.008	10 (1.000)	0.934	124.21
14	A14	2.187	0.035	0.007	0.008	0.002	0.003	10 (1.000)	2.115	71.42
15	A15	18.36	0.206	0.001	0.064	0.019	0.022	10 (1.000)	3.07	155.355
16	A16	3.628	0.04	0.009	0.013	0.004	0.004	10 (1.000)	1.932	43.192

Table 6-8 and 6-9 summarize the DEA analysis results with weight restrictions for all 10 contracts for input-oriented and output-oriented cases, respectively.

Table 6-8: Efficiency Scores – DEA Stage-I (Weight Restrictions) – Input Oriented

Number of Contractor	Contracts									
	A	B	C	D	E	F	G	H	I	J
1	0.612	0.067	0.336	0.057	**1.000**	0.132	0.286	0.093	0.057	0.038
2	0.146	0.091	0.661	0.105	0.281	0.194	0.350	0.763	**1.000**	0.014
3	0.139	**1.000**	0.177	0.654	**1.000**	0.222	0.674	0.108	0.105	**1.000**
4	0.398	0.075	0.225	0.847	0.071	0.422	0.174	0.661	0.084	0.954
5	0.419	0.204	**1.000**	0.223	0.079	0.226	**1.000**	0.415	0.220	0.613
6	0.166	0.083	0.572	0.034	0.654	**1.000**	0.299	0.501	0.272	0.124
7	**1.000**	0.040	**1.000**	0.075	0.034	0.068	0.752	0.374	0.287	0.064
8	0.248	0.047	**1.000**	0.268	0.163	0.130	0.376	**1.000**	0.265	0.047
9	0.192	**1.000**	0.177	0.062	0.083	0.364	0.204	0.505	0.067	0.126
10	**1.000**	0.089	0.309	0.116	0.129	0.165	0.741	**1.000**	**1.000**	0.166
11	0.729	0.078	0.601	0.112	0.046	0.154	0.486	0.415	0.380	0.122
12	0.716	0.153	0.967	0.056	0.577	0.067	0.087	0.326	0.429	0.175
13	0.212	0.075	0.213	**1.000**	0.137	0.164	0.279	0.320	0.168	0.018
14	0.318	0.092	0.107	0.052	0.094	0.277	0.150	0.168	**1.000**	0.098
15	0.179	0.292	0.114	**1.000**	0.089	0.289	0.355	0.727	0.155	0.186
16	0.364	0.311			0.475		0.403	**1.000**	0.102	0.071
17		0.470			0.143		**1.000**	0.866	0.197	0.046
18		0.041			0.058		0.303	0.093		0.050
19					0.060		0.419	0.705		**1.000**
20							0.331			0.176
Mean	0.43	0.23	0.50	0.31	0.27	0.26	0.43	0.53	0.34	0.25
S.D.	0.295	0.301	0.353	0.366	0.315	0.228	0.264	0.311	0.332	0.339
Max	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Min	0.14	0.04	0.11	0.03	0.03	0.07	0.09	0.09	0.06	0.01
# of Eff.	2	2	3	2	2	1	2	3	3	2
% Eff.	0.125	0.111	0.200	0.133	0.105	0.067	0.100	0.158	0.176	0.100

Table 6-9: Efficiency Scores – DEA Stage-I (Weight Restriction) – Output Oriented

Number of Contractor	Contracts									
	A	B	C	D	E	F	G	H	I	J
1	7.407	2.724	12.07	1.424	**1.000**	1.095	2.331	3.234	4.255	15.47
2	11.55	8.121	12.51	4.373	4.041	1.083	6.833	1.157	**1.000**	26.32
3	20.00	**1.000**	48.38	1.108	**1.000**	15.59	3.547	8.042	7.092	**1.000**
4	6.177	11.39	11.27	1.163	12.15	2.110	8.843	1.572	3.310	1.073
5	6.602	3.448	**1.000**	3.098	16.63	6.388	**1.000**	3.081	1.531	2.112
6	11.08	6.947	2.324	3.943	1.480	**1.000**	4.842	5.020	5.492	3.160
7	**1.000**	6.833	**1.000**	4.174	27.27	1.864	1.902	4.884	5.242	13.633
8	3.709	7.521	**1.000**	1.214	6.814	4.494	6.323	**1.000**	3.702	34.30
9	5.934	**1.000**	8.518	1.841	18.46	5.071	6.698	3.292	4.108	5.209
10	**1.000**	7.987	9.207	3.340	4.613	16.45	1.827	**1.000**	**1.000**	4.995
11	3.293	5.611	4.397	3.730	10.62	18.27	6.557	1.941	2.611	3.305
12	2.452	3.106	2.359	2.418	1.658	9.270	10.21	3.069	2.110	6.218
13	6.936	5.214	15.00	**1.000**	11.46	53.58	6.309	5.914	4.276	20.82
14	2.187	1.566	10.24	6.701	6.957	23.95	7.217	5.815	**1.000**	8.018
15	18.36	1.437	23.37	**1.000**	15.28	14.47	3.852	1.720	3.038	3.237
16	3.628	5.356			2.979		12.65	**1.000**	3.621	13.10
17		1.914			8.673		**1.000**	1.993	2.899	17.07
18		4.879			20.293		13.71	8.404		9.801
19					14.820		7.323	1.784		**1.000**
20							5.175			10.44
Mean	6.96	4.78	10.85	2.70	9.80	11.65	5.91	3.36	3.31	10.02
S.D.	5.713	2.970	12.17	1.679	7.517	13.76	3.588	2.345	1.711	9.134
Max	20.00	11.39	48.39	6.70	27.28	53.59	13.71	8.40	7.09	34.30
Min	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
# of Eff.	2	2	3	2	2	1	2	3	3	2
% Eff.	0.125	0.111	0.200	0.133	0.105	0.067	0.100	0.158	0.176	0.100

Comparing the results of the DEA with weight restrictions and the analysis with no restrictions, it is observed that the average efficiency score has reduced from the range of 0.80-0.88 to 0.23-0.53 for input oriented case and 1.36-5.84 to 2.7-11.56 for output-oriented case. With weight restrictions, the DEA in both the input and output-oriented cases produced the same efficient DMUs. The percentage of efficient DMUs has decreased significantly from the range of 33-66% to 6.7-10.0%. This indicates that the discrimination power of DEA was improved with the existence of the weight restrictions.

In contract F, the results from DEA with weight restrictions, both input-oriented and output-oriented, showed only one efficient contractor, F6. This is resulted from the fact that this contractor had extraordinary values of inputs and outputs, especially the *Sales History* and *Current Capacity* variables (See Appendix B).

To verify the improvement of the model with weight restrictions, the results of the basic DEA and the analysis with weight restriction were compared with the results of the actual prequalification performed by PMF. Since the rankings produced by PMF were established by prequalification experts with extensive experience, they were considered accurate and therefore used as the benchmarks for comparison. The comparison of rankings in Contract A is presented in table 6-10 and 6-11 for input and output-oriented cases, respectively.

Table 6-10: Ranking Comparison – Input Orientation

Contractors	PMF 50 Points System		DEA 1 No Weight Restrictions			DEA 2 With Weight Restrictions			DEA2 vs. DEA1		
	Score	*Rank*	*Score*	*Rank*	*DIF.*	*Score*	*Rank*	*DIF.*	Better	Same	Worse
A1	37	16	0.6176	13	3	0.6119	5	11			X
A2	39	15	0.9943	9	6	0.1458	15	0	X		
A3	42	12-13	1.0000	1	11	0.1393	16	-3	X		
A4	42	12-13	0.3995	14	-1	0.3977	7	5			X
A5	43	10-11	0.6536	12	-1	0.4193	6	4			X
A6	43	10-11	1.0000	1	9	0.1661	14	-3	X		
A7	44	3-9	1.0000	1	2	1.0000	1	2		X	
A8	48	1	1.0000	1	0	0.2476	10	-9			X
A9	45	2	0.3296	15	-13	0.1917	12	-10	X		
A10	44	3-9	1.0000	1	2	1.0000	1	2		X	
A11	44	3-9	0.8557	11	-2	0.7290	3	0	X		
A12	44	3-9	1.0000	1	2	0.7164	4	0	X		
A13	44	3-9	1.0000	1	2	0.2119	11	-2		X	
A14	44	3-9	0.9879	10	-1	0.3180	9	0	X		
A15	44	3-9	0.3249	16	-7	0.1794	13	-4	X		
A16	41	14	1.0000	1	13	0.3637	8	6	X		
					Sum=75			Sum=61			

Table 6-11: Ranking Comparison between DEA1 & DEA2 – Output Orientation

Contractors	PMF 50 Points System		DEA 1 No Weight Restrictions			DEA 2 With Weight Restrictions			DEA2 vs. DEA1		
	Score	*Rank*	*Score*	*Rank*	DIF.	*Score*	*Rank*	DIF.	*Better*	*Same*	*Worse*
A1	37	16	2.0833	13	3	7.407	12	4			X
A2	39	15	2.4872	15	0	11.555	14	1			X
A3	42	12-13	1.5263	10	2	20.004	16	-3			X
A4	42	12-13	2.1380	14	-1	6.177	9	3			X
A5	43	10-11	2.0407	12	-1	6.602	10	0	X		
A6	43	10-11	1.0000	1	9	11.089	13	-2	X		
A7	44	3-9	1.0000	1	2	1.000	1	2		X	
A8	48	1	1.0000	1	0	3.709	7	-6			X
A9	45	2	1.5625	11	-9	5.934	8	-6	X		
A10	44	3-9	1.0000	1	2	1.000	1	2		X	
A11	44	3-9	1.2197	9	0	3.293	5	0		X	
A12	44	3-9	1.0000	1	2	2.452	4	0	X		
A13	44	3-9	1.0000	1	2	6.936	11	-2		X	
A14	44	3-9	1.0520	8	0	2.187	3	0		X	
A15	44	3-9	5.8445	16	-7	18.363	15	-6	X		
A16	41	14	1.0000	1	13	3.628	6	8	X		
					Sum=53			Sum=45			

The detailed result comparison of Contracts B to F is presented in Appendix C. Comparison for contracts G, H, I, and J was not carried out due to the unavailability of prequalification results by PMF. Final results of ranking differences for contracts A to F are summarized in Table 6-12.

Table 6-12: Comparison of ranking difference between DEA1 & DEA2 (Contracts A-F)

Contract	DEA 1 No Weight Restrictions		DEA 2 With Weight Restrictions	
	Input-Oriented	*Output-Oriented*	*Input-Oriented*	*Output-Oriented*
A	75	53	53	45
B	72	60	62	55
C	65	57	68	55
D	71	60	45	48
E	95	67	69	37
F	59	43	51	33
Sum	**437**	**363**	**348**	**302**

The results of the comparison confirmed the improvement of the DEA model with the weight restrictions. For all six contracts (A to F), the rankings of PMF were better approximated by the output-oriented model with the weight restrictions. The absolute difference in rankings between the PMF's system and DEA had been reduced by an average of 15% with the incorporation of the weight restrictions. The use of DEA in contractor prequalification has the potential of eliminating bias from the decision maker (Ramani, 2000). The inclusion of the weight restriction in the DEA model, however, can be considered as a reasonable subjectivity of the process since it is logical and practical to evaluate the variables at their perceived importance to the project.

In the proposed model, it is believed to be more appropriate to use output orientation when comparing contractors. This is because the model was dominated by outputs, and these outputs, in reality, have the much greater effect on the prequalification decision. As observed from the prequalification scoring system of PMF, the combination mark for the three selected outputs (*Related Experience*, *Sales History* and *Employee Experience*) takes the majority of 32 out of 50 marks.

The ranking results of DEA-2 were also compared to the results obtained by Ramani (2000) using the UTCPM model. Table 6-13 shows the ranking comparison of UTCPM and DEA-2 with respect to PMF's results for Contract A.

Table 6-13: Ranking Comparison between UTCPM & DEA2 – Output Orientation

Contractors	PMF 50 Points System		UTCPM No Weight Restrictions			DEA 2 With Weight Restrictions			DEA2 vs. UTCPM		
	Score	*Rank*	*Score*	*Rank*	*DIF.*	*Score*	*Rank*	*DIF.*	*Better*	*Same*	*Worse*
A1	37	16	2.083	13	3	7.407	12	4			X
A2	39	15	2.490	15	0	11.555	14	1			X
A3	42	12-13	1.500	10	2	20.004	16	-3			X
A4	42	12-13	2.129	14	-1	6.177	9	3			X
A5	43	10-11	2.045	12	-1	6.602	10	0	X		
A6	43	10-11	1.000	1	9	11.089	13	-2	X		
A7	44	3-9	1.207	8	0	1.000	1	2			X
A8	48	1	1.000	1	0	3.709	7	-6	X		
A9	45	2	1.563	11	-9	5.934	8	-6	X		
A10	44	3-9	1.000	1	2	1.000	1	2		X	
A11	44	3-9	1.253	9	0	3.293	5	0		X	
A12	44	3-9	1.000	1	2	2.452	4	0	X		
A13	44	3-9	1.000	1	2	6.936	11	-2		X	
A14	44	3-9	1.052	6	0	2.187	3	0		X	
A15	44	3-9	5.779	16	-7	18.363	15	-6	X		
A16	41	14	1.075	7	7	3.628	6	8			X
					Sum=45			**Sum=45**			

Final results of ranking differences between UTCPM and DEA-2 model for contracts A to F are summarized in Table 6-14.

Table 6-14: Comparison of ranking difference - UTCPM & DEA2 (Output-Oriented)

Contracts	UTCPM (No weight restrictions)	DEA-2 (With weight restrictions)
A	45	45
B	62	55
C	56	55
D	77	48
E	69	37
F	50	33
Sum	**359**	**273**

From Table 6-14, it was observed that the DEA-2 model had approximated the PMF's ranking better than the UTCPM model. The two models produced similar results in contracts A and C, but DEA-2 showed significant improvements in the other four contracts. With the incorporation of the new variable (*Current Capacity*) and the weight restrictions, the UTCPM model is believed to be able to prequalify contractors at a higher degree of precision.

6.3 Stage II - Finding new Units

The objective of this stage was to determine the value of possible improvement in inputs and outputs of efficient contractors evaluated in Stage-I. This was done by using the "P-DEA+" model and the obtained management opinion on the input/output allowable ranges of variation, and the possible increase in efficiency of best practice contractors.

P-DEA+ is a linear programming model proposed for establishing the contractor practical frontier. P-DEA+ was adapted from the P-DEA model developed by Sowlati (2001) with one modification. The mathematical notations of the model are presented in Equation 6-1.

$$\text{Max} \quad \sum_{r=1}^{s} p_r + u_o \qquad \text{(EQ 6-1)}$$

s.t.

1. $\sum_{i=1}^{m} q_i = 1,$

2. $\sum_{r=1}^{s} u_r y_{rj} + u_o - \sum_{i=1}^{m} v_i x_{ij} \leq 0, \qquad \forall j,$

3. $\boxed{\sum_{r=1}^{s} u_r y_{ro} + u_o - \sum_{i=1}^{m} v_i x_{io} = 0}$

4. $\sum_{r=1}^{s} p_r + u_o - \sum_{i=1}^{m} q_i \geq 0,$

5. $\sum_{r=1}^{s} p_r + u_o - \sum_{i=1}^{m} q_i (1+\delta) \geq 0,$

6. $v_i.L_{xio} \leq q_i \leq v_i.U_{xio}$, $\forall i$,

7. $u_r.L_{yro} \leq p_r \leq u_r.U_{yro}$, $\forall r$,

8. $u_r, v_i \geq \varepsilon$ r = 1,...,s i = 1,...,m

9. u_o free

The addition of constraint #3 was the modification made to the P-DEA model. The objective of the model is to determine the weights and value of inputs and outputs that maximizes the efficiency of the unit under evaluation within an upper limit (δ). The unit under evaluation originally has the efficiency score of 1.0 and the new DMU developed from it will therefore have an efficiency score within the range of 1.0 and 1.0+δ.

Constraint #2 was applied into the model to ensure that the efficiency of all DMUs will not exceed 1.0 with the determined weights. This constraint (#2), however, allows the original efficient DMU under evaluation to have an efficiency score of less than 1.0 and eventually permits the difference in efficiency between the original DMU and the new artificial DMU to be more than δ, the upper limit value. Constraint #3, therefore, was included in the model to enforce the restriction of δ by controlling the efficiency score of the original efficient DMU under evaluation to be 1.0.

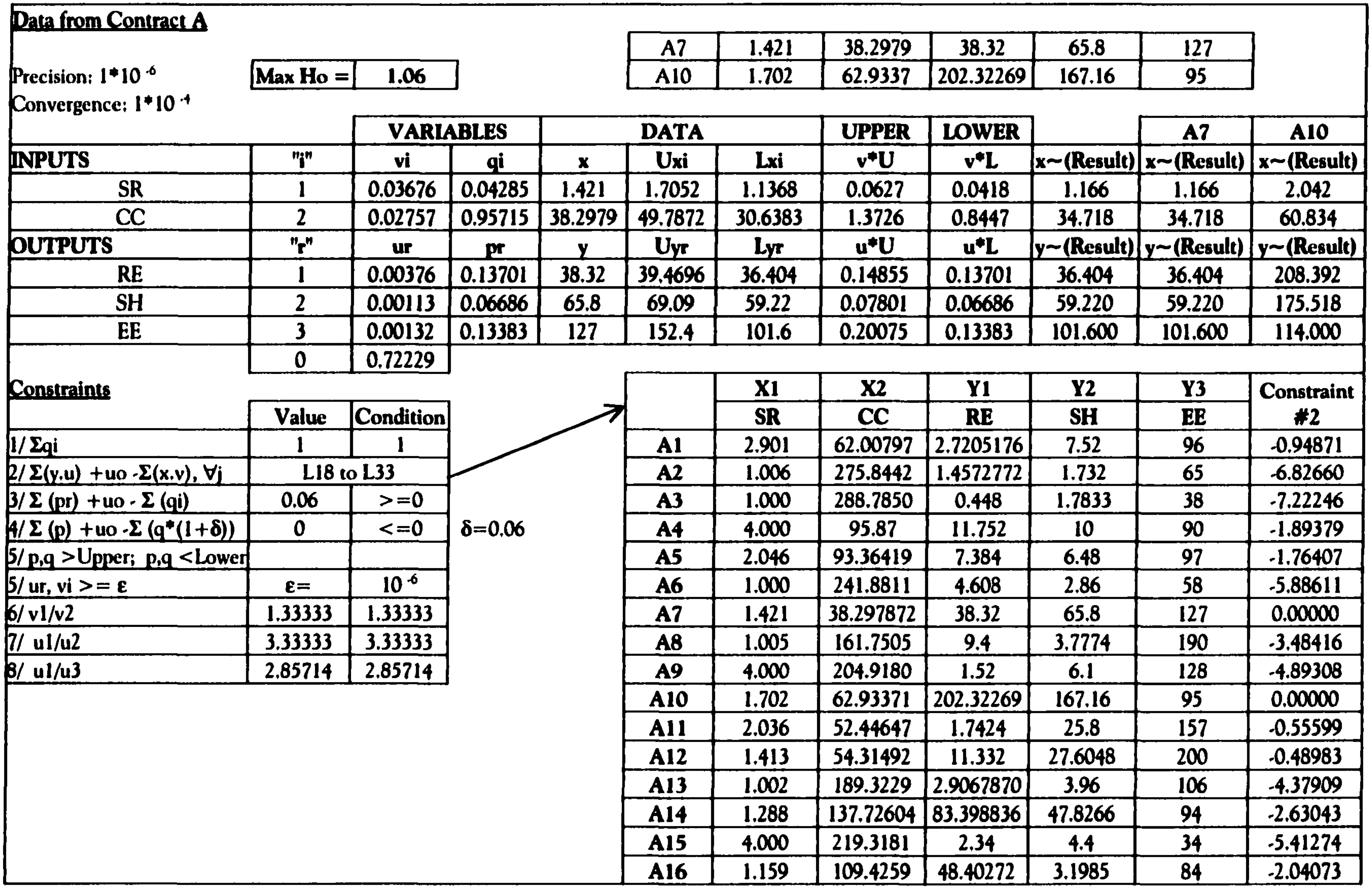
Examination had been done on both models with and without constraint #3. The results validated the modification by showing that the efficiency improvement of new artificial DMU evaluated by model with constraint #3 was within the range of δ (6% in this case), while model without constraint #3 allowed improvement up to 30%.

The P-DEA+ model was then incorporated with the obtained management opinions to find the inputs and outputs of the new DMUs. The parameters to be substituted in the model were the possible increase in efficiency of best practice units (δ), and the allowable ranges of variation of inputs and outputs ($L_{xio} \le \tilde{x}_{io} \le U_{xio}$, $L_{yro} \le \tilde{y}_{ro} \le U_{yro}$). The mathematical formats of the parameters are shown below:

- $\delta=0.06$
- Safety Records: $(1-0.20)*x_{io} \le \tilde{x}_{io} \le (1+0.20)*x_{io}$
- Current Capacity: $(1-0.20)*x_{io} \le \tilde{x}_{io} \le (1+0.30)*x_{io}$
- Related Experience: $(1-0.05)*y_{io} \le \tilde{y}_{io} \le (1+0.03)*y_{io}$
- Sales History: $(1-0.10)*y_{io} \le \tilde{y}_{io} \le (1+0.05)*y_{io}$
- Employee Experience: $(1-0.20)*y_{io} \le \tilde{y}_{io} \le (1+0.20)*y_{io}$

The proposed P-DEA+ model was then solved for each efficient contractor, which had scored 1.0 in the DEA Stage-I (DEA with weight restrictions). Excel's solver was used to execute the P-DEA+ linear programming for all ten contracts. Excel's solver was used as the inverse mechanism of EMS; it was able to determine the new values of inputs and outputs from a maximum efficiency score value by optimizing the weights. The weight restrictions used in DEA Stage-I were also included in the solver as constraints. A sample of Excel's solver calculation sheet is presented in Figure 6-1.

Figure 6-1: Sample Excel's solver calculation sheet – Contract A



Data from Contract A

Precision: $1*10^{-6}$

Convergence: $1*10^{-4}$

Max Ho =	1.06

A7	1.421	38.2979	38.32	65.8	127
A10	1.702	62.9337	202.32269	167.16	95

		VARIABLES		DATA			UPPER	LOWER		A7	A10
INPUTS	"i"	vi	qi	x	Uxi	Lxi	v*U	v*L	x~(Result)	x~(Result)	x~(Result)
SR	1	0.03676	0.04285	1.421	1.7052	1.1368	0.0627	0.0418	1.166	1.166	2.042
CC	2	0.02757	0.95715	38.2979	49.7872	30.6383	1.3726	0.8447	34.718	34.718	60.834
OUTPUTS	"r"	ur	pr	y	Uyr	Lyr	u*U	u*L	y~(Result)	y~(Result)	y~(Result)
RE	1	0.00376	0.13701	38.32	39.4696	36.404	0.14855	0.13701	36.404	36.404	208.392
SH	2	0.00113	0.06686	65.8	69.09	59.22	0.07801	0.06686	59.220	59.220	175.518
EE	3	0.00132	0.13383	127	152.4	101.6	0.20075	0.13383	101.600	101.600	114.000
	0	0.72229									

Constraints

	Value	Condition
1/ Σqi	1	1
2/ Σ(y.u) +uo -Σ(x.v), ∀j	L18 to L33	
3/ Σ (pr) +uo - Σ (qi)	0.06	>=0
4/ Σ (p) +uo -Σ (q*(1+δ))	0	<=0
5/ p,q >Upper; p,q <Lower		
5/ ur, vi >= ε	ε=	10^{-6}
6/ v1/v2	1.33333	1.33333
7/ u1/u2	3.33333	3.33333
8/ u1/u3	2.85714	2.85714

δ=0.06

	X1	X2	Y1	Y2	Y3	Constraint #2
	SR	CC	RE	SH	EE	
A1	2.901	62.00797	2.7205176	7.52	96	-0.94871
A2	1.006	275.8442	1.4572772	1.732	65	-6.82660
A3	1.000	288.7850	0.448	1.7833	38	-7.22246
A4	4.000	95.87	11.752	10	90	-1.89379
A5	2.046	93.36419	7.384	6.48	97	-1.76407
A6	1.000	241.8811	4.608	2.86	58	-5.88611
A7	1.421	38.297872	38.32	65.8	127	0.00000
A8	1.005	161.7505	9.4	3.7774	190	-3.48416
A9	4.000	204.9180	1.52	6.1	128	-4.89308
A10	1.702	62.93371	202.32269	167.16	95	0.00000
A11	2.036	52.44647	1.7424	25.8	157	-0.55599
A12	1.413	54.31492	11.332	27.6048	200	-0.48983
A13	1.002	189.3229	2.9067870	3.96	106	-4.37909
A14	1.288	137.72604	83.398836	47.8266	94	-2.63043
A15	4.000	219.3181	2.34	4.4	34	-5.41274
A16	1.159	109.4259	48.40272	3.1985	84	-2.04073

Table 6-15 summarizes the results of P-DEA+ calculations on all ten contracts. The inputs and outputs of new contractors are presented along with the original efficient DMUs upon which the new DMUs, denoted by N, were based.

Table 6-15: Inputs and Outputs of new DMUs.

	Contractor	SR {I}	CC {I}	RE {O}	SH {O}	EE {O}
Contract A	A7	1.421	38.2978	38.32	65.8	127
	A7N	1.1655	34.7175	36.40373	59.22	101.6
	A10	1.702	62.9337	202.3227	167.16	95
	A10N	2.0424	60.8343	208.3924	175.518	114
Contract B	B3	1.216	9.6220	22.2	133.6	71
	B3N	1.000	9.4570	21.09	140.28	85.2
	B9	1.645	13.3020	159.84	127.8	49
	B9N	1.974	11.8748	151.848	134.19	58.8
Contract C	C5	1.702	69.8133	282.0915	167.16	90
	C5N	2.0424	68.2992	290.3602	175.518	108
	C7	1.659	23.1119	1.76	15.36	102
	C7N	1.9908	21.7783	1.8128	16.128	122.4
	C8	1.435	35.7050	106.3227	38.72	177
	C8N	1.722	35.4284	109.5124	40.656	212.4
Contract D	D13	1.491	7.46234	8.8	258.9	46
	D13N	1.1928	5.9698	9.064	244.4367	55.2
	D15	1.314	24.4318	24.64	228.8	55
	D15N	1.5768	22.2288	25.3792	238.3902	44

	Contractor	SR {I}	CC {I}	RE {O}	SH {O}	EE {O}
Contract E	E1	1.216	10.3705	11.688	133.6	74
	E1N	1.000	8.2964	11.5303	120.24	59.5489
	E3	1.109	103.9185	507.52	127.6	42
	E3N	1.000	101.7803	522.7456	133.98	50.4
Contract F	F6	1.427	19.2053	85.6687	1546.446	143
	F6N	1.7124	15.4806	86.3143	1391.801	166.1014
Contract G	G5	1.417	76.0947	241.5143	167.16	88
	G5N	1.7004	70.4465	248.7597	150.444	70.4
	G17	2.026	27.9283	24.64	228.8	69
	G17N	1.6208	26.1617	23.4078	240.24	55.2
Contract H	H8	1.492	37.475	8	70.58	24
	H8N	1.1938	35.6170	7.6	74.109	21.1442
	H10	1.000	41.5761	31.264	82.86	48
	H10N	1.000	44.6562	29.7008	87.0030	56.7838
	H16	1.350	83.3333	40.656	24.6	128
	H16N	1.62	108.3333	41.8756	25.5956	148.659
Contract I	I2	1.552	7.9032	16.448	142.98	224
	I2N	1.2416	6.3225	15.6256	150.129	219.0126
	I10	1.702	88.2866	86.296	167.16	68
	I10N	2.0424	114.0748	68.2041	128.6819	179.2
	I14	1.908	7	3.424	74	68
	I14N	2.2896	5.7138	3.5267	70.2490	81.6
Contract J	J3	1.552	134.6902	483.232	142.98	162
	J3N	1.8624	132.1356	497.729	128.682	194.4
	J19	1.314	4.4973	9.32	228.8	89
	J19N	1.5768	5.4690	8.854	235.6596	102.8739

6.4 Stage III - Establishing the Practical Frontier

The objective of this stage was to run the DEA again with both the original contractors and the new contractors to define the practical efficient frontier. This new frontier may be formed by both the old efficient DMUs and the new DMUs. The Stage-III DEA was done on all ten contracts and the same weight restrictions used before were considered.

In this stage, the input-oriented DEA was used instead of the output-oriented analysis. As mentioned earlier, output-orientation was used in Stage-I for the comparison purpose because it focused on the variables that are essential to the prequalification ranking, the outputs. The objective in Stage-III, in the other hand, is to establish a practical frontier or the target for improvement for both efficient and inefficient contractors. According to management opinion, improvement in the outputs (*Related Experience, Sales History, Employee Experience*) is difficult to achieve in a short period of time. The value of inputs is not likely to be improved significantly after one construction season (Nicholls, 2002). The possible and practical improvements, therefore, can only be achieved by reducing the inputs (*Safety Records and Current Capacity*). Input-oriented DEA, with the goal of producing the existing outputs with a minimum resource level, provides the results that identify the sources and magnitude of possible reduction in inputs. The selection of input orientation is then believed to be appropriate in this situation.

With the availability of the new artificial contractors established in Stage-II, the DEA Stage-III analysis with Output Orientation, on the other hand, can be useful for other applications. The set of artificial and original contractors can be used as an efficient yardstick to evaluate a new contractor within the same work category. DEA Stage-III with Output Orientation can be performed on the combined group of the new and the available contractors to evaluate the performance of the new contractors with respect to others in the industry. If any of the new contractors gets a score of 1.0, it will be efficient and makes an update on the practical frontier of best practice contractors; if not, it will expand the contractor database for further use.

Table 6-16 and 6-17 show DEA Stage-III sample result sheets calculated by EMS for contract A with input orientation and output orientation, respectively. Table 6-18 and 6-19 summarize the DEA Stage-III results with input orientation and output orientation for all ten contracts.

Table 6-16: Stage-III DEA Results – Contract A – Input Orientation

DMU No.	DMU Name	Efficiency Score	Variable Weights					Benchmarks	Variable Slacks		
			SR	CC	RE	SH	EE		RE	SH	EE
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
1	A1	0.5506	0.02	0.015	0.026	0.008	0.009	17 (1.000)	21.834	39.967	49.512
2	A2	0.1309	0.005	0.004	0.04	0.016	0.014	17 (1.000)	30.448	44.788	60.339
3	A3	0.1250	0.005	0.003	0.066	0.029	0.024	17 (1.000)	31.299	42.082	90.065
4	A4	0.3584	0.013	0.01	0.021	0.007	0.008	17 (1.000)	17.198	37.91	42.59
5	A5	0.3775	0.014	0.01	0.02	0.007	0.008	17 (1.000)	22.217	33.884	40.199
6	A6	0.1491	0.005	0.004	0.038	0.014	0.014	17 (1.000)	28.129	44.033	64.643
7	**A7**	**0.9435**	0.033	0.025	0.01	0.003	0.003	17 (0.939), 18 (0.061)	0	0	0
8	A8	0.2224	0.008	0.006	0.013	0.004	0.005	17 (1.000)	6.006	16.327	5.122
9	A9	0.1725	0.006	0.005	0.02	0.016	0.007	17 (1.000)	11.012	28.528	62.883
10	**A10**	**0.9446**	0.02	0.015	0.003	0.001	0.001	17 (0.072), 18 (0.928)	0	0	0
11	A11	0.6576	0.024	0.018	0.015	0.005	0.005	17 (1.000)	14.821	18.588	14
12	A12	0.6454	0.024	0.018	0.011	0.003	0.004	17 (1.000)	0.074	0.082	0.051
13	A13	0.1902	0.007	0.005	0.024	0.009	0.008	17 (1.000)	22.857	27.748	49.582
14	A14	0.2980	0.01	0.007	0.008	0.002	0.003	17 (0.806), 18 (0.194)	0	0	0
15	A15	0.1615	0.006	0.004	0.062	0.028	0.021	17 (1.000)	30.774	42.681	87.404
16	A16	0.3269	0.012	0.009	0.013	0.004	0.004	17 (1.000)	1.928	17.131	11.145
17	[redacted]	[redacted]	0.037	0.028	0.011	0.003	0.004	[16]			
18	[redacted]	[redacted]	0.021	0.016	0.003	0.001	0.001	[3]			

Table 6-17: Stage-III DEA Results – Contract A – Output Orientation

DMU No.	DMU Name	Efficiency Score	Variable Weights					Benchmarks	Variable Slacks	
			SR	CC	RE	SH	EE		SR	CC
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
1	A1	7.8013	0.026	0.015	0.026	0.008	0.009	18 (1.000)	0.301	1.917
2	A2	12.170	0.015	0.004	0.04	0.012	0.014	18 (1.000)	15.601	192.827
3	A3	21.070	0.052	0.003	0.07	0.021	0.025	18 (1.000)	2.566	223.14
4	A4	6.5067	0.02	0.01	0.022	0.006	0.008	18 (1.000)	3.017	33.623
5	A5	6.9538	0.035	0.01	0.023	0.007	0.008	18 (1.000)	1.492	30.545
6	A6	11.680	0.539	0.002	0.039	0.012	0.014	18 (1.000)	1.133	178.146
7	**A7**	**1.1714**	0.033	0.025	0.01	0.003	0.003	17 (0.856), 18 (0.144)	0	0
8	A8	3.9067	0.01	0.006	0.013	0.004	0.005	18 (1.000)	5.285	92.486
9	A9	6.2502	0.045	0.004	0.021	0.006	0.007	18 (1.000)	5.128	139.857
10	**A10**	**1.0533**	0.02	0.015	0.003	0.001	0.001	18 (1.000)	0.626	0.811
11	A11	3.6620	0.024	0.018	0.016	0.005	0.005	17 (0.308), 18 (0.692)	0	0
12	A12	2.7226	0.024	0.018	0.011	0.003	0.004	17 (0.270), 18 (0.730)	0	0
13	A13	7.3055	0.01	0.005	0.024	0.007	0.008	18 (1.000)	6.027	119.065
14	A14	2.3035	0.055	0.007	0.008	0.002	0.003	18 (1.000)	1.431	73.978
15	A15	19.341	0.248	0	0.064	0.019	0.022	18 (1.000)	2.779	157.389
16	A16	3.8210	0.019	0.009	0.013	0.004	0.004	18 (1.000)	2.001	44.746
17	[redacted]	[redacted]	0.037	0.028	0.011	0.003	0.004	[3]		
18	[redacted]	[redacted]	0.021	0.016	0.003	0.001	0.001	[16]		

Table 6-18: Efficiency Scores – Stage-III DEA – Input Oriented

DMU	A	B	C	D	E	F	G	H	I	J
1	0.5506	0.0633	0.3249	0.0444	**0.9434**	0.1104	0.2544	0.0869	0.0522	0.0364
2	0.1309	0.0857	0.6352	0.0821	0.2226	0.1623	0.3212	0.6957	**0.9656**	0.0136
3	0.1250	**0.9597**	0.1696	0.2220	**0.9436**	0.1853	0.6188	0.1008	0.0961	**0.9434**
4	0.3584	0.0708	0.2162	0.6724	0.0559	0.3531	0.1595	0.6332	0.0770	0.8680
5	0.3775	0.1929	**1.0000**	0.1754	0.0627	0.1886	**1.0000**	0.3908	0.2054	0.6034
6	0.1491	0.0780	0.5253	0.0264	0.6088	**1.0000**	0.2738	0.4699	0.2497	0.1041
7	**0.9435**	0.0376	**0.9676**	0.0587	0.0269	0.0567	0.6907	0.3508	0.2621	0.0617
8	0.2224	0.0440	**0.9434**	0.2111	0.1291	0.1080	0.3457	**0.9442**	0.2431	0.0456
9	0.1725	**1.0000**	0.1688	0.0483	0.0659	0.3040	0.1875	0.4758	0.0612	0.1224
10	**0.9446**	0.0838	0.2971	0.0909	0.1187	0.1374	0.6817	**1.0000**	**1.0000**	0.1610
11	0.6576	0.0734	0.5676	0.0875	0.0363	0.1286	0.4455	0.3943	0.3510	0.1184
12	0.6454	0.1445	0.9316	0.0436	0.5383	0.0561	0.0794	0.3062	0.3988	0.1698
13	0.1902	0.0708	0.2038	**0.9434**	0.1086	0.1370	0.2556	0.3002	0.1534	0.0175
14	0.2980	0.0852	0.1023	0.0408	0.0850	0.2317	0.1375	0.1579	**0.9451**	0.0949
15	0.1615	0.2699	0.1091	**1.0000**	0.0705	0.2415	0.3259	0.6949	0.1421	0.1682
16	0.3269	0.2949			0.3784		0.3695	**1.0000**	0.0932	0.0685
17		0.4353			0.1133		**0.9434**	0.8125	0.1806	0.0441
18		0.0390			0.0461		0.2771	0.0870		0.0488
19					0.0478		0.3850	0.6694		**1.0000**
20							0.3040			0.1718
New DMUs (1.000)	A7N	B3N	C5N	D13N	E1N	F6N	G5N	H8N	I2N	J3N
	A10N	B9N	C7N	D15N	E3N		G17N	H10N	I10N	J19N
			C8N					H16N	I14N	
Mean	0.4586	0.3014	0.5646	0.3381	0.3144	0.2750	0.4571	0.5714	0.4238	0.3119
Max	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Min	0.1250	0.0376	0.1023	0.0264	0.0269	0.0561	0.0794	0.0869	0.0522	0.0136
# of Eff.	2	3	4	3	2	2	3	5	4	3
% Eff.	0.1111	0.1500	0.2222	0.1765	0.0952	0.1250	0.1364	0.2273	0.2105	0.1364

Table 6-19: Efficiency Scores – Stage-III DEA – Output Oriented

DMU	A	B	C	D	E	F	G	H	I	J
1	7.801	2.724	12.077	1.424	**1.048**	1.095	2.331	3.538	4.431	16.046
2	12.171	8.121	13.883	4.373	4.613	1.083	6.833	1.169	**1.001**	27.299
3	21.070	**1.235**	48.387	1.108	**1.036**	15.596	3.777	8.800	7.122	**1.037**
4	6.507	11.393	11.279	1.168	13.428	2.110	8.843	1.586	3.445	1.128
5	6.954	3.448	**1.000**	3.098	18.731	6.388	**1.000**	3.196	1.532	2.151
6	11.680	6.947	2.487	3.943	1.604	**1.000**	4.842	5.032	5.497	3.305
7	**1.171**	6.833	**1.405**	4.174	32.103	1.864	2.027	5.264	5.246	14.295
8	3.907	7.521	**1.113**	1.214	7.725	4.494	6.323	**1.367**	3.705	35.572
9	6.250	**1.000**	8.518	1.841	21.535	5.071	6.698	3.300	4.279	5.422
10	**1.053**	7.987	9.207	3.340	4.895	16.451	1.947	**1.000**	**1.000**	5.181
11	3.662	5.611	4.825	3.730	12.285	18.277	6.974	2.039	2.613	3.442
12	2.723	3.106	3.146	2.418	1.771	9.270	10.218	3.358	2.112	6.445
13	7.305	5.214	15.003	**1.003**	13.277	53.585	6.309	6.471	4.278	21.599
14	2.304	1.566	10.244	6.701	7.428	23.953	7.217	6.363	**2.538**	8.371
15	19.341	1.437	23.377	**1.000**	17.261	14.477	3.852	1.741	3.039	3.356
16	3.821	5.356			3.237		12.841	**1.000**	3.653	13.731
17		1.914			10.077		**1.068**	2.026	2.901	17.708
18		4.879			22.668		13.710	9.196		10.297
19					17.236		7.706	1.804		**1.000**
20							5.175			10.820
New DMUs (1.000)	A7N	B3N	C5N	D13N	E1N	F6N	G5N	H8N	I2N	J3N
	A10N	B9N	C7N	D15N	E3N		G17N	H10N	I10N	J19N
			C8N					H16N	I14N	
Mean	6.651	4.415	9.386	2.502	10.188	10.982	5.531	3.239	3.070	9.555
Max	21.070	11.393	48.387	6.701	32.103	53.585	13.710	9.196	7.122	35.572
Min	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
# of Eff.	2	3	4	3	2	2	3	5	4	3
% Eff.	0.111	0.150	0.222	0.176	0.095	0.125	0.136	0.227	0.211	0.136

Table 6-16, Input-oriented DEA results for Contract A, shows the efficiency score of both the real and artificial contractors, the weights used in the analysis, the benchmarks and the slacks for inefficient contractors to approach efficient frontier. It is observed that the new efficiency scores of the two contractors that were efficient in Stage-I, A7 & A10, had been reduced to 94.35% & 94.46%, respectively. While the efficiency score of the artificial contractors are 100%, these results confirmed the effect of the efficiency improvement restriction, δ=6%. Without the δ restriction, maximum efficiency improvement was found to be in the range of 30%. In all ten contracts, similar results were obtained; all new artificial contractors have achieved efficiency improvement in the range of 0% to 6%. A maximum efficiency improvement of 6% is equivalent to the increase from 94.34% to 100% in Stage-III.

Table 6-18, Input-oriented DEA efficiency score, summarizes the efficiency scores for all ten contracts and shows the statistics of the results. It was found that the average efficiency score in all contracts had been increased; this is predictable since the new artificial contractors with high efficiency scores were included in the analysis. The efficiency scores of the individual DMU, however, had been decreased because the presence of these new more efficient DMUs had raised the standard of best practice DMUs. In Stage-III, the number of efficient contractors also increased since all of the new artificial contractors obtained the score of 1.0, and some of the real contractors remained efficient after being evaluated. When a real contractor remains efficient after Stage-III evaluation, there is no further improvement suggested by DEA and this suggests that the contractor is highly efficient. It was notable that the same contractors were characterized as efficient in both the input and output orientation DEA in Stage-III.

After this stage, the contractors that were characterized as efficient by DEA formed the new efficient frontier, the wanted practical frontier. Ten different practical frontiers were developed from the ten contracts for different construction types (see Table 5.1). The frontiers are believed to reflect the industry's standard in the Southern Ontario region since the contracts under evaluation were relatively considerable in magnitude and the most of the contractors involved in the prequalification is representative of the regional market.

7.0 CONCLUSIONS & RECOMMENDATIONS

This chapter provides the conclusions of the research and the recommendations for future development of the proposed methodology. The main findings of the three stages, the practical application and the advantages and disadvantages of the proposed methodology are also discussed.

7.1 Conclusions

Prequalifying contractors in a construction project is a not a simple task since the process involves comparing units with multiple criteria and qualitative information. Data Envelopment Analysis, with its ability to measure the relative performance of organizational units that have multiple inputs and outputs, has been recognized as a feasible solution to the contractor prequalification problem.

The three objectives of this research were to establish an improved contractor prequalification model using DEA, to develop an adaptation of the P-DEA framework for the construction situation, and ultimately to define a procedure that can be used to identify the practical frontier of contractors. A 3-stage methodology that is able to create best-practice benchmarks (practical frontiers) for comparing contractors for a specific project type was successfully established. The first two stages of this methodology, which contain two models (UTCPM modified and P-DEA+), were also the results for the research's first two objectives.

UTCPM, a DEA-based prequalification model has been developed by Ramani (2000). This model has offered a computerizing procedure to compare the contractor's efficiencies and minimize the human biases that exist in the prequalification process. In this research, two modifications were suggested to improve the power and accuracy of the DEA framework in UTCPM. First, the new *Current Capacity* variable was introduced as an additional input to the model, and a formula for calculating this variable was developed with the contribution from management. The second modification was the incorporation of the weight restrictions into the DEA. The modifications were agreed by industry experts and the results found in Stage-I confirmed the improvements.

Stage-I of the proposed methodology therefore can be considered as an update version of the UTCPM model and used as a prequalification tool. The modified DEA model with output orientation was run separately on all ten contracts and the efficient contractors were identified. In each contract, the efficient contractors form an empirical frontier that envelops the inefficient ones. The results from DEA also provide valuable information about improvement sources and targets for inefficient contractors.

In Stage-II, a linear programming model for creating new artificial contractors from the efficient contractors evaluated in Stage-I was presented, the P-DEA+ model. The new "improved" contractors created by this model are believed to be more efficient than their "real" originals. This model was adapted from the P-DEA model that had been developed in the banking context by Sowlati (2001). A new constraint was added to the P-DEA model as an amendment and construction management inputs were collected to replace the parameters in the model. The P-DEA+ model successfully created artificial contractors that have efficiency improvement ranging from 0% to 6% from the original efficient ones where 6% is the possible maximum improvement suggested by management.

In the last stage of the proposed methodology, the practical frontier was established. The real efficient contractors from Stage-I and the artificial contractors found in Stage-II were put together in the DEA. The efficient contractors found in this stage defined the practical frontier. The results of DEA indicated the sources and improvements needed for inefficient contractors to approach the practical frontier. Some efficient contractors from Stage-I, however, were found efficient after Stage-III, still. This suggests that the contractor is highly efficient and no improvement is recommended by DEA.

The results of this stage had in fact established ten practical frontiers for the ten given contracts. The practical frontiers will only be applicable for each different work category because these contracts represent different project types and the prequalification variables (*Related Work* and *Employee Experience*) were specific to the type of work.

The frontiers are believed to reflect the industry's standard in the Southern Ontario region since the contracts under evaluation were relatively considerable in magnitude and the most of the contractors involved in the prequalification is representative of the regional market. The proposed model and analysis results were presented to the experts from whom management opinion were obtained and received positive acceptance.

The practical frontiers can be useful for both the owners and contractors as a regional performance benchmarks. The contractors could use the benchmarks to compare with others and identify possible improvements. Owners could use the benchmarks to compare and evaluate contractors with respect to the regional standard. The practical frontiers can also be helpful to any parties that are interested in the regional contractors' performance.

There are, however, some disadvantages in using the developed practical frontiers. The *Current Capacity* variable used to evaluate the contractors is project specific since it takes into account the project value. The current workload value used in determining the *Current Capacity* variable also changes constantly over time. These issues should be taken into consideration if the practical frontiers are used to compare new contractors. The current workload value at the similar period of time and the same project value and should be used when comparing a new contractor(s).

The other limitation in using the practical frontiers is the requirement of DEA knowledge since the analysis has to be run every time the practical frontier is used to compare with other contractor(s), or Stage-I of the methodology is used for prequalification. In addition, the practical frontiers require a large group of samples (contractors) to be able to represent best practices in the regional industry. The proposed framework, however, could be utilized to its full potential by sophisticated and frequent users such as municipal or governmental departments (e.g. Ministry of Transportation, Builders Association, etc.) where the practical frontiers can be comprehensively developed and regularly updated.

7.2 Recommendations

This research presents a Data Envelopment Analysis framework for contractor prequalification and identifying targets for empirically efficient contractors. The following is a list of recommendations for future work that can be done to enhance the effectiveness and applicability of this methodology.

- The selection of prequalification criteria as variable for the DEA can be modified by adding more variable(s) to improve the accuracy of the prequalification model.
- The evaluated contractor's workload should be the anticipated value at the time the construction begins rather than when the prequalification being made (Current Workload from the CCDC-11).
- The possibility of having multiple solutions for the proposed P-DEA+ model (Stage-II) can be further investigated. This may provide multiple improvement targets for efficient contractors.
- "Window Analysis" (Charnes et al., 1985) can be applied in Stage-III, when the practical frontier is used to compare a new contractor, to eliminate the time variance effect of the *Current Capacity* variable by considering each contractor as a separate one within each period.
- Prequalification information of new contractors can be added to the existing contracts to extend the database and update the practical frontier so it can better represent the regional standard.
- Investigation of other contracts with different work categories can be performed to produce other Practical Frontiers.

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APPENDIX - A

STANDARD CONSTRUCTION PREQUALIFICATION DOCUMENT
CCDC-11 – 1996

CONTRACTOR'S QUALIFICATION STATEMENT

This document is intended to provide information on the capacity, skill, and experience of the Contractor. Applicant may supplement information requested with additional sheets if required.

Project Number: ____________________

Project Title and Location: ____________________

____

1. **Submitted to:**

Firm Name: ____________________

Address: ____________________

Phone: ____________ Fax: ____________ E-mail: ____________

2. **Submitted by:**

Firm Name: ____________________

Address: ____________________

Phone: ____________ Fax: ____________ E-mail: ____________

3. **Legal Structure of Contractor:**

Year Established: _____ Joint Venture _

Corporation _ , Partnership _ , Registered _ , Sole Proprietor _ , Other: ____________

Names and Titles of Officers, Partners, Principal: ____________________

____

____

____

4. **Financial References**

a. Bank Name: ____________________

Location: ____________________

Contact Person(s): ____________________

Phone: ____________ Fax: ____________ E-mail: ____________

b. Bonding Company: ____________________

Location: ____________________

Contact Person(s): ____________________

Phone: ____________ Fax: ____________ E-mail: ____________

5. **Annual value of construction work for the past five years**

Year	Value	Year	Value	Year	Value
_____	$ ______________	_____	$ ______________	_____	$ ______________
_____	$ ______________	_____	$ ______________		

6. **Principal projects completed in the past five years. Listed in Appendix A.**
7. **Similar or related projects completed. Listed in Appendix B.**
8. **Major construction projects underway this date. Listed in Appendix C.**
9. **Key office personnel proposed for the project, attach resume of qualifications and experience:**

   (e.g. Principal in Charge, Project Manager, Estimator, etc)

Name	Title / Position
______________________	______________________
______________________	______________________
______________________	______________________

10. **Key site personnel proposed for the project, attach resume of qualifications and experience:**

    (e.g. Project manager, Superintendent, Foreman, etc)

Name	Title / Position
______________________	______________________
______________________	______________________
______________________	______________________

I declare that the information provided is true and correct to the best of my knowledge.

______________________________ *name and title of contact person*

______________ *date*

Principal projects completed in the past five years. **APPENDIX A**

Project Title and Location: ______________________________

____

Description: ____________________ Project Value: $____________________

Owner: ____________________ Date Completed: ____________________

Refer to: ____________________ Phone: __________ Fax: __________

Consultant: ______________________________

Refer to: ____________________ Phone: __________ Fax: __________

Project Title and Location: ______________________________

____

Description: ____________________ Project Value: $____________________

Owner: ____________________ Date Completed: ____________________

Refer to: ____________________ Phone: __________ Fax: __________

Consultant: ______________________________

Refer to: ____________________ Phone: __________ Fax: __________

Project Title and Location: ______________________________

____

Description: ____________________ Project Value: $____________________

Owner: ____________________ Date Completed: ____________________

Refer to: ____________________ Phone: __________ Fax: __________

Consultant: ______________________________

Refer to: ____________________ Phone: __________ Fax: __________

Project Title and Location: ______________________________

____

Description: ____________________ Project Value: $____________________

Owner: ____________________ Date Completed: ____________________

Refer to: ____________________ Phone: __________ Fax: __________

Consultant: ______________________________

Refer to: ____________________ Phone: __________ Fax: __________

Project Title and Location: ______________________________

____

Description: ______________________ Project Value: $______________

Owner: ______________________ Date Completed: ______________

Refer to: ______________________ Phone: __________ Fax: __________

Consultant: ______________________________

Refer to: ______________________ Phone: __________ Fax: __________

Project Title and Location: ______________________________

____

Description: ______________________ Project Value: $______________

Owner: ______________________ Date Completed: ______________

Refer to: ______________________ Phone: __________ Fax: __________

Consultant: ______________________________

Refer to: ______________________ Phone: __________ Fax: __________

Project Title and Location: ______________________________

____

Description: ______________________ Project Value: $______________

Owner: ______________________ Date Completed: ______________

Refer to: ______________________ Phone: __________ Fax: __________

Consultant: ______________________________

Refer to: ______________________ Phone: __________ Fax: __________

Project Title and Location: ______________________________

____

Description: ______________________ Project Value: $______________

Owner: ______________________ Date Completed: ______________

Refer to: ______________________ Phone: __________ Fax: __________

Consultant: ______________________________

Refer to: ______________________ Phone: __________ Fax: __________

Project Title and Location: ______________________________

____

Description: ______________________ Project Value: $______________

Scheduled Completion Date: ______________ Percent Completed: ____ %

Owner: ______________________________

Refer to: ______________________ Phone: __________ Fax: __________

Consultant: ______________________________

Refer to: ______________________ Phone: __________ Fax: __________

Project Title and Location: ______________________________

____

Description: ______________________ Project Value: $______________

Scheduled Completion Date: ______________ Percent Completed: ____ %

Owner: ______________________________

Refer to: ______________________ Phone: __________ Fax: __________

Consultant: ______________________________

Refer to: ______________________ Phone: __________ Fax: __________

Project Title and Location: ______________________________

____

Description: ______________________ Project Value: $______________

Scheduled Completion Date: ______________ Percent Completed: ____ %

Owner: ______________________________

Refer to: ______________________ Phone: __________ Fax: __________

Consultant: ______________________________

Refer to: ______________________ Phone: __________ Fax: __________

Project Title and Location: ______________________________

____

Description: ______________________ Project Value: $______________

Scheduled Completion Date: ______________ Percent Completed: ____ %

Owner: ______________________________

Refer to: ______________________ Phone: __________ Fax: __________

Consultant: ______________________________

Refer to: ______________________ Phone: __________ Fax: __________

APPENDIX - B

CONTRACTOR DATA - CONTRACTS A TO J

CONTRACT A

Contractor	SR {I}	CC {I}	RE {O}	SH {O}	EE {O}
A1	2.901	62.008	2.72052	7.52	96
A2	1.006	275.844	1.45728	1.732	65
A3	1.000	288.785	0.448	1.78333	38
A4	4.000	95.87	11.752	10	90
A5	2.046	93.3642	7.384	6.48	97
A6	1.000	241.881	4.608	2.86	58
A7	1.421	38.2979	38.32	65.8	127
A8	1.005	161.751	9.4	3.77742	190
A9	4.000	204.918	1.52	6.1	128
A10	1.702	62.9337	202.323	167.16	95
A11	2.036	52.4465	1.7424	25.8	157
A12	1.413	54.3149	11.332	27.6048	200
A13	1.002	189.323	2.90679	3.96	106
A14	1.288	137.726	83.3988	47.8266	94
A15	4.000	219.318	2.34	4.4	34
A16	1.159	109.426	48.4027	3.19851	84
A7N	1.16555	34.7175	36.4037	59.22	101.6
A10N	2.0424	60.8344	208.392	175.518	114

where:

- SR: *Safety Records* *(I: Input)*
- CC: *Current Capacity* *(I: Input)*
- RE: *Related Experience* *(O: Output)*
- SH: *Sales History* *(O: Output)*
- EE: *Employee Experience* *(O: Output)*

CONTRACT B

Contractor	SR {I}	CC {I}	RE {O}	SH {O}	EE {O}
B1	1.159	168.829	48.6787	3.19851	84
B2	1.006	124.646	7.9016	4.8802	49
B3	1.216	9.62201	22.2	133.6	71
B4	1.790	150	0	0	54
B5	1.000	54.6012	22.56	16.3	100
B6	1.329	136.525	9.44	6.51894	56
B7	2.756	283.03	3.224	3.3	78
B8	1.428	243.171	0	19.6	65
B9	1.645	13.302	159.84	127.8	49
B10	1.001	127.43	0.7336	5.7522	70
B11	2.046	144.29	7.384	6.48	83
B12	1.019	73.3333	35.28	12	87
B13	1.906	149.813	5.35799	6.6316	97
B14	1.500	140.814	104.72	78.84	26
B15	1.014	45.1638	133.08	23.2	28
B16	1.429	34.6848	13	79	10
B17	1.314	24.4318	24.64	228.8	55
B18	1.000	275.177	28	14.1	34
B3N	1.000	9.45707	21.09	140.28	85.2
B9N	1.974	11.8748	151.848	134.19	58.8

CONTRACT C

Contractor	SR {I}	CC {I}	RE {O}	SH {O}	EE {O}
C1	4.000	70.0966	5.72384	5.48	65
C2	1.000	37.2429	0.416	4.73916	37
C3	1.000	143.133	0.484	1.2778	19
C4	2.651	109.821	3.0448	1.68	82
C5	1.702	69.8134	282.091	167.16	90
C6	1.854	56.5352	5.76	21.04	327
C7	1.659	23.112	1.76	15.36	102
C8	1.435	35.7051	106.323	38.72	177
C9	1.118	143.669	0.8552	1.81947	118
C10	2.088	79.691	6.6816	6.7448	88
C11	1.814	40.7543	16.1455	4.67451	86
C12	1.000	24.97	0.5824	10	54
C13	1.000	118.879	0.96	1.78333	65
C14	1.000	238.275	1.1484	1.3588	97
C15	4.000	219.318	2.34	4.4	34
C5N	2.042	30.0456	268.98	150.444	108
C7N	1.456	21.3016	1.672	13.824	81.6
C8N	1.148	35.3184	109.513	40.656	212.4

CONTRACT D

Contractor	SR {I}	CC {I}	RE {O}	SH {O}	EE {O}
D1	1.159	168.829	48.6787	3.19851	84
D2	1.014	90.7441	0.024	11.02	64
D3	2.046	31.3291	8	94.8	186
D4	1.216	9.62201	27.3131	133.6	62
D5	1.990	40.4545	1.7224	22	80
D6	2.756	283.03	3.3976	3.3	69
D7	1.001	127.43	0.7336	5.7522	70
D8	1.908	33.2649	22.2208	74	138
D9	1.352	154.709	31.1862	57.8	36
D10	1.478	81.2098	3.72	18.2244	70
D11	2.046	83.6538	7.8	10.4	55
D12	1.000	172.12	9.52	4.37992	102
D13	1.491	7.46234	8.8	258.9	46
D14	1.000	184.186	6.0536	4.3	27
D15	1.314	24.4318	24.64	228.8	55
D13N	1.1928	5.969873	9.064	244.437	55.2
D15N	1.5768	22.22885	25.3792	238.39	44

CONTRACT E

Contractor	SR {I}	CC {I}	RE {O}	SH {O}	EE {O}
E1	1.216	10.371	11.688	133.6	74
E2	1.000	41.926	15.233	16.3	99
E3	1.109	103.92	507.52	127.6	42
E4	2.020	169.58	18.16	20.593	54
E5	1.329	151.87	9.44	6.5189	56
E6	1.702	71.907	176.87	167.16	103
E7	1.000	356.2	0	1.95	50
E8	1.000	73.244	14.66	82.86	44
E9	1.001	144.81	0.7336	5.7522	70
E10	1.352	156.44	84.827	57.8	47
E11	1.000	264.04	5.04	8.9	113
E12	1.803	44.931	119.28	58.2	53
E13	1.478	86.697	7.8	18.224	70
E14	1.246	132.5	51.216	56	29
E15	1.296	134.89	8.7855	10.5	62
E16	1.429	23.544	14.417	79	28
E17	1.445	83.077	5.52	65	65
E18	2.012	206.43	9.2626	5.5	42
E19	1.159	200.09	3.3248	3.1985	84
E1N	1.000	8.29641	11.5304	120.24	59.5489
E3N	1.000	101.78	522.746	133.98	50.4

CONTRACT F

Contractor	SR {I}	CC {I}	RE {O}	SH {O}	EE {O}
F1	1.552	158.903	435.232	142.98	198
F2	1.957	106.875	323.53	597.8	145
F3	2.192	92.9231	14	32.5	42
F4	1.795	47.9207	51.04	695.316	70
F5	1.379	92.3678	14.7058	63.2	172
F6	1.427	19.2053	85.6688	1546.45	143
F7	3.286	308.671	239.477	167.8	91
F8	1.288	162.817	83.3988	47.8266	102
F9	1.421	56.535	51.6	65.8	134
F10	1.007	127.908	17.492	18.86	38
F11	1.640	135.96	10.7267	15.2755	50
F12	2.689	312.981	30.1962	5.30617	94
F13	1.482	127.69	1.4106	32.6	0
F14	1.640	74.4671	13.6944	37.8	0
F15	1.735	71.25	5.6	28.4	78
F6N	1.712	15.3643	88.2388	1391.8	171.6

CONTRACT G

Contractor	SR {I}	CC {I}	RE {O}	SH {O}	EE {O}
G1	1.276	129.77	16.448	156.58	214
G2	1.010	86.842	5.88	15.2	105
G3	1.240	44.118	5.28	27.2	109
G4	1.005	176.22	14.432	8.1148	56
G5	1.417	76.095	241.51	167.16	88
G6	1.721	101.16	1.7424	27.2	162
G7	1.182	39.428	11.125	30.435	186
G8	3.056	77.846	18.496	32.5	65
G9	4.000	145.73	13.04	12	90
G10	1.631	39.371	28.8	66.8	118
G11	1.004	62.235	17.492	21.4	45
G12	1.000	355.61	4.536	3.74	74
G13	1.000	109.5	17.04	17.9	82
G14	2.197	203.09	7.384	6.48	101
G15	1.443	84.98	0	63.2	185
G16	1.640	74.467	13.694	37.8	0
G17	2.026	27.928	24.64	228.8	69
G18	1.002	100.87	6.936	12.115	37
G19	1.735	71.25	5.6	28.4	78
G20	1.749	90.826	11.367	33.3	117
G5N	1.7004	70.4465	248.76	150.44	70.4
G17N	1.6208	26.1618	23.4079	240.24	55.2

CONTRACT H

Contractor	SR {I}	CC {I}	RE {O}	SH {O}	EE {O}
H1	1.000	427.099	1.352	1.358	77
H2	1.000	59.7711	20.2	22.72	124
H3	1.000	367.647	1.336	1.36	28
H4	1.000	61.2288	11.6	23.6	96
H5	4.000	89.8684	15.6	7.6	35
H6	1.000	77.8443	1.228	6.68	42
H7	1.000	104.745	4	5.69	38
H8	1.492	37.4752	8	70.58	24
H9	2.499	74.872	5.6	20.702	44
H10	1.000	41.5762	31.264	82.86	48
H11	1.814	96.25	16.136	5.28	86
H12	2.566	118.1	11.248	5	50
H13	1.000	122.615	5.6	5.66	24
H14	1.000	234.259	6.216	2.16	26
H15	1.225	53.8927	17.672	57.8	31
H16	1.350	83.3333	40.656	24.6	128
H17	1.428	43.8982	15.36	18.224	47
H18	1.000	426.17	1.672	2.0825	25
H19	1.443	55.443	1.6	63.2	69
H8N	1.193	35.6171	7.6	74.109	21.14424
H10N	1.000	44.65625	29.7008	87.003	56.78387
H16N	1.620	108.3333	41.87568	25.5956	148.659

CONTRACT I

Contractor	SR {I}	CC {I}	RE {O}	SH {O}	EE {O}
I1	1.159	170.31	7.304	3.2	84
I2	1.552	7.9032	16.448	142.98	224
I3	1.616	91.206	6.4	9.654	38
I4	1.631	114.86	8.592	5.572	109
I5	1.288	43.775	38.72	47.836	124
I6	1.645	33.739	6.2	23	38
I7	1.000	32.896	10.88	18.3	32
I8	1.513	34.895	5.904	29.46	70
I9	1.329	144.75	9.44	5.216	80
I10	1.702	88.287	86.296	167.16	68
I11	1.413	23.91	5.92	27.604	115
I12	1.421	21.028	14.48	64.2	95
I13	1.007	57.158	17.472	18.86	35
I14	1.908	7	3.424	74	68
I15	1.144	61.985	11.28	29.62	86
I16	1.000	95.056	3.44	8.9	109
I17	1.352	48.218	19.68	57.8	41
I2N	1.8624	7.1464	15.626	128.68	238.83
I10N	2.0424	114.77	87.826	171.94	78.512
I14N	1.6901	6.7188	3.5267	66.6	54.4

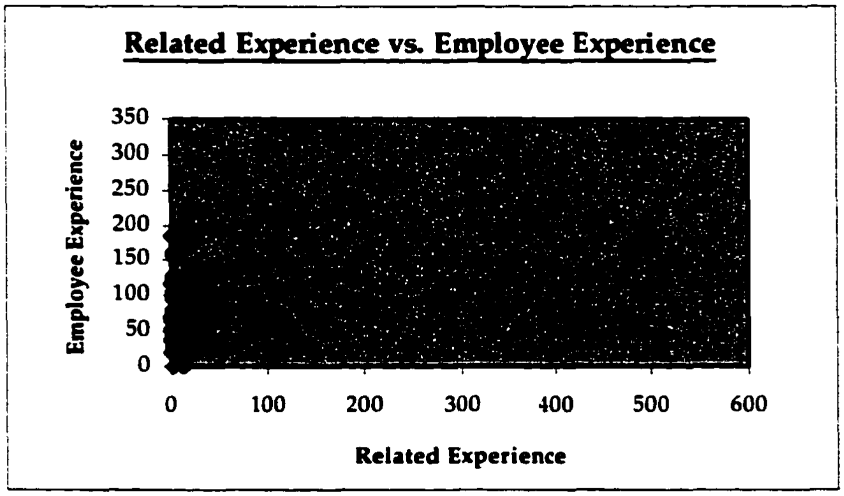
CONTRACT J

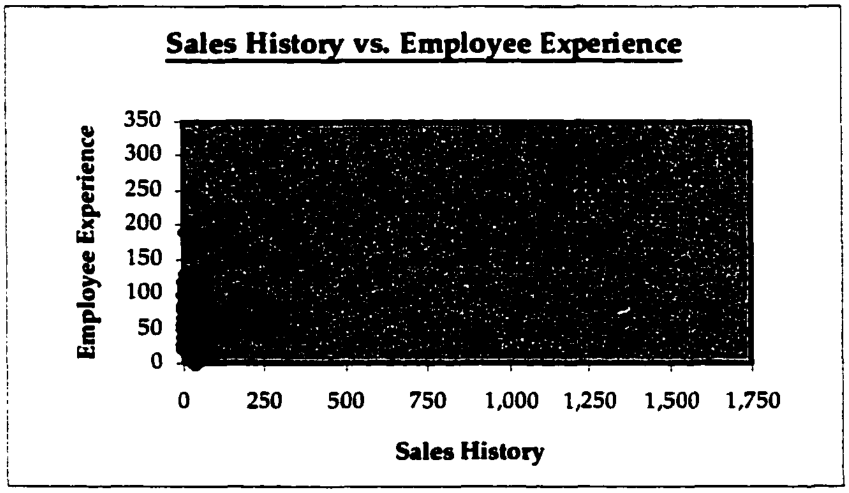
Contractor	SR {I}	CC {I}	RE {O}	SH {O}	EE {O}
J1	1.159	170.31	7.304	3.2	84
J2	3.624	454.16	2.496	1.309	55
J3	1.552	134.69	483.23	142.98	162
J4	1.957	131.75	323.6	597.8	92
J5	1.216	8.735	2.5304	133.6	46
J6	1.288	77.24	83.4	47.838	58
J7	2.046	98.606	17.6	10.4	36
J8	1.457	135	5.44	7	27
J9	2.036	48.357	1.736	25.8	122
J10	1.413	36.934	11.328	27.606	74
J11	1.000	51.46	31.264	82.86	80
J12	1.007	35.472	17.48	18.86	35
J13	3.973	357.52	4.024	1.6922	67
J14	1.352	64.066	12.408	57.8	31
J15	1.479	142.77	77.952	165.4	150
J16	1.482	89.294	13.688	32.6	24
J17	1.969	139.09	5.856	6.744	75
J18	2.681	124.53	30.168	5.3	70
J19	1.314	4.4974	9.32	228.8	89
J20	1.735	34.057	5.2	24.4	24
J3N	1.8624	132.136	497.729	128.68	194.4
J19N	1.5768	5.46907	8.854	235.66	102.874

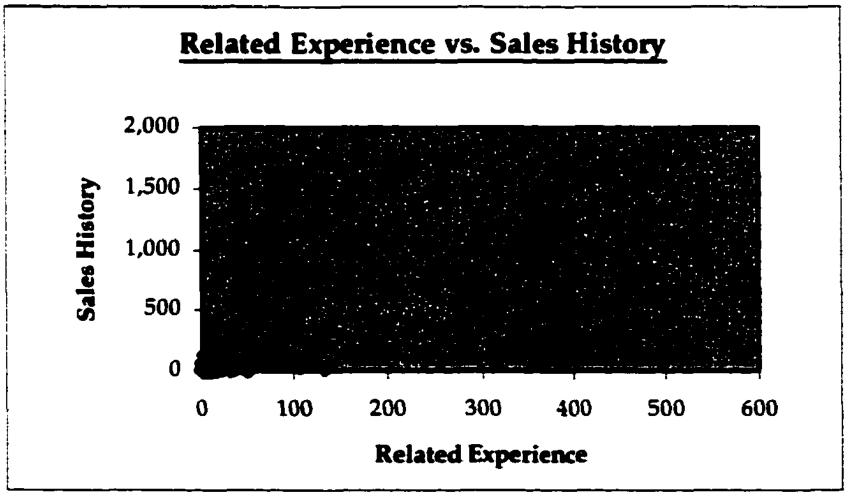
APPENDIX - C

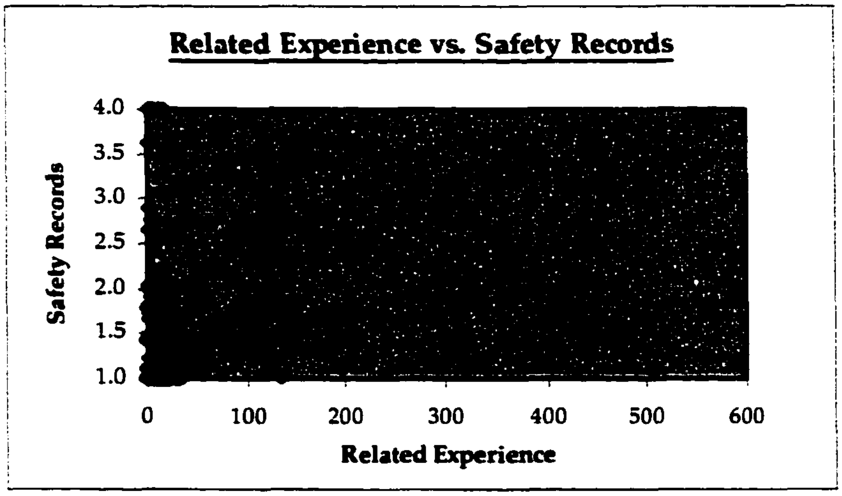
CORRELATION ANALYSIS RESULTS

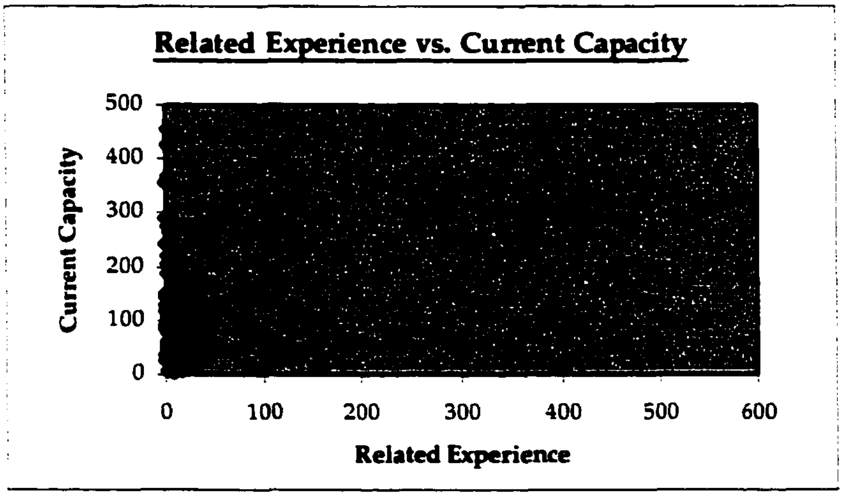
SCATTER PLOTS OF INPUTS & OUTPUTS

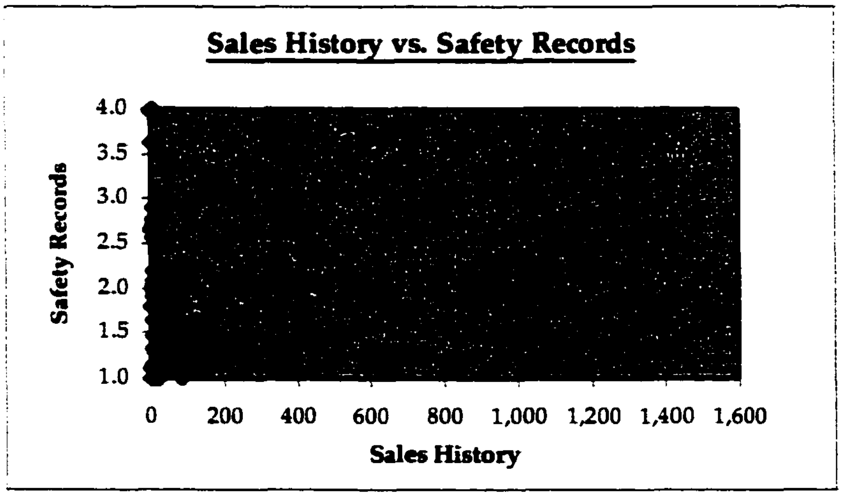

Related Experience vs. Employee Experience
Employee Experience
350
300
250
200
150
100
50
0
0
100
200
300
400
500
600
Related Experience

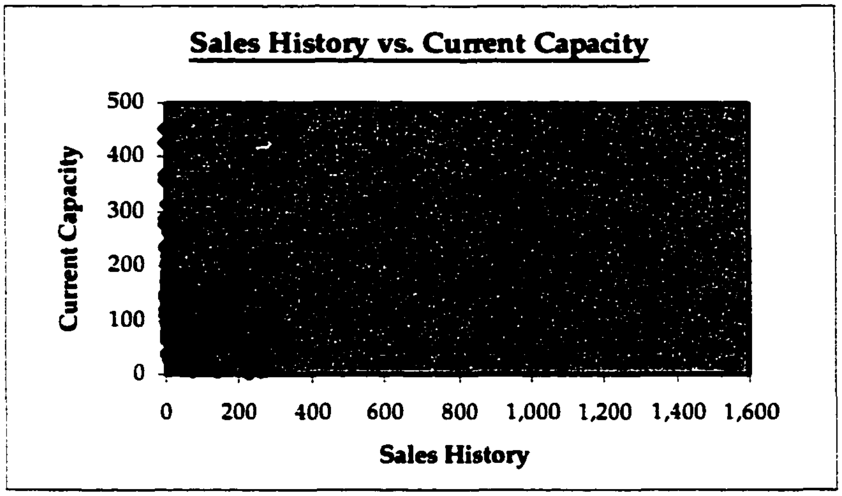

Sales History vs. Employee Experience
Employee Experience
350
300
250
200
150
100
50
0
0
250
500
750
1,000
1,250
1,500
1,750
Sales History

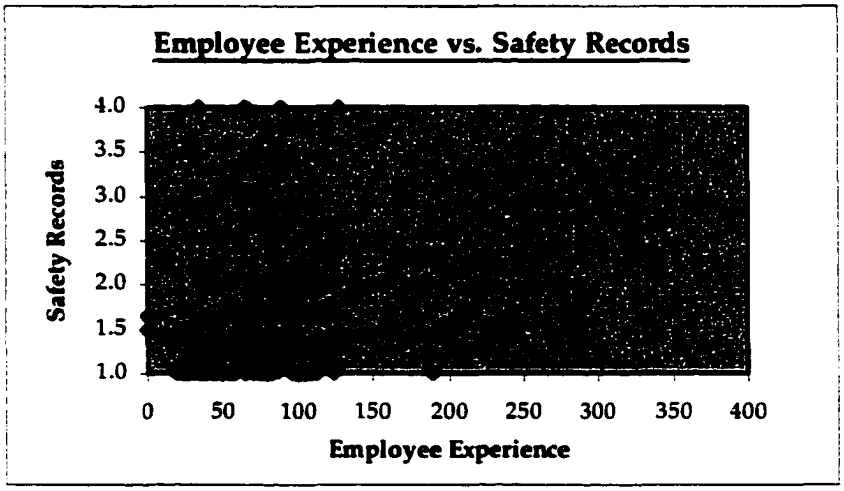

Related Experience vs. Sales History
Sales History
2,000
1,500
1,000
500
0
0
100
200
300
400
500
600
Related Experience

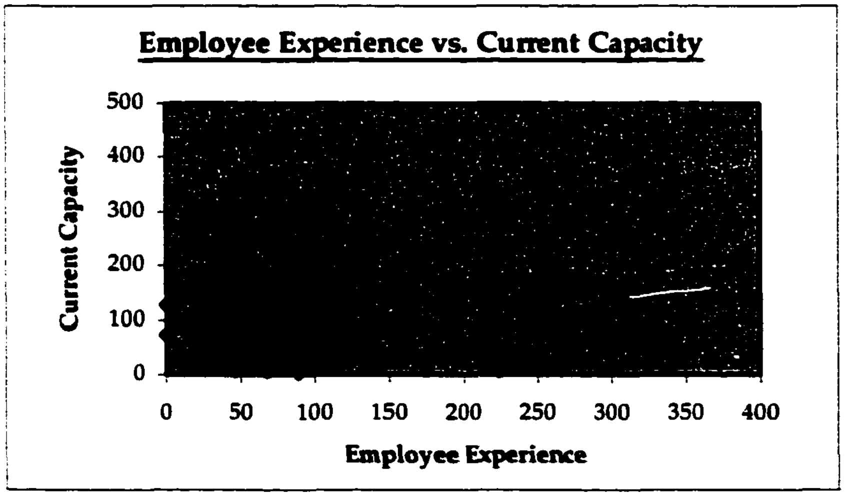

Related Experience vs. Safety Records
Safety Records
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0
100
200
300
400
500
600
Related Experience


Related Experience vs. Current Capacity
Current Capacity
500
400
300
200
100
0
0
100
200
300
400
500
600
Related Experience


Sales History vs. Safety Records
Safety Records
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0
200
400
600
800
1,000
1,200
1,400
1,600
Sales History


Sales History vs. Current Capacity
Current Capacity
500
400
300
200
100
0
0
200
400
600
800
1,000
1,200
1,400
1,600
Sales History


Employee Experience vs. Safety Records
Safety Records
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0
50
100
150
200
250
300
350
400
Employee Experience


Employee Experience vs. Current Capacity
Current Capacity
500
400
300
200
100
0
0
50
100
150
200
250
300
350
400
Employee Experience