Utilizing data envelopment analysis to benchmark safety performance of construction contractors

Mohammad S. El-Mashaleh a,*, Shaher M. Rababeh b, Khalied H. Hyari a

a Department of Civil Engineering, The Hashemite University, P.O. Box 150459, Zarqa 13115, Jordan
b Department of Architectural Engineering, The Hashemite University, P.O. Box 150459, Zarqa 13115, Jordan

Received 20 August 2008; received in revised form 9 April 2009; accepted 14 April 2009

Abstract

The purpose of this paper is to utilize data envelopment analysis (DEA) to benchmark safety performance of construction contractors. DEA has been recognized as a robust tool that is used for evaluating the performance of business organizations. The proposed approach is deployed based on empirical data collected from 45 construction contractors. On a scale of 0–1.0, DEA analysis assesses the relative efficiency of every contractor relative to the rest of the contractors in terms of safety performance. For inefficient contractors, DEA analysis provides quantitative guidance on how to become efficient.

© 2009 Elsevier Ltd and IPMA. All rights reserved.

Keywords: Organization resources; Safety and health; Benchmarking; Performance measurement; Data envelopment analysis

1. Introduction

The purpose of this paper is to utilize data envelopment analysis (DEA) to benchmark safety performance of construction contractors. DEA has been recognized as a robust tool that is used for evaluating the performance of business organizations. The proposed approach is deployed based on empirical data collected from 45 construction contractors. On a scale of 0–1.0, DEA analysis assesses the relative efficiency of every contractor relative to the rest of the contractors in terms of safety performance. For inefficient contractors, DEA analysis provides quantitative guidance on how to become efficient.

Construction literature includes several methods for assessing safety performance of construction contractors. Two of the most commonly used ones are OSHA recordable incidence rates and experience modification rating (EMR) [27,28]. OSHA recordable incidence rates are based on the US Occupational Safety and Health Act (1970), which requires employers to record and report accident information. Incidents are recorded and a formula is used to compute the incidence rates.

EMR, on the other hand, is established by independent rating bureaus. It dictates the contractor’s premium of the workers’ compensation insurance. EMR formula is criticized for its complexity and because of the existence of different versions in practice [19]. It is also argued that EMR is sensitive to company size [12,23,33].

Ng et al. [31] develop a safety performance evaluation (SPE) framework for evaluating contractor’s safety performance. The model includes a range of organization-related and project-related SPE factors. Based on a survey, the authors assign weights to the different SPE factors to calculate a weighted average safety performance score for each contractor. Generally, it is well-accepted that weighted average scores have an inherent weakness due to the biases introduced in the development of the weights and the additive assumptions utilized in the computations of the weighted score average.
Teo and Ling [37] develop a model to measure the effectiveness of safety management systems (SMS) of construction sites. The authors utilize surveys and experts interviews and workshops to collect the important factors affecting safety. The analytic hierarchy process and factor analysis are used to identify the most crucial factors and attributes affecting safety. Using the model, a construction safety index can be calculated. The authors indicate that the limitations of their model include the small number of experts and respondents involved in the study. The importance weights and attributes are developed within the context of Singapore. Another limitation is that their model includes 590 attributes that must be evaluated on the site.

Despite the limitations associated with some of the existing methods, they are useful measures of construction safety performance. However, new methods are still needed as they offer new insights to both researchers and practitioners. A point of departure for the DEA approach compared to existing methods is that DEA relates resources expended on a certain performance to the level of success for that particular performance. Under existing methods, two contractors that suffer the same numbers and types of accidents are considered of identical performance. This is clearly not the case if one contractor is expending more resources (i.e., money, etc.) on safety than the other contractor. It makes more sense to consider the contractor that commits fewer resources to arrive at a certain safety performance as a better performer.

The rest of the paper unfolds as follows: data envelopment analysis, data collection, results and analysis, future extension of the research, and conclusions.

2. Data envelopment analysis (DEA)

Data envelopment analysis (DEA) was initiated by Charnes et al. [3–5]. Since that time, many studies across different disciplines have utilized DEA [11]. In the construction domain, only few studies made use of DEA. El-Mashaleh et al. [17] propose the DEA methodology to measure and compare subcontractors’ productivity at the construction domain, only few studies made use of DEA. El-Mashaleh et al. [18] makes use of DEA to quantify the impact of information technology on contractors’ performance. Chiang et al. [8] combine DEA to the I–O tables to examine repercussions of consumptions placed on the construction sector. Cheng et al. [6] propose a DEA approach for credit scoring to evaluate borrowers with respect to certain types of projects.

DEA is concerned with evaluations of performance of organizations (i.e., business firms, hospitals, government agencies, universities, etc.), where the presence of multiple input, multiple output makes comparison difficult. In DEA, the organization under study is called a decision making unit (DMU). A DMU is regarded as the entity responsible for converting inputs (i.e., resources, money, etc.) into outputs (i.e., sales, profits, certain performance measures, etc.) and whose performance is to be evaluated. In this study, a DMU refers to a construction contractor.

DEA utilizes mathematical linear programming to determine which of the set of DMUs under study form an envelopment surface. This envelopment surface is referred to as the efficient frontier. DEA provides a comprehensive analysis of relative efficiency for multiple input-multiple output situations by evaluating each DMU and measuring its performance relative to this envelopment surface. Units that lie on (determine) the surface is deemed efficient in DEA terminology. Units that do not lie on the surface are termed inefficient and the analysis provides a measure of their relative efficiency.

Cooper et al. [11] and Coelli et al. [9] argue that DEA has gained its popularity from three inherent powerful features. First, its capability to incorporate multiple inputs and multiple outputs as a result of the use of linear programming. Linear programming can handle large numbers of variables and relations (constraints). Second, DEA has no priori assumptions. There is no need to assign weights to the different inputs and outputs. The weights are derived directly from the data relaxing the user from arbitrary subjective weighting. DEA provides a set of weights, which optimize a unit’s performance subject to the weights not leading to any other unit violating the bounds of the frontier. Third, the measurement units of the different inputs and outputs need not be congruent. Some may involve number of persons, or areas of floor space, money expended, etc.

2.1. Charnes–Cooper–Rhodes (CCR) DEA model

This study makes use of the Charnes–Cooper–Rhodes (CCR) model of DEA to benchmark safety performance of construction contractors. The mathematical form is shown below (Eqs. (1),(2),(3),(4),(5)). Interested readers may refer to Cooper et al. [11] for details.

\[
\begin{align*}
\text{max } & \quad h_0 = \sum_{r=1}^{s} u_r y_{ro} \\
\text{subject to } & \quad \sum_{i=1}^{m} v_i x_{io} = 1 \\
& \quad \sum_{r=1}^{s} u_r y_{rj} - \sum_{i=1}^{m} v_i x_{ij} \leq 1 \\
& \quad i = 1, \ldots, m; \quad j = 1, \ldots, n; \quad r = 1, \ldots, s \\
& \quad u_r, v_i \geq 0
\end{align*}
\]
Where:

- $h_0$ the measure of efficiency for DMU₀ (the DMU under evaluation), which is a member of the set $j = 1, \ldots, n$ DMUs
- $\mu_r$ the output weight. It is determined by the solution of the model and is assigned to the observed $r$th output
- $\nu_i$ the input weight. It is determined by the solution of the model and is assigned to the observed $i$th input
- $y_{r0}$ the known amount of the $r$th output produced by DMU₀
- $x_{i0}$ the known amount of the $i$th input used by DMU₀
- $y_{rj}$ the known amount of the $r$th output produced by DMU$j$
- $x_{ij}$ the known amount of the $i$th input used by DMU$j$

The objective function is to maximize the efficiency of DMU₀ (the DMU under evaluation). This is done by maximizing the sum of its outputs (Eq. (1)), while forcing the sum of its inputs to be equal to 1.0 (Eq. (2)). Eq. (3) means that the efficiency of all DMUs is ≤ 1.0. This implies that all DMUs are either on the efficient frontier or below it, and that the efficiency scores range between 0 and 1.0.

Briefly stated, the CCR model of DEA will be used to benchmark safety performance of construction contractors. The model yields efficiency scores that range between 0 and 1.0. A contractor is considered efficient if it has an efficiency score of 1.0. This means that this contractor is on the efficient frontier. Compared to the rest of contractors, this particular contractor effectively converts its inputs into outputs.

2.2. Inputs and outputs selection

As mentioned earlier, DEA considers a DMU as the entity responsible for converting inputs (i.e., resources, money, etc.) into outputs (i.e., sales, profits, certain performance measures, etc.). In the context of construction safety performance, Fig. 1 shows the related input and outputs. In terms of input, safety performance of a construction contractor is impacted by the contractor’s expenses on safety as a percentage of total revenues. These expenses include contractor’s annual cost of safety programs and salaries of safety personnel.

As for the outputs, a contractor’s safety performance is measured by the numbers of the different types of accidents that are suffered by that construction contractor. Since this study is implemented in the Jordanian construction industry, the Jordanian Social Security Organization (SSO) classification of accidents is adopted. According to SSO, work accidents are classified into 5 types as follows:

- Type 1: accidents that do not cause any disability and do not involve any lost work days.
- Type 2: accidents that do not cause any disability but involve lost work days.
- Type 3: accidents that cause temporary disability.
- Type 4: accidents that cause permanent partial disability.
- Type 5: accidents that cause permanent full disability or fatality.

Since the numbers of accidents are unfavorable, the reciprocals of the numbers of the different types of accidents that are defined by SSO are used as outputs.

3. Data collection

Potential participants in the study were selected at random from member lists of the Jordanian Contractors Association. These potential participants were assured that their identities and their companies’ identities will be kept confidential. Additionally, the researchers pointed out that the responses will be coded and kept separate from the names of the participants and their companies’ names. It was explained that when the study is completed and the data is analyzed, the codes will be destroyed. Potential participants were informed that the results of the research study will be published, but the identities of the participants and their companies’ names will not be used. It was emphasized that the anticipated benefit for respondents’ participation is benchmarking their firms’ safety performance compared to other firms in the construction industry. Potential participants were offered to receive a free hard copy of the research report after it has been published if they choose so.

Seventy contractors, out of 164 contractors that were contacted for potential participation, agreed to participate in the research project. However, only 45 contractors supplied the required data to be included in the DEA model. For a particular fiscal year, contractors were asked to report the following:

- Expenses on safety as a % of total revenues.
- Number of the 5 types of accidents (as classified by SSO) that are suffered by the contractor.

![Fig. 1. Input and outputs of a construction contractor safety performance.](image-url)
The DEA-Solver software of Cooper et al. [11] is used to run the CCR model. Table 2 summarizes the descriptive statistics of the results. Out of 45 contractors, only 8 are efficient in their safety performance. The maximum efficiency score is 1.0, while the minimum efficiency score is 0.02. The efficiency scores average is 0.32. This means that the input for an average unit could be reduced by 68%.

Table 3 shows the efficiency scores and the ranks of the 45 contractors. The results show how each contractor performed in comparison with the rest of the contractors. The following 8 contractors are deemed efficient and are considered to have superior safety performance: E, CC, RR, SS, TT, ZZ, AAA, and CCC. These efficient contractors have an efficiency score = 1.0. They are on the efficient frontier. Compared to the rest of the contractors, these 8 contractors are more efficient in converting the money they spent on safety into less number of accidents.

Table 3 shows that the efficiency scores went down from 1.0 for efficient contractors to 0.59 (Contractor PP) then to 0.5 (Contractor J and Contractor OO). We need to note here that the efficiency values are valid within this particular group of contractors. The efficiency scores will vary depending on the contractors that are included in the analysis. As mentioned before, the best performers create an envelopment surface and every DMU’s performance is measured against this envelopment surface. As such, the gaps in scores depend on the specific performance numbers for the DMU in question. To explain the gaps in efficiency scores, assume that we added a new contractor that has better performance than Contractor G (efficiency score = 0.59), but yet is not as efficient as the industry leaders. So, in this case, the efficiency score of this added new contractor will fall within the following range: 0.59 < efficiency score < 1.0.

Table 4 compares averages of the input and outputs between efficient and inefficient contractors. Note that
efficient contractors spent less than their inefficient counterparts on safety as a percentage of total revenues. The average for the first group is 0.01, while that average for the second group is 0.09. Similarly, efficient contractors suffered less number of accidents compared to the inefficient contractors.

A major motivation behind measuring performance is to identify opportunities for possible efficiency improvements by looking at the differences between efficient firms and inefficient ones. To realize their potentials, the inefficient contractors need to compare themselves with the best practice contractors that “make-up” the efficient frontier. DEA analysis provides quantitative guidance for inefficient contractors to be recognized as efficient frontier contractors. As an example, let’s take Contractor G with efficiency score = 0.2. Table 5 shows both current and projected values of the input and outputs of Contractor G. To be recognized on the efficient frontier, Contractor G needs to reduce its input and three of its outputs. In particular, expenses on safety have to be reduced from 0.05 to 0.01. Additionally, number of Type 1, Type 2, and Type 5 accidents need to be reduced to 1 down from their current values.

Note that the above recommendation to decrease expenses on safety for contractor G should be considered from a performance point of view. As demonstrated in the analysis, superior safety performance contractors spent, on average, 0.01% of their total revenues on safety. Contractor G spent 0.05% of its total revenues on safety, while suffering higher number of accidents compared to superior safety performance contractors. The recommendation to reduce expenses on safety is an indication that Contractor G is not effectively converting its committed resources (i.e., money) into lower number of accidents. Contractor G should spend less on safety and yet enjoy fewer numbers of accidents. Clearly, a decision to commit fewer resources to safety requires substantial consideration by the organization. Having an informed result regarding its expenses on safety, the organization needs to examine the specifics of its safety expenses (i.e., training, salaries, etc.) and identify cost minimization opportunities without negatively impacting safety performance of the organization.

5. Future extension of the research

The next step for the research team is to attempt to associate variability in safety performance with certain explanatory variables. Safety research within the construction domain identifies several factors that drive safety performance. Table 6 lists these factors and summarizes key statements made by previous research. The research team plans to broaden the size and scope of data collection to statistically test 8 research hypotheses that are shown in Table 7. Analysis of Variance (ANOVA), for example, will examine the existence (or non-existence) of statistical significance differences between efficient and inefficient contractors regarding the 8 factors that drive safety performance.

6. Conclusions

This paper contributes a DEA approach for benchmarking safety performance of construction contractors. A point of departure for the DEA approach compared to existing methods is the input–output framework. Compared to each other, DEA measures the efficiency of construction contractors in utilizing their expenses on safety to minimize the number of suffered accidents. Therefore, the DEA approach relates resources expended on safety to safety performance.

DEA analysis scores safety performance of construction contractors on a scale of 0–1.0. The analysis identifies contractors E, CC, RR, SS, TT, ZZ, AAA, and CCC as efficient frontier contractors. Compared to the rest of the contractors, these eight contractors are the industry leaders in safety performance. They serve as the “benchmark” for the industry and can be utilized as role models to which inefficient contractors may adjust their practices in order to become efficient.

An excellent utilization for the results of this study is programs like the US Malcolm Baldrige National Quality Award [35] and the UK Department of Trade and Industry Business-to-Business Exchange Program [30]. These programs aim at improving the performance of particular industries. For example, the UK Department of Trade and Industry Business-to-Business Exchange Program offers visits to UK best practicing organizations in manufacturing and service industries. The goal of these visits is to transfer best practices across interested organizations for the purpose of improving their performance.
Therefore, the deployment of the DEA methodology makes it possible for programs like the ones described above to utilize the results and target industry leaders in order to publicize their strategies and procedures for the benefit of the whole industry.

The Jordanian construction industry currently lacks any readily available safety performance measure to assess safety performance of construction contractors. To judge safety performance, the industry currently relies on the segregated reported numbers of the different types of accidents. As such, the DEA approach is well suited to fill this gap and assesses contractors’ safety performance.

The DEA approach presented in this paper can be utilized by a particular contractor to gauge its own safety performance over time. With data available for several numbers of years, every year might be considered as a single DMU. By conducting such analysis a contractor would be able to quantitatively determine whether or not the safety performance of the firm is getting better over time. Additionally, the proposed methodology is deployable at the project level. Every project is regarded as a single DMU and projects as a result are “benchmarked” against each other. Consequently, contractors will be able to identify their best performing projects and to isolate internal factors that contributed to better performance.
Even though the development in this paper is based on data collected from the Jordanian construction industry, the methodology would suggest a much broader geographical applicability on evaluating safety performance for construction projects internationally as well as other projects in other disciplines like manufacturing projects.

The next step for the research team is to attempt to associate variability in safety performance with certain explanatory variables (i.e., organizational safety policy, safety training, safety equipment, etc.). Clearly, to test such hypotheses, both a larger sample size and a larger scope of data collection are required.

Acknowledgments

The authors acknowledge two anonymous referrees for their constructive comments that significantly improved the final presentation of the paper.

References