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A Robust Construction Safety Performance Evaluation Framework for Workers' Compensation Insurance: A Proposed Alternative to EMR

Maha Al-Kasasbeh [1,*], Osama Abudayyeh [2], Hosam Olimat [2], Hexu Liu [2], Rabia Al Mamlook [3] and Bilal Abu Alfoul [1]

[1] Department of Civil Engineering, Faculty of Engineering, The Hashemite University, Zarqa 13113, Jordan; bilala@hu.edu.jo
[2] Department of Civil and Construction Engineering, Western Michigan University, Kalamazoo, MI 49008, USA; osama.abudayyeh@wmich.edu (O.A.); hosammuhsentawfiq.olimat@wmich.edu (H.O.); hexu.liu@wmich.edu (H.L.)
[3] Department of Industrial and Entrepreneurial Engineering and Engineering Management, Western Michigan University, Kalamazoo, MI 49008, USA; rabiaemhamedm.almamlook@wmich.edu
* Correspondence: malkasasbeh@hu.edu.jo

Abstract: The construction work environment remains one of the most hazardous among all industries. Construction injuries directly impact the workers and the work itself, including personal suffering, construction delays, productivity losses, higher insurance premiums, and possible liability suits for all parties involved in the project. The costs resulting from personal injuries, combined with the associated financial impact resulting from schedule disruptions, insurance hikes, and workers' compensation, can impact a project's profitability. Many of these impacts can be minimized or avoided through the continuous assessment and improvement of safety policies and practices. This paper aims to propose a new safety assessment methodology that equips insurance companies and construction managers with an optimal mechanism for evaluating the safety performance of construction companies. The proposed model consists of 20 evaluation criteria that are used to establish the efficiency benchmarks and provide comparison feedback for improving the company's safety plans and procedures. These criteria are determined based on leading and lagging safety performance indicators. The data envelopment analysis (DEA) technique is used as the underlying model to assess the relative efficiency of safety practices objectively. Two illustration case studies are provided to demonstrate the dual effectiveness of the DEA model. The presented research contributes to the body of knowledge by formalizing a robust, effective, and consistent safety performance assessment. The model equips the company with the ability to track both the progression and the retrogression over time and provides feedback on ineffective practices that need more attention. Simultaneously, the model gives them more detailed safety performance information that can replace the current experience modification rating (EMR) approach. It provides insurance companies with an objective and robust evaluation model for selecting optimum rates for their clients. In addition, the data comparison utility offered by the DEA model and its criteria can be helpful for insurance companies to provide effective advice to their clients on which safety aspects to improve in their future strategies.

Keywords: construction's safety; safety practices; data envelopment analysis; construction management; workers' compensation insurance; EMR

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1. Introduction

The construction industry is a major player in the nation's economy and contributes approximately USD 654 billion to the national gross domestic product, according to the US Bureau of Economic Analysis [1–4]. The US construction industry employed over 7.2 million workers in 2018, making it a significant economic sector with the largest number of professionals and workers. Although the construction industry workforce equated to only 5% of the United States workforce, it accounted for 20% of workplace fatalities and 12% of the occupational injuries and illnesses, making it the single largest contributor of work-related injuries and fatalities among all industries [2,5–15]. The US Occupational Safety and Health Administration (OSHA) indicates that one of the most important elements of a successful safety program is management commitment [8,16–22]. To eliminate injuries and fatalities at construction sites, management must be fully committed to the organization's safety policies and procedures, and effective strategies need to be employed to identify and assess hazards [22–25]. To assist safety management in this regard, OSHA categorizes safety performance indicators (including safety policies and procedures) into leading and lagging groups. Leading indicators are proactive and predictive measures that provide construction companies with mechanisms for continuously improving the effectiveness of their safety strategies and programs. On the other hand, lagging indicators give information on past incidents, such as the number of injuries and rate of fatalities. Leading indicators allow management to take preventive actions against hazards before incidents occur. In contrast, lagging indicators alert managers to the existence of these hazards [3,26]. Therefore, OSHA encourages construction companies to consider leading and lagging indicators when creating safety strategies and programs that drive change and measure effectiveness [22].

Not only do injuries and fatalities affect the employees' quality of life, but they also have direct and indirect impacts on the organizations themselves in many aspects such as productivity reduction, the possibility of lawsuits, owner's loss of revenues, and the reduction of workforce morale [27]. Taking preventative measures and actions to reduce the number of injuries and fatalities can happen only if construction managers frequently evaluate the safety performance of their companies and identify the causes of accidents [6,28]. Ineffective safety practices negatively impact workers' compensation insurance premiums [29]. Several studies identified the management's commitment to safety as one of the most effective means to ensure a high level of safety. Construction managers should demonstrate a record of safety excellence and demand that design professionals address worker safety in the project. Additionally, they can mandate the inclusion of safety requirements in the standards and policies. Notably, assessment of safety performance is a major strategy that management can implement to improve construction safety and project performance outcomes in terms of quality, cost, and schedule. In addition, estimating workers' compensation insurance premiums for construction projects needs a comprehensive assessment of safety performance and accident risks. However, this is accomplished through the experience modification rating (EMR) for each construction company. Despite criticism by many researchers, EMR remains the primary approach used by insurance companies for estimating workers' compensation premiums [30–35]. Meanwhile, many research efforts have focused on safety performance assessment. However, they have limitations, such as (1) exclusivity on certain types of projects; (2) not going beyond specific case studies; (3) characteristics such as subjectivity, complexity, cost, and being time-consuming; and (4) working with a particular constraint, such as the availability of more than one company, to perform a comparison.

Hence, an innovative model is introduced in this research to equip insurance companies with a mechanism to evaluate the safety performance of their construction clients. The proposed model is built using the data envelopment analysis (DEA) technique to produce efficiency scores that describe the safety performance of the construction company. The model will also provide managers the ability to evaluate the company's safety performance and procedures over the years to allow for continuous improvement actions as well as to address some of the limitations identified above.

2. Literature Review

The assessment of the safety performance of organizations includes many criteria, and two of the most common factors are EMR and OSHA's total recordable incidence rates. EMR uses the company's previous experience in predicting future performance [34]. It is usually employed to estimate the premium for the contractor's workers' compensation insurance (WCI) based on the contractor's past claims [32]. The WCI standard premium is calculated as a function of the EMR, the manual rate, and the number of payroll units. The basic formula of calculating the standard premium is as follows:

$$\text{Standard Premium} = \text{MR} \times \text{PU} \times \text{EMR} \tag{1}$$

where MR is a manual rate value identified each year by a rating bureau or insurance carrier, PU is the payroll units determined by dividing an employer's straight-time direct labor costs by USD 100, and MR denotes the experience modification rating factor that is based on the past safety record of the company.

Manual rates are assigned based on the idea that each type of work has a predictable loss frequency [32]. Hence, the manual rate is determined each year by a state rating bureau or insurance carriers based on the claims reported in each state. As a result, when the company's EMR is less than one, the employer pays less than the manual rate. Since the manual rate and the payroll units do not describe the owner's losses, EMR is used to indicate the owner's experience in the premium calculation. EMR calculation differs from one state to another. Most states depend on the National Council on Compensation Insurance (NCCI), while the rest have their own calculating agencies [33]. Generally, the primary method of calculating the EMR is to compare (divide) the owner's actual losses to (by) its expected losses, with adjustments for the company size and the frequency and severity of injuries [34]. The actual losses represent the accidents that led to compensation claims by workers, whereas the expected losses depend on the work classification and its past claims experience [33]. Consequently, companies with excellent safety records pay less for workers' compensation insurance than those with poor performance [34]. Nevertheless, the EMR method was criticized for many reasons. First, the EMR is considered a lagging indicator, as it uses data from the past three full years. Khalafallah [3] stated that "*EMR is calculated based on the average running scores of previous years. Accordingly, this indicator is not a leading indicator because it does not consider or depict current contractor performance*". In addition, it depends on a worker's classifications instead of on their job tasks. Some tasks in the same classification may be perceived as lower-risk [33]. Second, the EMR value can be manipulated by changing the payroll of workers or misreporting the work classifications. It was criticized as being complex and unfair [34]. In addition, Hinze [35] criticized the method, as the firm size directly affects the EMR value. The EMR value decreases when the company size increases, and contractors who pay more will have lower EMRs. Their study evaluated the EMR value for several firms by changing one variable while holding the rest constant. They observed that when a firm paid higher hourly wages, it had a lower EMR. Furthermore, when the total annual labor cost was high, the resulting EMR value was lower. Additionally, there are various formulas for calculating EMR, and the use of this single indicator can be misleading [3]. The EMR is based on the past safety record of the company, resulting in lower premiums for those companies with good safety histories [34].

The total recordable incidence rate (TRIR) is a standard safety formula created by OSHA to rate the safety of organizations, where a lower TRIR is considered better. In OSHA recordable incidence rates, employers have to report the details of accidents and other information, including the number of injuries and illnesses with and without lost workdays, number of injuries and illnesses involving restricted workdays, number of fatalities, and number of hours worked. The formula for calculating the TRIR is as follows:

$$\text{TRIR} = \frac{\text{NI} \times 200{,}000}{\text{NHW}} \tag{2}$$

where NI represents the number of incidents that need some medical treatment and are considered OSHA recordable injuries and NHW represents the firm's total number of hours worked in a year.

The 200,000 h in the formula represent the equivalent of 100 employees working 40 h per week 50 weeks per year, which is the standard base of the incidence rates [36]. Given this, management can compute the incidence rate over the years and evaluate the company's safety performance. However, judging the safety performance of an organization cannot only be limited to the number of accidents and hours worked. Furthermore, when using OSHA TRIR, management may not keep records of all incidents that occurred to keep the rate in a certain range, which violates OSHA requirements and can result in penalties [33]. In addition, this method does not readily provide management (or users) with specific shortcomings in safety practices, since it only depends on reporting the aggregate number of injuries and hours worked. Additionally, Khalafallah [3] asserted that this method depends on lagging indicators for past performance and cannot reflect current or future performance. Moreover, it has multiple definitions and indices used for calculation, such as the recordable incident rate, severity rate, and lost time case rate. El-Mashaleh [31] proposed a methodology that utilizes the DEA to evaluate the safety performance of contractors. The model calculates the relative efficiency of each contractor based on their safety expenditures as a percentage of the total revenues and the number of accidents after classifying them into five categories. The contractor with the highest efficiency has the lowest number of accidents or the lowest safety expenditures as a percentage of the total revenues, or both. While the model used in the research is robust, it only studies the effect of the safety expenses on the number of accidents. It does not cover the numerous other criteria that directly affect the safety performance. In addition, this model does not identify ineffective practices that should be enhanced.

Awolusi [16] suggested an approach to evaluate the safety performance during the construction phase. The framework produced a tool by which the safety activities on construction sites are collected and analyzed to measure the safety performance. The methodology starts with identifying activity categories, including safe behavior and conditions, unsafe behavior, and unsafe conditions. An observation of the site is conducted by high-resolution cameras to take snapshots or live videos after making a checklist of activities that reflect the mentioned categories. For example, one of the activities in the checklist may be workers not wearing a hard hat, which goes under the unsafe behavior category. This observation by trained safety representatives is meant to monitor the behaviors and conditions of the workers at the construction site. With this observation, the number of safe behaviors and conditions along with the number of unsafe behaviors and conditions are recorded. After that, the safety index, which is the percentage of safe behaviors and conditions, is calculated along with the other percentages of the remaining categories. The results are presented in the form of frequencies or probabilities (P). The formulas for these percentages are as follows:

$$\mathrm{P}\,(\text{safe behavior and condition}) = \frac{\mathrm{NSBC}}{\mathrm{TNO}} \tag{3}$$

$$\mathrm{P}\,(\text{unsafe behavior}) = \frac{\mathrm{NUB}}{\mathrm{TNB}} \tag{4}$$

$$\mathrm{P}\,(\text{unsafe condition}) = \frac{\mathrm{NUC}}{\mathrm{TNO}} \tag{5}$$

where NSBC represents the number of safe behavior and conditions, TNO denotes the total number of observations, NUB represents the number of unsafe behaviors, TNB is the total number of observations, and NUC denotes the number of unsafe conditions.

This safety index represents the overall safety performance of the construction site. Corrective actions from the observation are introduced, and a follow-up observation is conducted with an updated checklist to obtain performance feedback. The approach is well organized and provides insights to management on the unsafe behaviors and conditions to be corrected. However, the process is time-consuming and requires significant effort to evaluate each activity performed as safe or unsafe for the overall duration of many projects. In addition, some level of subjectivity might occur in the data collection process.

Khalafallah [3] developed a computerized platform for evaluating contractor safety performance that incorporated leading and lagging parameters. However, his study is limited to the building industry sector (not including other construction types such as heavy construction and civil infrastructure) and the Middle East region. Additionally, operating such a platform is considered costly since it will typically include the hardware and software costs and the cost of labor required to collect and record contractor data. In addition, Al-Saffar [4] developed a decision-making tool for evaluating construction contractors based on their safety performance. The decision equation proposed in his study depends on the survey and ranking of the indicator by experts. However, this decision mainly relies on a subjective opinion. Additionally, the experts were recruited from safety committees and safety professionals who might be biased toward safety over other essential criteria, such as cost and quality. Moreover, the study was mainly based on inputs from safety experts in the United States. Thus, the results may not be applicable in different countries.

Additionally, Liu [26] identified safety prequalification criteria without quantifying the criteria or developing a tool that could be used in the evaluation process. Karakhan [37] proposed a decision-making framework to evaluate the safety maturity of construction contractors. The result of this evaluation is only limited to the selected case study example and cannot be generalized beyond his case study. In addition, this method is not applicable if there is only a single alternative. Therefore, management cannot evaluate their company performance using this method. Liu [38] proposed a composite safety assessment based on on-site conditions to facilitate proactive construction safety management. The data used in this research was only collected from safety inspection reports of seven residential projects in China. Therefore, this study cannot be generalized beyond his case study. Additionally, it is limited to the quantitative evaluation of dynamic safety performance for on-site construction management. This study could not be adapted for overall construction management, since many critical management factors, such as safety planning, safety costs, and education training, were not considered. Finally, Gunduz [39] formulated a safety performance index of construction sites based on a multidimensional safety performance model. A full-fledged model has been proposed, but it is challenging and time-consuming. Therefore, a relatively short model as an alternative to the full model has been proposed. However, user manuals explaining how to evaluate observed variables are needed to use this model. Additionally, the model needs more data to assess the performance of the short model and determine whether it can be used to replace the full-fledged model.

Regardless of the limitations found in some of the current approaches, they are still useful for evaluating safety performance. However, new methods are required to provide a robust and optimal mechanism to assess safety performance. In particular, the new methods should incorporate all the critical safety performance leading and lagging indicators for all types of construction industries. These methods could eliminate subjectivity and provide feedback on ineffective practices that need more attention.

3. Research Goals and Methodology

The presented research aims to develop a framework that assists insurance companies in estimating premiums for their clients based on their safety performance. As a secondary goal, the framework will also provide construction managers with a continuous safety improvement mechanism by establishing efficiency benchmarks and data comparisons for optimizing their companies' safety programs. To achieve the goals of this study, a structured content review and analysis of the relevant construction safety literature as well as a linear programing modeling methodology (i.e., the DEA model) are accomplished as described below.

3.1. Criteria Selection through a Comprehensive Literature Analysis

In the data collection process, a literature review of related construction safety publications was conducted. The main goal was to identify the comprehensive criteria that affect the safety commitment. In some of the literature, the criteria were clearly delineated and extracted, while in others, the criteria had to be inferred from the research objectives and results.

For example, Khalafallah [3] stated clearly that safety performance indicators include management commitment, accident investigation, personal protective equipment, fire safety tools and equipment, and general site safety and environment controls. Additionally, Al-Saffar [4] mentioned many safety performance criteria, including management's commitment to safety, project safety planning, training, and meetings, employee involvement in safety decision-making, recognition and reward, technology for safety management, safety inspection, and audits, and accident documentation. Liu [26] described several safety performance criteria, such as safety recognition and rewards, accident records, management commitment, safety education and training, and safety policies and standards. Therefore, in the current model, we considered the following criteria significant: (1) incentives, awards, and recognition; (2) training programs and safety orientation; (3) conducting accident investigation; (4) required personal proactive equipment; (5) safety audits; (6) safety inspection; and (7) managers or safety personnel at construction sites. An example of an inferred criterion was proposed by Abudayyeh [27]. In this investigation of management's commitment to construction safety, the authors concluded that the companies with long working hours per week (more than 50 h) had more injuries and illnesses than other companies with fewer working hours. As a result, it was inferred that working hours per week could be used as a criterion, as it addressed the concern about the health and well-being of the employees. In addition, Vinodkumar [17] highlighted the need for workforce safety training and stated that it was the most important finding of their study. Given this, safety training was concluded to be a vital evaluation criterion. Furthermore, it is worth noting that not all inferred attributes were selected as safety criteria. Many criteria were repeated in more than one research work, which indicated that they were essential and of primary concern to management. Table 1 shows the final list of criteria, categorized into leading and lagging indicators based on OSHA's definitions [4,13,17,23,24,26,36,38–40].

Table 1. A list of safety performance criteria.

Number	Criteria	Method of Measurement	Inputs (I)/Outputs (O)	Type of Indicator	Number	Criteria	Method of Measurement	Inputs (I)/Outputs (O)	Type of Indicator
1	Fatalities	Number of fatal accidents In the past 1 year	I1	lagging	12	Conducting accident investigations	Yes/No	O9	lagging
2	Working hours per week	Number of hours	I2	leading	13	Requiring personal protective equipment	Yes/No	O10	leading
3	Safety budget	Monetary value $	O1	leading	14	Safety audits/inspections	Number of inspections per project	O11	leading
4	Safety management position represented in the company	Number of positions	O2	leading	15	Non-fatal accidents	Number of non-fatal accidents In the past 1 year	I3	lagging
5	Safety managers or safety personnel at the construction sites	Number of personnel	O3	leading	16	Posting safety signs for identifying hazards	Yes/No	O12	leading
6	Training programs and safety orientation/refresher	Average number of hours per construction workers and field supervisors	O4	leading	17	Drugs and alcohol consumption of employees during working hours	Number of inspections	O13	leading
7	First-aid trained personnel	Number of first-aid trained personnel	O5	leading	18	Availability of hazards reporting system	Yes/No	O14	leading
8	Safety handbooks/manuals	Yes/No	O6	leading	19	Cost of accidents	Monetary value $	I4	lagging

Table 1. *Cont.*

Number	Criteria	Method of Measurement	Inputs (I)/Outputs (O)	Type of Indicator	Number	Criteria	Method of Measurement	Inputs (I)/Outputs (O)	Type of Indicator
10	Incentives, awards and recognition	Number of awards offered each year	O7	leading	20	Fines and penalties	Monetary value $	I5	lagging
11	Safety committees	Number of meetings made by committees each year	O8	leading	21	Lost construction days	Number or lost days in the past 1 year	I67	lagging

3.2. DEA Modeling for Safety Evaluation

The DEA modeling methodology is a nonparametric data-oriented methodology that helps in the performance evaluation of comparable units [41]. The relative efficiency scores (from 0 to 1) in DEA are calculated to make selection decisions [42–46]. Several research efforts successfully demonstrated its application in the construction industry [31,42,47].

The DEA methodology is based on the linear programming technique where multiple criteria can be used to make a comparison. The entities under evaluation are called decision-making units (DMUs), which may be contractors, suppliers, managers, and so forth. In this study, the DMUs could represent the clients under evaluation or the years if the evaluation was for the historical safety record. The variables (i.e., criteria) in Table 1 are categorized into inputs and outputs in the DEA process to generate a performance measure (efficiency score). This methodology provides the ability to merge as many variables as needed in the evaluation model. Additionally, there is no need for the criteria to have the same measurement units. For example, the safety budget is in a monetary unit while the working hours are in a time unit. The most efficient DMUs (clients or years) under evaluation will form an envelopment surface when running the DEA model. This surface is called the efficient frontier and has the group of the best DMUs with efficiency scores of one [41,43,46,47]. Consequently, relative to the other clients (or years), they have the best performance. The efficiency scores of the remaining DMUs, namely the inefficient ones, are calculated based on their distances from the efficient frontier [43]. To be on the efficient frontier, a DMU must utilize fewer inputs to generate higher outputs [45]. In our case, reducing the unsafe aspects of a project is desired to improve overall safety. No assumptions are made for the weights of the variables (i.e., inputs and outputs) or the underlying distribution of the data in the DEA model. Consequently, the DEA model is regarded as nonparametric [45]. The relative efficiency of the DMUs is calculated by generating the DEA linear programming model based on the following formulas:

$$\text{Max h1} = \frac{\sum_{r=1}^{s} \text{ur} \times \text{yr1}}{\sum_{i=1}^{s} \text{vi} \times \text{Xi1}} \tag{6}$$

$$\frac{\sum_{r=1}^{s} \text{ur} \times \text{yrj}}{\sum_{i=1}^{s} \text{vi} \times \text{Xij}} \leq 1 \text{ ur, vi} \geq 0\text{j} = 1, \ldots\ldots, \text{n}; \text{r} = 1, \ldots., \text{s}; \text{i} = 1, \ldots., \text{m} \tag{7}$$

where h_1 is the measured efficiency for DMU_1 (clients or years), u_r is the rth output weight derived from the model, v_i is the ith input weight derived from the model, y_{r1} is the rth output amount of DMU_1, x_{i1} is the ith input amount of DMU_1, y_{rj} is the rth output quantity of DMU_j, x_{ij} is the ith input quantity used by DMU_j, DMUs is the number of outputs, and m is the number of inputs.

The weights of the variables produced when running the DEA model are estimated so that each DMU gets the best possible efficiency score [48,49]. Hence, the distribution of the weights cannot be argued by the managers to be unfair or unjust as they reflect the strength of each manager.

Based on the DEA equations, the primary function when running the model is to maximize the efficiency score of the DMU under assessment while ensuring that all the efficiency scores are on or below the efficient frontier by maintaining the constraint values.

Each DMU will have an efficiency score between 0 and 1. As mentioned before, the scores are produced based on the ability of each DMU to utilize fewer inputs to generate higher outputs. The DMUs with a score of one are considered to be relatively the best, as they form the envelopment surface [50]. One of the limitations of DEA is that the linear programming model requires that the number of entities under evaluation is at least three times more than the number of the variables (i.e., inputs and outputs) [46]. Nevertheless, this limitation can be avoided by creating an artificial DMU with the lowest and highest outputs of the DMUs under evaluation [51].

To generate the DEA model, each criterion must be classified as either an input or output, as shown in Table 1. This classification is based on simple facts. For example, suppose the reduction of the variable's quantity increases the efficiency of the DMU (i.e., improves the safety). In that case, this criterion is considered to be an input, such as the number of fatalities. On the other hand, if the increase of the variable's quantity increases the DMU efficiency (i.e., improves the safety), then it is called an output, such as a safety budget. Table 1 shows the identification of the evaluation criteria as inputs or outputs and their units of measurement. All criteria with YES or NO answers were quantified on a 1 or 0 binary scale, respectively. In the case of multiple efficiency scores, some order statistics could be performed on the results to give a better sense of the safety performance. One of these statistics is the quartile, which splits the scores into four even parts [52]. This division of data was executed by ordering it from smallest to largest and then computing the first, second, and third quartile by the known methods in the case of an odd or even amount of data. The first quartile was a number that had 25% of the data below it, the second quartile (the median) split the data in half, and the third quartile had 25% of the data above it. Consequently, these three numbers, along with the maximum and the minimum of the data, provided a summary regarding the spread of scores and on which side the data were skewed. This is useful in the case of clients' history efficiency scores, where the quartile will be an efficient tool in comparing the distribution of safety performance of each client over their history. Consequently, the clients with outstanding history will have their data skewed toward higher efficiency scores.

4. Results and Discussion

The proposed DEA model enables insurance companies to identify the efficiency scores of their clients as a fast and robust mechanism for assessing the quality of their safety records. The management may also use the proposed model to evaluate the annual improvements (or lack of) and effectiveness of the safety measures undertaken for their work environments by determining the efficiency scores for the time period they choose. The following case studies illustrate how the proposed model can be effectively adopted by insurance and construction companies.

4.1. Case Study of Insurance Company

A case study of an insurance company is used to demonstrate how insurance companies use this model to evaluate contractors' safety records. The insurance company wished to track five clients' performance over a period of 10 years. The evaluation process began by inputting the criteria values for each year. The number of entities under evaluation should be at least three times more than the number of variables. The artificial client "DMU" was also created by taking the lowest inputs and the highest outputs from all 50 DMUs. This artificial DMU maintained the discriminatory power of the DEA model, as shown in Table 2. The efficiency scores of each company per year over 10 years were then obtained from the DEA model, as shown in Figure 1. As shown in Figure 1A, Client 1 had a step back in the fourth year due to many issues, including the increased number of lost construction days, increased fines and penalties, and removing the hazard reporting system. These changes were reflected in their efficiency score, which was 0.71. However, they overcame this situation in the next year, as their score improved to 0.97. This represents the capability of the client to enhance their safety performance through the years. The scores of Client 2 showed that they were not consistent and kept having ups and downs. This fluctuation was mainly due to their lack of effort to reduce the number of fatalities and working hours per week.

Table 2. The 10-year criteria values of an insurance company's clients.

Year / Criteria	Client	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10
Fatalities (I1)	1	10	6	8	8	7	4	5	3	4	7
	2	2	10	7	8	7	5	5	1	5	1
	3	9	3	3	3	9	4	3	10	0	2
	4	4	10	1	1	7	5	0	2	7	3
	5	10	6	6	5	8	3	5	10	5	2
	Artificial = 0										
Working hours per week (I2)	1	43	54	42	44	37	51	48	39	39	40
	2	45	52	43	46	47	36	49	53	51	51
	3	50	41	37	42	50	43	36	44	50	36
	4	53	50	45	39	54	36	38	48	38	44
	5	45	46	38	39	53	46	38	47	46	47
	Artificial = 36										
Safety managers or safety personnel at the construction sites (O3)	1	3	8	1	8	5	6	1	1	0	8
	2	9	1	0	2	0	2	10	1	10	8
	3	10	6	2	1	4	1	4	5	5	5
	4	3	2	3	7	1	0	6	8	9	4
	5	0	4	10	6	5	1	4	6	9	9
	Artificial = 10										
Training programs and safety orientation/refresher (O4)	1	2	1	5	2	4	1	2	0	1	2
	2	3	4	2	4	0	5	5	4	4	2
	3	1	4	3	5	5	4	3	3	3	0
	4	3	4	3	4	5	2	4	5	4	1
	5	4	4	3	4	5	0	5	5	5	2
	Artificial = 5										
Fines and penalties (I5)	1	15350	5081	13676	15866	14544	21688	21593	21367	28684	14702
	2	8956	21453	5186	16641	28579	17248	11095	21803	27009	19260
	3	15269	18480	5105	21187	20120	29919	29123	17692	24056	8187
	4	29119	29935	9623	13390	8094	5095	20025	18219	5712	10391
	5	26675	19857	8559	29396	6397	7660	19101	14887	19575	12209
	Artificial = 5081										
Cost of accidents (I4)	1	43188	28899	66741	46229	60318	58237	73405	46679	65825	37549
	2	66675	66577	57531	45895	36745	52745	47070	45812	25441	61078
	3	51281	58375	58678	58417	37096	61162	66046	26626	47715	54210
	4	54721	73915	26066	50891	46007	42649	30936	58288	71425	67609
	5	50286	67932	46398	48935	62835	51272	51810	62940	25379	56830
	Artificial = 25379										

Table 2. *Cont.*

Year / Criteria	Client	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10
Safety budget (O1)	1	47738	57089	40115	68974	42547	32129	37032	49410	59592	70274
	2	49095	53939	68287	44769	56536	70846	31860	53871	46621	63825
	3	65225	64111	75990	33159	64101	45495	41715	41992	75536	30265
	4	60190	71282	44912	71998	77412	42168	33287	79530	56814	51744
	5	31082	45540	61141	69152	30989	33284	69265	37257	53418	38586
	Artificial = 79530										
Lost construction days (I6)	1	15	40	15	31	30	6	9	15	25	38
	2	14	30	10	28	32	39	7	37	16	19
	3	30	33	13	6	38	27	22	35	40	14
	4	39	38	9	37	33	9	34	9	21	14
	5	12	8	18	39	40	10	39	9	10	35
	Artificial = 6										
Availability of hazards reporting system (O14)	1	0	1	1	0	1	1	0	1	1	0
	2	1	1	0	1	0	0	1	1	1	0
	3	0	1	0	1	1	0	0	0	1	0
	4	0	1	0	1	0	0	0	1	0	0
	5	1	0	0	0	1	1	1	1	1	0
	Artificial = 1										
Safety management position represented in the company (O2)	1	5	6	0	6	5	6	8	5	1	7
	2	9	6	0	3	5	3	4	3	2	5
	3	8	2	4	1	4	7	6	10	10	7
	4	3	2	3	7	1	0	6	8	10	4
	5	6	4	2	8	7	2	4	6	10	5
	Artificial = 10										
First-aid trained personnel (O5)	1	6	3	5	0	7	0	1	3	3	6
	2	7	8	1	6	4	0	10	5	2	7
	3	9	6	7	7	8	2	3	2	6	1
	4	5	3	1	4	0	2	3	1	10	0
	5	0	1	10	4	0	8	6	0	7	3
	Artificial = 10										
Safety hand-books/manuals (O6)	1	1	0	1	0	1	1	1	0	0	1
	2	1	0	1	1	0	1	0	1	0	0
	3	1	0	0	1	1	1	0	1	0	0
	4	0	1	1	0	0	1	1	0	0	1
	5	0	1	0	1	***0***	0	0	0	0	0
	Artificial = 1										

Table 2. *Cont.*

Year / Criteria	Client	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10
Safety committees (O8)	1	4	3	2	3	1	7	2	6	6	1
	2	6	0	4	5	4	2	5	4	2	6
	3	6	5	1	2	2	0	6	6	7	7
	4	5	0	2	5	7	7	4	1	6	6
	5	3	2	6	0	4	4	3	3	0	1
	***Artificial* = 7**										
Safety audits/inspections (O11)	1	2	4	1	2	1	4	7	6	1	1
	2	5	2	2	5	0	1	6	0	3	3
	3	0	1	0	0	3	6	3	2	6	4
	4	7	5	1	3	5	0	2	1	3	0
	5	0	2	3	5	2	4	6	6	4	6
	***Artificial* = 7**										
Year / Criteria	**Client**	**Y1**	**Y2**	**Y3**	**Y4**	**Y5**	**Y6**	**Y7**	**Y8**	**Y9**	**Y10**
Incentives, awards and recognition (O7)	1	4	4	3	4	3	3	4	0	5	3
	2	0	4	2	0	0	4	0	0	3	4
	3	4	2	3	0	4	0	3	3	5	2
	4	1	4	1	2	2	4	2	4	3	1
	5	5	4	2	5	5	5	5	4	5	5
	***Artificial* = 5**										
Non-fatal accidents (I3)	1	11	4	4	9	7	10	8	11	15	12
	2	7	16	5	18	6	7	12	16	4	16
	3	14	16	14	12	11	6	14	7	9	7
	4	14	11	4	14	15	11	5	5	15	10
	5	14	5	12	5	5	4	5	5	17	10
	***Artificial* = 4**										
Posting safety signs for identifying hazards (O12)	1	1	0	1	0	1	1	1	0	0	1
	2	1	0	1	0	1	0	0	1	0	1
	3	0	0	0	0	1	0	0	1	1	0
	4	1	1	0	1	0	0	0	1	0	1
	5	1	1	0	0	1	1	1	0	0	0
	***Artificial* = 10**										
Drugs and alcohol consumption of employees during working hours (O13)	1	4	2	4	2	5	3	8	2	3	2
	2	4	5	3	5	0	4	4	10	1	3
	3	5	10	3	5	5	3	9	5	1	3
	4	0	4	10	1	6	5	3	4	4	5
	5	3	6	6	4	8	3	6	9	8	10
	***Artificial* = 10**										

Table 2. *Cont.*

Year / Criteria	Client	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10
Conducting accident investigations (O9)	1	0	1	0	0	1	1	1	1	1	0
	2	1	0	0	0	1	0	1	1	0	0
	3	1	1	1	0	0	1	0	0	1	0
	4	1	0	1	0	0	0	0	1	1	0
	5	0	0	1	0	1	0	0	0	0	1
	Artificial = 1										
Requiring personal protective equipment (O10)	1	1	0	1	0	1	0	0	1	1	1
	2	1	1	0	1	1	1	0	0	0	0
	3	0	0	0	1	0	1	1	1	0	0
	4	1	0	0	0	0	0	1	0	1	1
	5	1	0	0	1	1	1	1	0	1	0
	Artificial = 1										

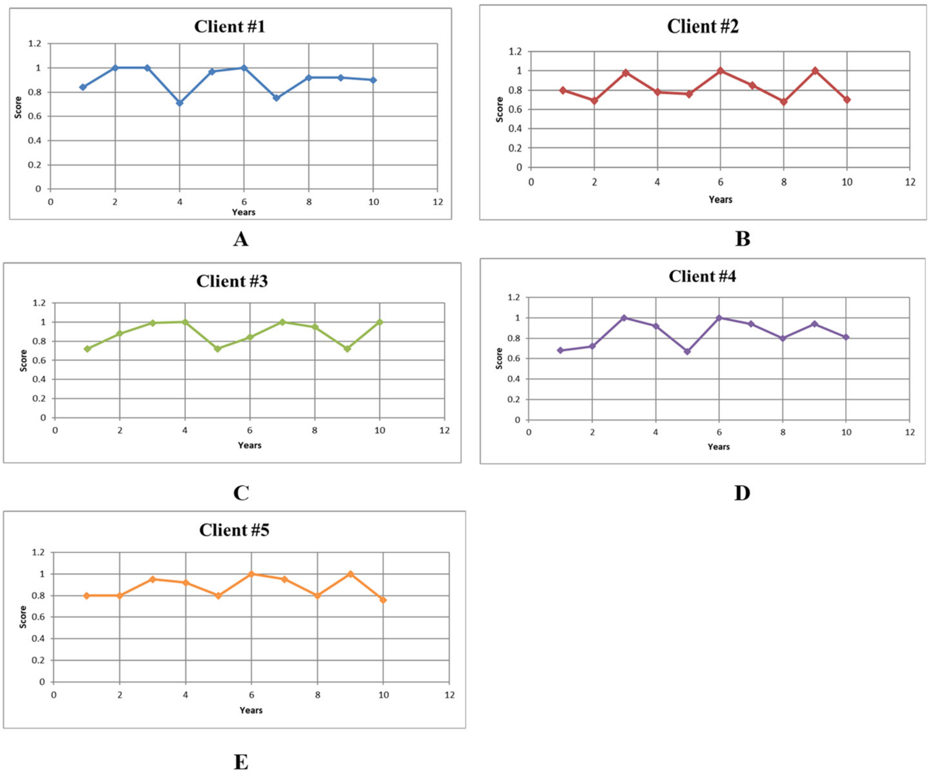

Figure 1. Safety performance of insurance company's clients: (**A**). Client #1, (**B**). Client #2, (**C**). Client #13, (**D**). Client #4, and (**E**). Client #5.

However, they improved the safety procedure in the third, sixth, and ninth years, which was clearly apparent in their scores (see Figure 1B). Figure 1C represents Client 3, which had good safety record improvement except for the fifth and the ninth year, where a step back was noticed. It also shows that this company always came back to the right track after having some safety issues.

The scores of Client 4, relative to the other companies' performances, were improved in the first few years, jumping from 0.68 to 1 in just 2 years. Its performance continued to improve until the fourth year, where its efficiency score dropped from 1 to 0.92 and then from 0.92 to 0.67 in the next year. However, their scores recovered. The fact that they reached the lowest efficiency score compared with the other companies and then managed to come back proves that they developed their safety procedures and improved their record very well (see Figure 1D). Client 5 had good safety performance without large drops in their efficiency scores, except for the last year. As shown in Figure 1E, the efficiency score for the 9 years always remained above 0.8. Although the score started at 0.8 and ended at 0.76 (in year 10), this client was the only one with a 9-year performance record above 0.8. Still, the drop in year 10 needed to be investigated to ensure that safety performance did not continue to decline in future years. Quartile distribution was created to help the insurance manager evaluate premium determination (see Table 3). For example, Client 1 had the highest quartiles, indicating its scores were relatively higher than the others. Client 2 had the lowest median quartile compared with the others. Client 3 had the highest third quartile and was the only company to end the 10 years with a score of 1. The quartiles, together with graphs, can give the insurance company an idea about each company's safety performance and its distribution of scores over the years. Additionally, this assessment can provide insights into whether the company is progressing with its safety practices and record or not taking any actions to improve its record. Consequently, the insurance company can have the ability to alter the rates for its clients if they cannot improve their performance or reach a certain threshold. Furthermore, a data comparison can be made for each criterion value with the artificial one to provide the client with the adjustments needed to improve their safety efficiency scores. It is worth noting here that these client efficiency scores are relative to each other's performance, which means, for example, that a certain client is the best relative to the rest of the clients.

Table 3. Insurance company's clients' quartiles.

Quartile	Client 1	Client 2	Client 3	Client 4	Client 5
Q1	0.905	0.77	0.7825	0.75	0.8
Q2 (Median)	0.95	0.845	0.935	0.93	0.9
Q3	0.9975	0.9625	0.9975	0.97	0.95

4.2. *Case Study of a Company's Annual Safety Assessment*

The following case study is used to demonstrate how the DEA model can also be used to evaluate a company's annual progress with its safety measures. A company had been facing many safety issues for the past 6 years. As described in the first case study, the evaluation process started by inserting the criteria data in the DEA model (see Table 4).

Table 4. Criteria data for the company over 6 years.

Year / Criteria	Y1	Y2	Y3	Y4	Y5	Y6	Year / Criteria	Y1	Y2	Y3	Y4	Y5	Y6	Year / Criteria	Y1	Y2	Y3	Y4	Y5	Y6
Fatalities (I1)	5	5	5	5	3	3	**Lost construction days (I6)**	30	30	22	22	22	22	**Incentives, awards and recognition (O7)**	0	0	0	0	0	1
	Artificial = 3							*Artificial = 22*							*Artificial = 1*					
Working hours per week (I2)	56	45	45	40	40	40	**Availability of hazards reporting system (O14)**	0	0	0	0	0	1	**Non-fatal accidents (I3)**	10	10	10	10	8	8
	Artificial = 40							*Artificial = 1*							*Artificial = 8*					

Table 4. *Cont.*

Year / Criteria	Y1	Y2	Y3	Y4	Y5	Y6	Year / Criteria	Y1	Y2	Y3	Y4	Y5	Y6	Year / Criteria	Y1	Y2	Y3	Y4	Y5	Y6
Safety managers or safety personnel at the construction sites (O3)	0	0	0	0	0	0	**Safety management position represented in the company (O2)**	1	1	2	2	2	3	**Posting safety signs for identifying hazards (O12)**	0	0	0	0	0	1
	Artificial = 0							***Artificial = 3***							***Artificial = 1***					
Training programs and safety orientation/refresher (O4)	10	10	10	10	10	17	**First-aid trained personnel (O5)**	3	3	3	4	4	5	**Drugs and alcohol consumption of employees during working hours (O13)**	0	0	0	0	0	0
	Artificial = 17							***Artificial = 5***							***Artificial = 0***					
Fines and penalties (I5)	10000	10000	6700	6700	6700	6700	**Safety handbooks/manuals (O6)**	0	0	0	0	0	0	**Conducting accident investigations (O9)**	0	0	0	0	0	1
	Artificial = 6700							***Artificial = 0***							***Artificial = 1***					
Cost of accidents (I4)	50000	40000	40000	40000	37000	37000	**Safety committees (O8)**	2	2	2	2	2	6	**Requiring personal protective equipment (O10)**	0	0	0	0	0	0
	Artificial = 37000							***Artificial = 6***							***Artificial = 0***					
Safety budget (O1)	30000	40000	40000	40000	50000	50000	**Safety audits/inspections (O11)**	1	1	1	1	1	4							
	Artificial = 50000							***Artificial = 4***												

Since this case study only discussed a period of 6 years that represented 6 DMUs and 20 criteria, an artificial year (DMU) was added to maintain the discriminatory power of the DEA. It was produced by taking the lowest values of the inputs and the highest values of the outputs from all 6 years. The efficiency scores of each year are shown in Table 5. Each year's efficiency score was produced in comparison with the rest of the years. Consequently, both the development and the retrogression of each year in comparison to the rest will be presented. Moreover, the shortfalls for each criterion can be known by comparing the criterion value with the artificial one. For example, in the third year, the working hours per week were 45. However, the artificial DMU with the best score had 40 working hours. Based on that, the working hours must be reduced by five to be more efficient. This advantage will help the company's management understand their performance better and know whether they are proceeding in the right direction. In this example case study, the fifth year had an improved safety record with an efficiency score of one, which indicates that it had the best mix of safety measures and procedures relative to all the previous years.

Furthermore, the efficiency scores increased annually, except for the fourth year, indicating that the company was moving in the right direction but with no improvement in the fourth year. This situation was addressed by carefully improving the safety measures, such as reducing the number and cost of fatal and non-fatal accidents, increasing the safety budget, and reducing the number of working hours per week to achieve higher scores.

Table 5. Efficiency score for company A over 6 years.

Year	Efficiency Score
Y1	0.48
Y2	0.74
Y3	0.8
Y4	0.8
Y5	1
Y6	1
$Y_{\text{Artificial}}$	1

In this case study, the management of the company made annual changes to its safety policies and procedures to improve its safety performance. They were able, through this DEA model, to evaluate the progress over this 6-year period. The changes that were made included reducing the number of working hours per week, increasing the safety budget, and reducing the costs of accidents by conducting more comprehensive job site safety analysis and hazard assessment.

5. Limitations

Despite the aforementioned significant contributions, some limitations on the proposed methodology and applicability of the results exist. The identification of safety performance criteria in the current study was based on the frequency of occurrence in previous studies reported in the literature. Although indicating the awareness and possible connection of criteria to safety performance, this frequency does not necessarily reveal the importance of these criteria for influencing construction safety performance. In addition, the current study did not consider input from insurance companies when the criteria were developed. Additionally, the thresholds for developing insurance rates need comprehensive analysis and input or feedback from both construction and insurance industries to allow for developing fair and realistic rates. The proposed model also relies on a comprehensive database of workers and their companies, which are regularly maintained by companies themselves or national authorities. However, for countries that do not maintain databases of construction companies, it may take some years to collect the annual safety data for deploying the developed model. More research and development efforts are still needed to standardize the safety performance evaluation criteria across the construction industry and to formalize the DEA-based computation of workers' compensation premiums in the insurance industry.

6. Conclusions

The construction industry is more hazardous than many other industries. Consequently, the safety strategies utilized by construction companies need to achieve a higher level of safety performance. Given this, the main focus of this research project was assessing the safety performance of construction companies by proposing a safety performance model that consisted of 20 leading and lagging evaluation criteria gathered from a comprehensive literature review. The DEA methodology was used as the underlying model for assessing the relative efficiency of safety practices. Two case studies were presented to demonstrate how the model was used to objectively evaluate the safety performance of construction companies from the insurance company and the construction managers' perspectives.

In the first case study, the model demonstrated the ability of the model to evaluate as many insurance company clients as needed over a long period of time. Additionally, the quartiles and graphs provided the insurance company with a mechanism for estimating premiums based on each company's safety performance. This efficiency score was simple to obtain and considered a fair and objective indicator. Furthermore, the data comparison utility offered by the DEA model and its criteria can be helpful for insurance companies to provide effective advice to their clients on which safety aspects to improve in their future strategies. Consequently, the proposed DEA safety performance evaluation model presents a better mechanism than the exiting EMR approach for estimating fair insurance premiums and addressing the criticisms discussed in the EMR research literature. However, the roles and responsibilities should be well-defined and obligatory for both the management of construction companies and national occupational safety administration inside each state or country (e.g., OSHA in the United States) to effectively use the proposed model. The management of construction companies should be responsible for reporting, obtaining, and auditing safety data from their projects. In addition, the national occupational safety administration should be responsible for maintaining the safety database records to ensure accurate representation for the construction companies. It should carry out audits and inspections to ensure the validity of construction companies' reported data.

The research effort in this project also addressed the continuous improvement of safety performance of an individual company over its history in the second case study. It was shown that each company could evaluate its performance year after year to be informed about its safety progress by using the DEA model and framework. The model equips the company with the ability to track both the progression and the retrogression over time. Therefore, the results from this research study could help the construction industry focus more attention on the importance of safety performance evaluation and improvement and will provide insurance companies with an objective and robust evaluation model for selecting the optimum rates for their clients.

The proposed DEA model does not depend on inputs from specific case studies or projects in a certain country and does not rely on weights provided by safety experts to weigh the criteria. Rather, it derives the weights of the different criteria directly from the data, overcoming the subjectivity of the experts and the difficulty of achieving a consensus about the weights of the criteria. Thus, the model is applicable for all types of construction industries worldwide. However, more research development is still needed to standardize the safety performance evaluation criteria across the construction industry and formalize the DEA-based computation of workers' compensation premiums in the insurance industry.

The DEA model proposed in this research endeavor is a significant step toward developing a comprehensive, fair, and robust approach to safety performance evaluation. The model establishes the efficiency benchmarks and provides comparison feedback for improving a company's safety plans and procedures. Additionally, it offers an effective safety performance evaluation mechanism for workers' compensation insurance companies that can replace the current experience modification rating (EMR) approach. Additionally, the data comparison utility offered by the DEA model and its criteria can be helpful for insurance companies to provide effective advice to their clients on which safety aspects to improve in their future strategies. Future research is required to consider input from insurance and construction companies when fine-tuning the criteria and developing the thresholds for insurance rates to allow for fair and realistic rates. A survey of both insurance and construction companies could be used to develop a concise set of criteria that is trackable by both industries. Finally, field testing to measure the effectiveness of the model is another important future research direction.

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