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A Framework for an Automated Decision Support System for Selecting Safety-Conscious Contractors

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***Abstract*—**Selection of competent contractors for construction projects is usually accomplished through competitive bidding or negotiated contracting in which the contract bid price is the basic criterion for selection. The evaluation of contractor's safety performance is still not a typical criterion in the selection process, despite the existence of various safety prequalification procedures. There is a critical need for practical and automated systems that enable owners and decision makers to evaluate contractor safety performance, among other important contractor selection criteria. These systems should ultimately favor safety-conscious contractors to be selected by the virtue of their past good safety records and current safety programs. This paper presents an exploratory sequential mixed-methods approach to develop a framework for an automated decision support system that evaluates contractor safety performance based on a multitude of indicators and metrics that have been identified through a comprehensive review of construction safety research, and a survey distributed to domain experts. The framework is developed in three phases: (1) determining the indicators that depict contractor current and past safety performance; (2) soliciting input from construction safety experts regarding the identified indicators, their metrics, and relative significance; and (3) designing a decision support system using relational database models to integrate the identified indicators and metrics into a system that assesses and rates the safety performance of contractors. The proposed automated system is expected to hold several advantages including: (1) reducing the likelihood of selecting contractors with poor safety records; (2) enhancing the odds of completing the project safely; and (3) encouraging contractors to exert more efforts to improve their safety performance and practices in order to increase their bid winning opportunities which can lead to significant safety improvements in the construction industry. This should prove useful to decision makers and researchers, alike, and should help improve the safety record of the construction industry.

***Keywords*—**Construction safety, contractor selection, decision support system, relational database.

I. Introduction

COMPETITIVE bidding and negotiated contracting are the traditional mechanisms for selecting a competent contractor to undertake a construction project. In these mechanisms, the bid price is the basic criterion for evaluating and selecting a competent contractor. Contractor safety performance, on past and current projects, is not typically evaluated in the selection process, despite the availability of procedures for contractor prequalification. The consequences of such apathy are compounded by the high rates of construction injuries and fatalities, which ultimately adds extra costs to contractors and owners. The construction industry is currently among the top four hazardous industries in the United States with a fatality rate of 9.7 per 100,000 workers [1].

Neglecting contractor safety performance, as an important criterion in contractor evaluation and selection, might lead to major problems, such as accident rate increase, delays, shutdowns, and productivity losses. These problems usually result in significant cost overruns. In addition, project delays, caused by injuries and fatalities, often lead to additional indirect costs that reduce a project's profit or obliterate it completely [2].

It is clearly evident that there is a crucial need for practical, automated systems to assist owners and decision makers in evaluating contractor safety performance, among contractor selection criteria; and accordingly rewarding safety-conscious contractors by the virtue of their safety performance and programs. The benefits of developing such a system include: (1) increasing the likelihood of selecting safety-conscious contractors, leading to safer job sites and reduced construction risks [3], [4]; (2) decreasing the odds of experiencing accident-related productivity losses and project cost overruns [5]; and (3) inspiring contractors to improve their safety performance to become more competitive, ultimately leading to significant safety improvements in the construction industry [6].

The purpose of this paper is to present a newly developed framework for automating contractor safety performance evaluation based on a number of indicators - and their related metrics – which have been proposed by various agencies and researchers, including the Occupational Safety and Health Administration (OSHA). OSHA's indicators include the Incident Rate, and Lost Time Case Rate.

In order to develop the framework, a research study has been conducted in three main phases: (1) establishing safety indicators that represent contractor current and past safety performances - and their metrics; (2) conducting a survey to solicit expert input regarding the indicators, their metrics, and relative significance; and (3) developing a decision support system that integrates the identified indicators and metrics into a relational database system for assessing and rating the safety performance of contractors (see Fig. 1). The following sections discuss these three phases in more detail.

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A. Phase 1: Establishing the Indicators of Contractor Safety Performance

Various methods were proposed in the relevant literature to evaluate contractor safety performance and prequalify contractors for construction jobs. These methods included developing safety performance indicators such as OSHA's Incident Rate, the Experience Modification Rate (EMR) and the Score Card (SC) system. Despite the contribution of these studies and indicators to safety performance assessment, most of these studies and indicators are inefficient in evaluating contractor safety performance as they are either non-comprehensive, unreliable due to the lack of reliable data on contractors, or only reflect the contractor past safety performance – without consideration to the contractor's current performance. A more comprehensive method of safety performance evaluation is needed to avoid the aforementioned shortcomings. To ensure that the envisioned system will be comprehensive, reliable, and includes current and historical performances, special attention was paid to the process of identifying and selecting safety performance indicators and their related metrics. In order to produce a comprehensive list of indicators that depict contractor current and past safety performance, a detailed literature review of relevant research studies was conducted. In the course of this process, several indicators and metrics were identified from studies on evaluating contractor safety performance [6]-[8], studies on analyzing construction site accidents [9], standardized checklists adopted by major construction companies to assess safety aspects at the construction sites, and safety standards published by international organizations or adopted by the construction industry (including OSHA).

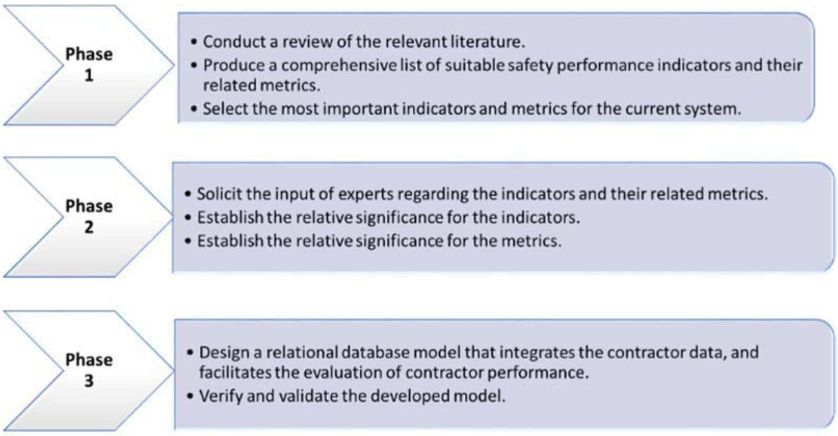

Fig. 1 Framework development phases

The identified indicators were consolidated to a list that represents the most critical and common indicators, in order to facilitate evaluating their relative significance and integrating them into a practical system for contractor safety performance evaluation. It was necessary to ensure that the list of selected indicators is not just limited to the project level but also extends to cover the company-level safety policies, as safety issues at the project level are usually influenced by decisions made at the company level [8]. Despite the complexity that results from including company-level safety policies in the assessment, it is considered essential in order to ensure providing a comprehensive evaluation.

The list of identified indicators includes ten major indicators: (1) safety policy and management commitment; (2) accident investigation, recording and analysis; (3) project occupational health, safety and environmental controls; (4) personal protective and lifesaving equipment; (5) fire protection and prevention; (6) tools and equipment; (7) scaffolds; (8) fall protection and prevention; (9) stairways and ladders and (10) excavations. Fig. 2 illustrates the selected indicators.

B. Phase 2: Soliciting Expert Input

In order to design the envisioned comprehensive, objective decision support system it is essential to solicit input from field experts on the validity of the list of identified indicators and establish the relative significance of the valid indicators and their metrics. To this end, a questionnaire survey has been designed as a means for soliciting such input from experts, including safety managers, engineers, supervisors, superintendents, owners, and field workers.

The questionnaire focuses on rating the 10 identified indicators and their individual metrics in order to establish their relative significance, using rank ordering and a Likert bipolar scale of 1-5; representing "very low" to "very high" effect, respectively.

In order to establish the relative significance of the indicators and their related metrics, the method used by the author of [10] is adopted. Using this method, the Mean Ranking (MR) and Relative Significance (RS) of each indicator can be computed as illustrated by (1) and (2), respectively.

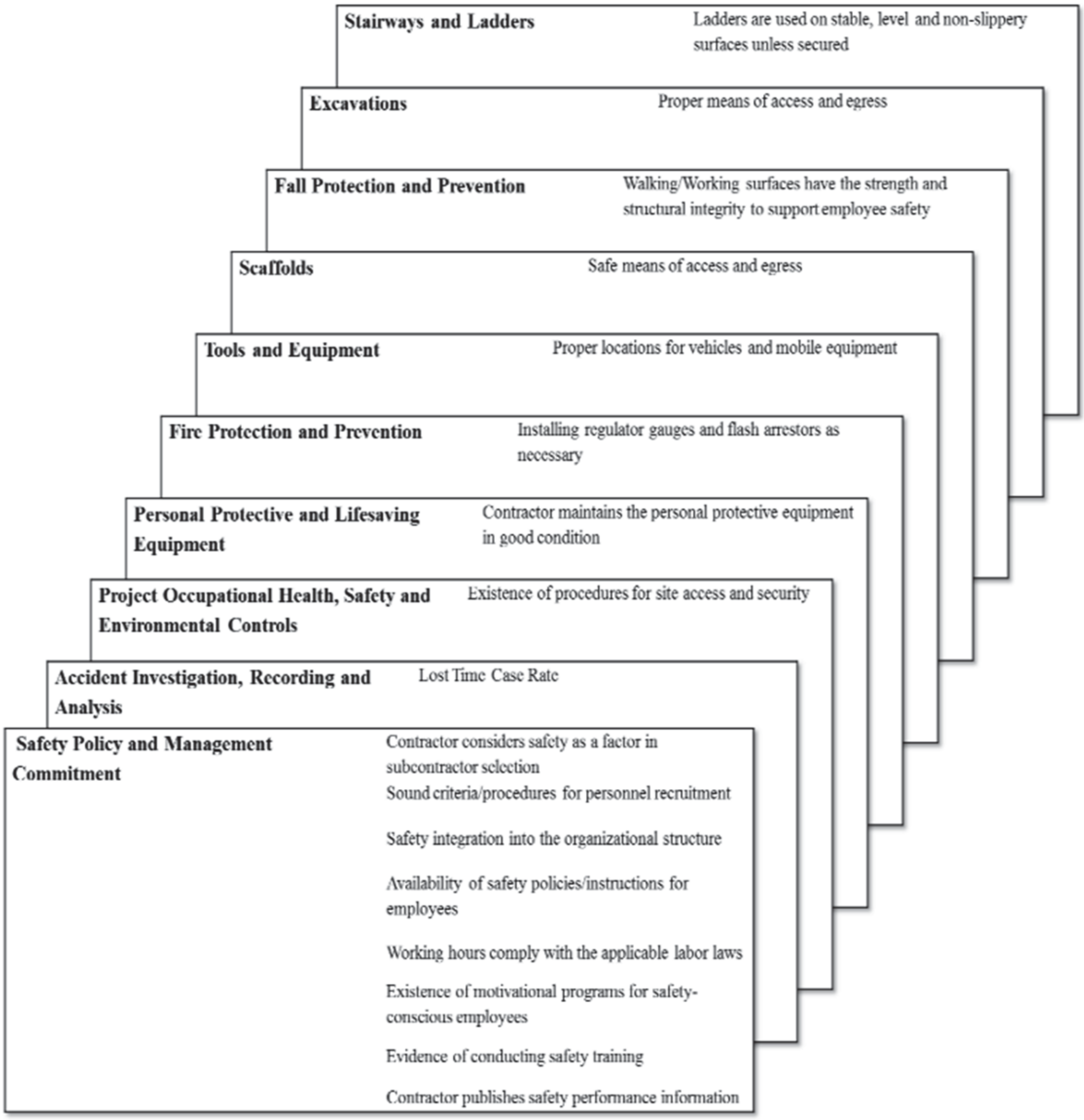

Fig. 2 Major Safety Performance Indicators in the Current System and their Related Metrics

$$\text{MR indicator} = \sum \frac{f * r}{N}, (1 \leq \text{MR} \leq 5) \quad (1)$$

where f = rating frequency of the responses obtained for each individual indicator; r = ranking given to each indicator by the respondents; and N = total number of responses for the relevant indicator.

$$\text{RS}_i = \frac{\frac{\sum_{i=1}^{N} \text{MR}_i}{\text{MR}_i}}{\sum_{i=1}^{N}\left(\frac{\sum_{i=1}^{N} \text{MR}_i}{\text{MR}_i}\right)} \quad (2)$$

where RSi= relative significance of ith indicator; and MRi = mean ranking of ith indicator.

Similarly, in order to compute the Mean Score (MS) for each metric of an indicator, (3) is used; and, accordingly, the RS for each metric can be computed as illustrated in (4):

$$\text{MS metric} = \sum \frac{f * s}{N}, (1 \leq \text{MS} \leq 5) \quad (3)$$

where f = rating frequency of the responses obtained for each individual metric; s = score given to each metric by the respondents; N = total number of responses for the relevant metric.

$$\text{RS}_{ji} = \frac{\text{MS}_{ji}}{\sum_{j=1}^{N} \text{MS}_{ji}} \quad (4)$$

where RSji= relative significance of the jth metric of the ith indicator; MSji = mean score of jth metric of the ith indicator.

C. Phase 3: Developing a Decision Support System

A relational database model has been designed as the backbone of a decision support system that enables owners and decision makers to investigate, and rate the performance of each bidding contractor. This model is developed to achieve a number of objectives. First, it facilitates the integration of the metrics of the identified indicators, and the overall system of indicators. Second, it enables the storage and retrieval of the essential contractor safety performance parameters. These parameters include the Weight Score (WS) for each metric. Third, it facilitates computing the Performance Index (PI) that reflects the score assigned to each individual metric of an indicator based on the contractor performance and the contractor overall safety performance score which is the sum of all PIs. Based on this score, the contractor is categorized into one of four groups (weak, satisfactory, good and very good), as illustrated in Tables I and II. This categorical method has been recommended in the literature [6]. Fourth, the model facilitates the storage and retrieval of the generated results on the safety performance evaluation for each contractor.

The model is composed of two main tables: "Contractors" table and "Safety Performance Evaluation" table. The "Contractors" table is designed to store information about the state's contractors, including contractor name, ID, type, year of establishment, capital, membership, address, etc. The "Safety Performance Evaluation" table is designed to store data about the safety performance evaluation, including year of evaluation, WS and PI for each metric and the contractor overall safety performance score. The "Contractors" table is linked to the "Safety Performance Evaluation" table using a one-to-many relationship.

$$\mathrm{PI}_{ji} = \frac{\mathrm{WS}_j * \mathrm{RS}_{ji} * \mathrm{RS}_i}{4} * 100 \qquad (5)$$

where PIji= performance index of jth metric under ith indicator; and WSj = weighted score of the jth metric

Fig. 3 illustrates the data flow within the proposed system and the beneficiary parties.

The system is designed to aid owners in evaluating contractor safety performance. However, owners may not have enough experience to enable them to assign scores to the individual metrics, which is essential for the system to function. To assist owners with this issue, the database of the system is proposed to be maintained and operated by the local or national safety administration responsible for handling safety and health records (e.g. OSHA in the US). Such an authority would be responsible for collecting contractor safety data on a regular basis, and facilitating access to the database for interested owners.

To facilitate the use of the system, a graphical user interface is developed. It consists of a set of forms and reports that streamline entering, processing and storage/retrieval of all necessary contractor data and safety performance evaluations data.

TABLE I
HIERARCHY FOR CLASSIFYING CONTRACTORS BASED ON SAFETY PERFORMANCE

Indicator *i*	Metric *j*	True contractor performance weak (1) $\mathrm{PI}_{ji}=\frac{1*\mathrm{RS}_{ji}*\mathrm{RS}_i}{4}*100$	Satisfactory (2) $\mathrm{PI}_{ji}=\frac{2*\mathrm{RS}_{ji}*\mathrm{RS}_i}{4}*100$	good (3) $\mathrm{PI}_{ji}=\frac{3*\mathrm{RS}_{ji}*\mathrm{RS}_i}{4}*100$	very good (4) $\mathrm{PI}_{ji}=\frac{4*\mathrm{RS}_{ji}*\mathrm{RS}_i}{4}*100$
1-10	1	PI_{1i}	PI_{1i}	PI_{1i}	PI_{1i}
	2	PI_{2i}	PI_{2i}	PI_{2i}	PI_{2i}
	.	.	.	.	.
	.	.	.	.	.
	.	.	.	.	.
	N	PI_{ni}	PI_{ni}	PI_{ni}	PI_{ni}
Total		PI_{ji} Total 1	PI_{ji} Total 2	PI_{ji} Total 3	PI_{ji} Total 4

Note: n is the number of the metrics related to each indicator

II. POTENTIAL BENEFITS OF THE SYSTEM

The system is designed to be simple-to-use as a direct tool for evaluating contractor safety performance. First, the system evaluates and records the contractor safety performance using the aforementioned indicators and their respective metrics, and then the contractors are classified according to their evaluations. As such, the system should facilitate selecting safety-conscious contractors for construction jobs, and as such, on the long term, it is expected to improve the safety of the construction industry.

TABLE II
CATEGORIZING CONTRACTORS ACCORDING TO THEIR OVERALL SAFETY PERFORMANCE SCORE

Overall safety performance score	Contractor Performance
< PI_{ji} Total 1	Weak
PI_{ji} Total 1 to PI_{ji} Total 2	Satisfactory
PI_{ji} Total 2 to PIji Total 3	Good
PI_{ji} Total 3 to PI_{ji} Total 4	Very Good

A. Safety-Conscious Contractor Selection

In order to increase the opportunity of having a safe work environment on construction sites, owners are encouraged to include contractor safety performance as a criterion among the criteria they use for contractor selection. This is essentially important in such cases when the bidding prices are close, or when there is limited tolerance toward accepting risk of accidents/delays. Government authorities and other public owners might find the proposed system useful in prequalifying and clearing only contractors with good safety records to bid on government projects. As the system records and tracks the contractor safety performance history, it is expected to provide such support and should also be useful in determining how to penalize contractors with consistently poor safety records.

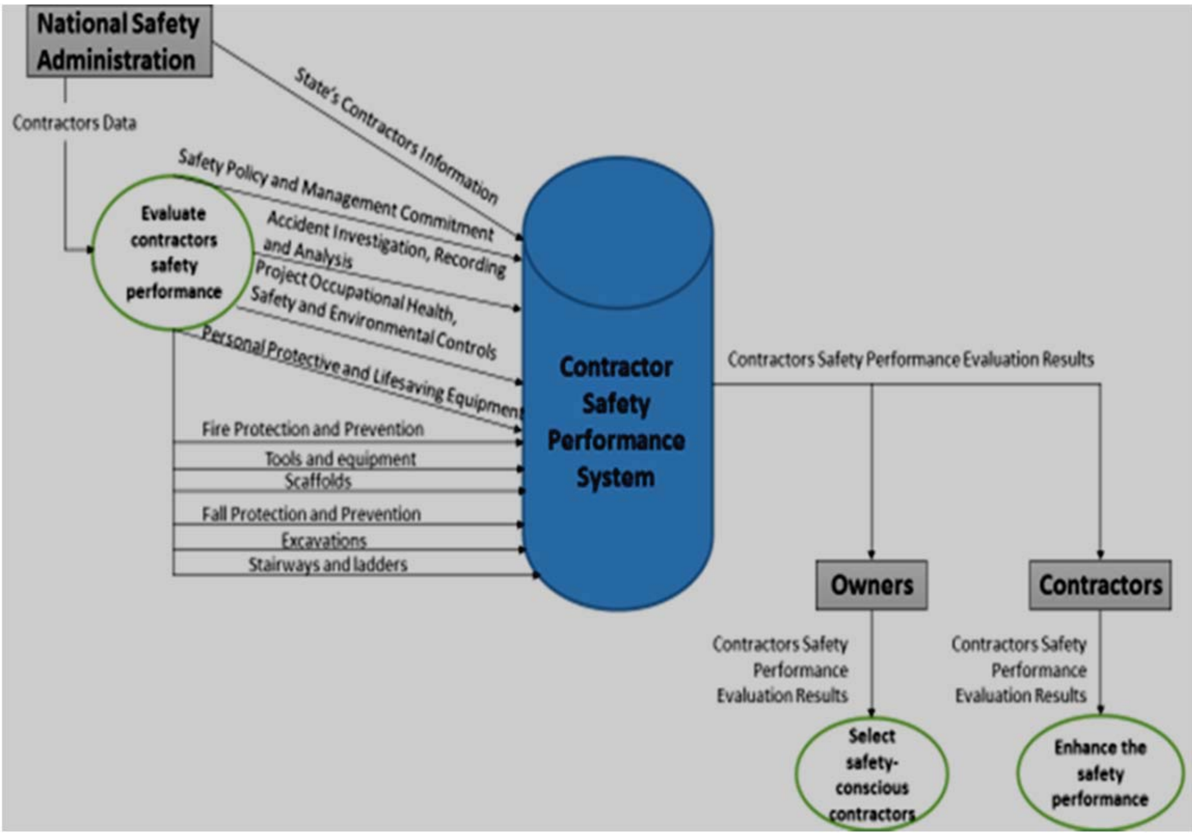

Fig. 3 Data Flow Diagram

B. Enhancing Contractor Safety Performance

The existence of this system may increase the likelihood of including contractor safety performance as one of the contract selection criteria. As such, it can put pressure on contractors to exert more efforts towards enhancing their safety performance in order to increase their opportunity for winning bids and avoiding civilian and criminal penalties that might result from consistently poor safety records. In addition, the results of the safety performance evaluation generated by the proposed system should assist contractors in identifying the critical factors that contribute to their safety evaluation, and the areas where improvement is needed. Necessary corrective actions can then be taken if needed to enhance contractor safety performance. In the long term, this should lead to significance improvements to the safety of the construction industry.

III. Conclusion

This paper presents a framework for a proposed decision support system that supports owners and decision makers in evaluating contractor safety performance. The system is envisioned to be used when contractor safety performance is considered among the criteria for selecting a contractor for a construction job. The development of the framework is in three phases: (1) selecting the indicators that portray contractor both current and past safety performance and their metrics; (2) soliciting experts input regarding the indicators, their metrics, and RS; and (3) developing a decision support system based on a relational database model to integrate the metrics of the identified indicators. The system rates the safety performance of the contractor and accordingly the contractor is categorized in one of four categories that reflect the safety performance. The proposed system should prove useful to owners and decision makers in selecting safety-conscious contractors for construction projects, and in the long term is expected to contribute to improving the safety of the construction industry.

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