

Framework for Monitoring and Measuring Construction Safety Performance

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Due to the hazardous nature of the construction environment, the construction industry experiences one of the highest rates of occupational injuries, illnesses, and fatalities when compared with other industries. Incidents statistics in the construction industry obviously show an immediate need to reduce the prevalence of these severe and costly occurrences. Research needs exist to transition from the use of lagging indicators (outcomes of injury, illness, or accident) to the strategic analysis of leading indicators (preventive actions). These leading indicators can be used to monitor and predict safety performance in order to prevent future accidents. The objective of this research is to present and validate a framework for monitoring and measuring safety performance on construction sites through the statistical analysis of safety indicators data. The proposed framework is intended to proactively identify hazardous behaviors and conditions that can be analyzed to determine predictor variables of future incidents on construction sites. A statistical modeling process is utilized to identify specific variables that have high correlations of events and incidents that pose dangers to the safety and health of workers on construction sites. The analysis and predictive capabilities of the framework are tested using an illustrative case study of data containing safety incidents. Results of the study elicit the potential capability of the framework for monitoring and measuring construction safety performance. The findings of the illustrative case study also indicate that leading indicators such as near misses and safe work observations influence safety performance and can be used to predict future injuries or accidents (i.e. lagging indicators) on construction sites.

Keywords: Construction safety performance, leading and lagging indicators, monitoring, measuring, statistical analysis and prediction.

Introduction

The construction industry experiences one of the highest rates of occupational injuries, illnesses, and fatalities when compared with other industries (Bansal, 2011; BLS, 2015). Construction workers are exposed to hazards and conditions that are somewhat complex to measure due to the unique nature of construction activities. As the work locations for any group of workers change frequently, each work site also advances as construction progresses, changing the hazards workers face daily (McDonald et al., 2009). Poor safety on construction sites physically and psychologically affects workers and impacts the project financially by increasing direct and indirect costs (Bansal, 2011). The statistics of incidents in the construction industry clearly show an immediate need to reduce the prevalence of fatal and non-fatal injuries in construction (Seo et al., 2015) and thus a need for continuous monitoring and measurement of construction safety performance.

The probability of injuries or accidents can be described as a joint outcome of hazardous conditions and at-risk behaviors (such as near misses, unsafe conditions, unsafe actions, etc.), and chance variations as theorized by Heinrich's safety pyramid (Abdelhamid & Everett, 2000; Marks et al., 2016). The safety pyramid depicts the concept that a multitude of minor incidents (such as hazardous conditions and at-risk behaviors) are required for one major incident to occur. Data from these minor injuries or leading indicators can be analyzed to predict safety performance and can help preclude major injuries or fatalities on construction sites.

A proactive measurement requires the adoption of a safety approach that is not dependent on the monitoring of injuries after they occur. Safety-related practices can be actively measured during the construction phase to trigger positive responses before an injury occurs (Hallowell, et al., 2013; Awolusi & Marks, 2016; Akroush, 2017). The main purpose of measuring safety performance is to create and implement intervention strategies for potential avoidance of future accidents (Grabowski et al., 2007). To achieve zero incidents, proactive and active methods of safety management should also occur during the construction phase (Hallowell et al., 2013). Current safety performance and potential risks in the operation or in the facility can be predicted in advance, and one can take proactive actions to avoid the occurrence of an accident (Chen & Yang, 2004). There is, therefore, a need for continuous monitoring of safety performance indicator to reduce illnesses, injuries, and fatalities on construction sites and enhance safety performance. The objective of this research is to present and validate a framework for monitoring and measuring safety performance on construction sites through the statistical analysis of safety indicators data. The analysis and predictive capabilities of the framework are tested using an illustrative case study of safety data containing 297 records of safety incidents (i.e. leading and lagging indicators) that can be used for measuring safety performance on a construction site.

Construction Safety Performance Measurement

Construction safety performance has traditionally been measured by "after-the-loss" type of measurements such as accident and injury rates, incidents and costs (Grabowski et al., 2007). However, most of these methods are reactive or subjective approaches because accident statistics only show the performance of safety management in the past (Dagdeviren et al., 2008) and are reactionary. The fundamental goal of measuring safety performance is to intervene in an attempt to mitigate unsafe behaviors and conditions that can lead to accidents on construction sites.

The term "indicators" is used to mean observable measures that provide insights into a concept that is difficult to measure directly; a safety performance indicator is a means for measuring the changes over time at the level of safety as the result of actions taken (OECD, 2003). An indicator is a measurable and operational variable that can be used to describe the condition of a broader phenomenon or aspect of reality. An indicator can be considered any measure (quantitative or qualitative) that seeks to produce information on an issue of interest (Reiman & Pietikainen, 2012). Safety indicators can play a key role in providing information on organizational performance, motivating people to work on safety, and increasing the organizational potential for safety.

Performance measurements can either be reactive monitoring or active monitoring (HSE, 2006). The former means identifying and reporting on incidents, and learning from mistakes, whereas the latter provides feedback on performance before an accident or incident occurs. Safety metrics fall into two categories: 1) lagging indicators, which are linked to the outcome of an injury or accident; and 2) leading indicators, which are measurements linked to preventive actions (Toellner, 2011). Lagging and leading indicators are further described in the following section.

Lagging and Leading Indicators

Safety performance metrics can be divided into lagging and leading indicators (Hallowell et al., 2013). Lagging indicators are related to reactive monitoring and show when the desired safety outcome has failed, or when it has not been achieved (Oien et al., 2011). When a lagging indicator of safety is used, the information is by definition historical in nature. If the number of injuries is unacceptable, a response is generated that will hopefully prevent or reduce the number of future occurrences. Despite such efforts, they are implemented only after injuries have already occurred (Hinze, 2005). Lagging indicators do not provide further insights into the existing safety conditions once an accident has occurred. The most commonly used lagging indicators are accident rate, lost workday injuries, medical aid cases, first aid cases, and Experience Modification Rate (EMR).

Conversely, leading indicators are a form of active monitoring which determines that risk control systems are operating as intended (Fearnley & Nair, 2009). Leading indicators are simply those metrics associated with measurable systems or individual behaviors linked to accident prevention. These indicators focus on maximizing safety performance by measuring, reporting, and managing positive, safe behaviors (Toellner, 2011). Leading indicators of safety performance are used as predictors of safety performance to be realized. They are used as inputs that are essential to achieving the desired safety outcome (Oien et al., 2011). Leading indicators are directly related to the project that is to be undertaken and are concentrated on the safety management process (Hinze, 2005). Leading indicators give the probability that a safe project will be delivered by providing the opportunity to make changes as soon as there is an indication that the safety program has a weakness. The common leading indicators used in construction are near miss reporting, worker observation (to determine unsafe conditions and acts), job site audits, stop work authority, housekeeping, safety orientation, and training, etc.

Method

This section explains the research methodology implemented for this study. The research approach involves the presentation of a framework for monitoring and measuring construction safety performance through the statistical analysis of safety indicators data. An illustrative case study is also designed to test the analysis and predictive capabilities of the framework. In this case study, 297 records of leading indicators (unsafe conditions, unsafe act, and near misses), lagging indicators (property damage, first aid, and medical aid), and other metrics for measuring safety performance were extracted from a safety data collected on a construction site over a one-year duration. The identified safety indicators were input into multiple statistical predictive models to better understand how individual safety metrics or indicators can predict incidents on construction sites.

Results and Discussion

The results and discussion of the findings of this research are presented in this section. The presented framework for the monitoring and measurement of construction safety performance provides a procedure that can be used to identify, collect, and analyze safety indicators for incidents prediction and prevention on construction sites. The results of the illustrative case study implemented to test the framework are also presented and described.

Framework for Monitoring and Measuring Safety Performance

This framework is presented as the basic procedure for the identification, collection, and analysis of safety performance indicators for incidents prediction and prevention on construction sites. This framework implements a systematic and statistical data collection and analysis technique and can be a vital component in the data flow within a safety program. Part of the important factors considered when setting up a safety monitoring procedure is the size and structure of the organization and the operational environment. The scope of monitoring should encompass operational, technical, and organizational safety management aspects which are rooted in the organization's safety program. The basic steps involved in the proposed framework for monitoring and measuring safety performance in construction are illustrated in Figure 1 and further described in the following sections.

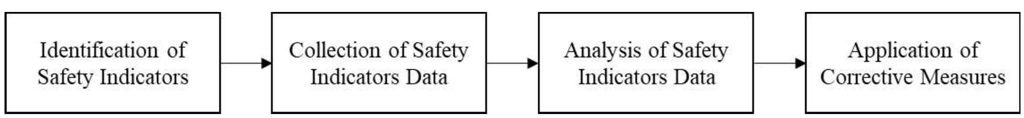

Figure 1: Framework for Monitoring and Measuring Safety Performance

Step 1: Identification of Safety Indicators

This step involves the identification of safety metrics or indicators that need to be captured in order to measure safety performance on a given construction project. These safety indicators will include both leading (proactive) and lagging (reactive) indicators as described previously in this paper and can either be quantitative or qualitative. Information about the types of indicators to be monitored can be obtained from the organization's safety program. Indicators selected are most efficient when they are aligned with the specific safety goals of an organization and the associated work process. The criteria used to select the indicators may involve the organization's present safety performance level, such as the stages of development of their safety program and their safety culture. For example, an organization that is already implementing auditing process to achieve safety compliance can transition into continuous safety monitoring and measurement to improve their safety program by introducing other leading indicator programs such as near-miss reporting, worker observation process, safety activity analysis, etc. Examples of leading indicators that can be tracked on construction sites are near-misses, unsafe behaviors or acts, unsafe conditions, etc. Common lagging indicators that can be monitored on construction sites are OSHA recordable incidents, lost workday injury or lost time, medical case injury, first aid, property damage, environmental incidents, etc.

Step 2: Collection of Safety Indicators Data

This involves the collection of safety indicators data through the active tracking or monitoring of work environment and workers activities on construction sites. This process can be achieved through an effective safety program involving proactive safety practices such as near-miss reporting, project management team safety process involvement, worker observation process, job site audits, housekeeping program, stop work authority, and safety orientation and training. The data obtained from these processes are documented and recorded in a safety management repository for the organization with database capabilities to house the collected data. The collection of data from all safety monitoring activities should be a systematic process to ensure interrelationships are identified. For instance, in the work observation process where workers on site are observed in order to identify critical safety behaviors and conditions, snap-observation or snap-reading method could be adopted. Examples of such observations could include workers entering confined space without a harness or standing in an open and unshored trench, workers not wearing hard hats while on a construction site, or workers picking up a load without bending the knees. Automated activity recognition of construction workers and their work environments can also be used to capture safety indicators data.

Step 3: Analysis of Safety Indicators Data

In this step, statistical modeling processes are used to analyze the safety indicators data to identify specific variables that have high correlations and effects on events and incidents experienced on the construction sites. The safety indicators are analyzed and incidents trends, associated causes, and influencing factors are established. Details from safety incident data will be analyzed to proactively identify predictor variables (e.g. hazardous acts and conditions) of future incidents on construction sites. Since leading indicators of safety performance require meaningful and actionable metric (which measures actions and conditions that can be controlled), they must be quantifiable and numeric. For instance, a hazardous act (i.e. unsafe act) which is qualitative in nature can be observed and quantified numerically as a binary data (which indicates either the absence or presence of the act and usually represented by 0 and 1), or count data (which indicates number of occurrences and can take only non-negative integer values). To supply deeper information on qualitative data such as a hazardous act or condition, a Likert scale can be used to express the severity (e.g. low, medium, or high severity). A broad range of statistical prediction models or analytical tools (such as Poisson regression model, Binary logistic regression model, etc.) can be implemented to identify correlations of multiple variables derived from the safety incidents data obtained from construction sites. These models are selected based on the nature of variables extracted from the safety data. Additionally, various computations are carried out on the collected data to transform the safety indicators data into useful information. The graphical presentation of the results is also produced to reflect the measurements of safety performance on the construction site.

Step 4: Application of Corrective Measures

This stage involves the correction of hazardous acts or conditions (such as near misses, unsafe behaviors, and conditions) that have the potential for future accidents by training the workers and making necessary changes on the construction site. At this stage, decisions are made by the management of the organization based on the results of the analysis and the recommendations for corrective measures and improvements are provided by the safety management team in the organization. Corrective actions are determined and acted on wherever the monitoring indicates that an element is approaching a point which may affect safety to an intolerable level. Coordination with pertinent units and departments should take place as required. Appropriate plans are made to implement the required corrective measures which should follow a continuous improvement process. Results are tracked and feedback on performance is provided to the relevant audiences within the organization. A broader audience (including all other site personnel) should be informed of the reported indicator events and corrective actions taken; both steps should be communicated as soon as possible (i.e. the next day’s toolbox talks if possible). Safety managers should integrate lessons learned from the reported leading indicators events and data analysis results into existing safety training.

Case Study for the Analysis of Safety Indicators Data

Although, several efforts have been made to mitigate injuries and accidents on construction sites, the benefits of developing predictive models to analyze the effects of construction safety indicators need to be explored. In an attempt to create such a predictive model, a possible mistake would be to simply opt for the traditional regression techniques using linear regression methods. The use of linear regression analysis apparently imposes certain limitations on the model, especially because certain observations may be nonlinear, and cannot be modeled as such. The main drawback associated with nonlinear regression is the increase in complexity compared with traditional linear regression. Poisson regression is rarely mentioned as a modeling technique for construction concepts. Poisson regression is a form of regression analysis used to model count data, which assumes that the dependent variable consists of nonnegative integers. For example, the number of first aid cases or injuries that occur on a construction site can be analyzed using a Poisson regression model. The events must be independent in the sense that the occurrence of one will not make another more or less likely, but the probability per unit time of events is understood to be related to covariates.

Count data are often modeled as a continuous variable instead of a discrete variable, using traditional least squares regression methods (Wallace et al., 1999). This approach is not strictly correct because regression models yield predicted values that are non-integers and can also predict values that are negative, both of which are inconsistent with count data. These limitations make standard regression analysis inappropriate for modeling count data without modifying the dependent variable (Washington et al., 2011). In this study, 297 observations of leading indicators (unsafe conditions, unsafe act, and near misses), lagging indicators (property damage, first aid, and medical aid), and other metrics for measuring safety performance were collected on a construction site over a one-year duration. The data are non-negative integers with the mean approximately equal to the variance, thus, the data are well suited to the Poisson regression approach. The Poisson model is specified in Equation 1 (Washington et al., 2011; Devore, 2015):

$$P(y_i)=\frac{EXP(-\lambda_i)\lambda_i^{y_i}}{y_i!} \tag{1}$$

where $P(y_i)$ is the probability of a construction site i having y number of lagging indicators (e.g. first aid cases), and λ_i is the Poisson parameter for construction site i. The Poisson parameter is equal to the expected number of lagging indicators (e.g. first aid cases) that occur on the construction site [i.e., $E(y_i)$]. The Poisson parameter is specified as (Washington et al., 2011; Devore, 2015):

$$\lambda_i=EXP(\beta X_i) \text{ or equivalently } LN(\lambda_i)=\beta X_i \tag{2}$$

where X_i is a vector of explanatory variables and β is a vector of estimable parameters or coefficients. This model can therefore be estimated by using standard maximum likelihood methods, with the likelihood function given in Equation 3 (Washington et al., 2011; Devore, 2015).

$$L(\beta)=\prod_i \frac{EXP[-EXP(\beta X_i)][EXP(\beta X_i)]^{y_i}}{y_i!} \tag{3}$$

The log of the likelihood function is simpler to manipulate and more appropriate for estimation and is given in Equation 4 (Washington et al., 2011; Devore, 2015).

$$L(\beta)=\sum_{i=1}^{n}\left[-EXP(\beta X_i)+y_i\beta X_i-LN(y_i!)\right] \tag{4}$$

The variables available for model specification are presented in Table 1. From the summary statistics, the mean of the number of first aid cases experienced on the construction site was 0.138 while the standard deviation was 0.383 (i.e. variance of 0.146). Since, the mean, $E(y_i)$ and variance, $var(y_i)$ are very close (i.e. approximately equal), the assumption of a Poisson regression model for the analysis of this distribution holds.

Table 1: Variable Available for Model Specification

Variable Description	**Mean**	**Standard Deviation**
Day of the Week Indicator	3.798	1.921
Season of the Year Indicator	6.781	3.156
Proactive Interventions Indicator	0.953	1.413
Safe Work Observations Indicator	0.657	1.521
Unsafe Conditions Indicator	3.579	6.520
Unsafe Acts Indicator	2.990	3.557
Near Misses Indicator	0.259	0.573
Property Damage Cases Indicator	0.182	0.443
First Aid Cases Indicator	0.138	0.383
Medical Aid Cases Indicator	0.007	0.082

The model estimation results are shown in Table 2 and the corresponding average partial (marginal) effects are also presented in Table 3. Out of the variables available for model estimation, five variables were found to have significant effects on the number of first aid cases recorded on the construction site. One of the variables was the indicator for midweek which had a parameter estimate of 0.789 and z-statistic of 2.110. These results indicate that more first aid cases are more likely to be experienced midweek and the partial effects also show that the number of first aid cases recorded is likely to increase by 0.141. Similarly, first aid cases are more likely to be experienced on the fourth day of the workweek as indicated in the parameter estimate (0.569) and the value of the partial effects implies that the number of first aid cases recorded on the construction site is likely to rise by 0.097 on that day. The reasons for these results could be that construction activities on the site might be at the peak midweek and the day after which can correspondingly increase the number of first aid cases. According to Bryson and Forth (2007), people work the longest days, on average, in the middle of the week. These days can be taken as the days in the middle of the week and the workers would have been very much submerged into their various tasks on those days of the week. The busier the workers are (i.e. the longer they work), the more likely it is that they experience more incidents due to fatigue and other harsh conditions of the construction environment.

The other variable that significantly affected the number of first aid cases was last month of autumn indicator which had a parameter estimate of -1.413 and z statistics of -1.390. This implies that first aid cases are less likely to be recorded in this month. The result of the partial effects also suggests that the number of first aid cases recorded on the construction site is likely to reduce by 0.112 in the last month of autumn. This could be due to the peculiarities of the construction project such as the nature of tasks executed in that month of the year. It could also be that less amount of work is undertaken in that month due to weather which might reduce the first aid cases experienced during that period.

Table 2: Truncated Poisson regression of the first aid cases

Variable Description	**Estimated Parameter**	**z-statistic**
Midweek Indicator (1 if day of the week is Midweek, 0 otherwise)	0.789	2.110
Fourth Day of Workweek Indicator (1 if day of the week is fourth day of workweek, 0 otherwise)	0.569	1.370
Last Month of Autumn Indicator (1 if month is Last month of Autumn, 0 otherwise)	-1.413	-1.390
Safe Work Observations Indicator	-0.448	-1.710
Near Misses Indicator	-0.486	-1.260
Number of observations	297	
Log-likelihood (at zero)	-124.960	
Log-likelihood at convergence	-116.858	
Chi-squared	16.202	

Table 3: Average partial (marginal) effects for the truncated Poisson regression model

Variable Description	**Partial Effect**
Midweek Indicator (1 if day of the week is Midweek, 0 otherwise)	0.141
Fourth Day of Workweek Indicator (1 if day of the week is fourth day of workweek, 0 otherwise)	0.097
Last Month of Autumn Indicator (1 if month is Last month of Autumn, 0 otherwise)	-0.112
Safe Work Observations Indicator	-0.062
Near Misses Indicator	-0.067

Another major variable that had a significant influence on the number of first aid cases recorded on the construction site was the number of safe work practices observed on the site. This variable had a parameter estimate of -0.448 and z statistic of -1.710 which implies that the more the number of safe work observations, the less the number of first aid cases recorded on the site. The partial effects also show that the number of first aid cases experienced will reduce by 0.062 when workers are seen exhibiting safe work practices. This result is very realistic in the sense that workers' exposure to hazards or unforeseen events are reduced if workers engage in safe practices by, for instance, exhibiting safe working behavior, working in a safe condition, and using the correct personal protective equipment.

The last variable that significantly impacted the number of first aid cases experienced in the construction site was the number of near misses. This variable had a parameter estimate of -0.486 and z statistic of -1.260. This indicates that the more the number of near misses experienced, the less likely it is to experience first aid cases on the construction site. The result of the partial effects also suggests that near-miss reporting is likely to reduce the number of first aid cases by 0.067. The justification for these results could be that the construction workers are using the lessons learned from near miss reporting to forestall or prevent lagging indicators such as first aid cases. The ρ^2 statistic (or McFadden ρ^2) which gives a measure of the overall model fit is computed in Equation 5 (Washington et al., 2011).

$$\rho^2 = 1 - \frac{LL(\beta)}{LL(0)} = 1 - \frac{-116.858}{-124.960} = 0.065 \tag{5}$$

where $LL(\beta)$ is the log-likelihood at convergence with parameter or coefficient vector β and $LL(0)$ is the initial log-likelihood (with all parameters or coefficients set to zero).

The perfect model would have likelihood function equal to one (all selected alternative outcomes would be predicted by the model with probability one, and the product of these across the observations would also be one) and the log-likelihood would be zero, yielding ρ^2 of one. The ρ^2 statistic will be between zero and one, while the closer it is to one, the more variance the estimated model is explaining. For the model in this study, ρ^2 = 0.065.

Conclusion

In this paper, a framework for monitoring and measuring construction safety performance through the statistical analysis of safety indicators was presented. As part of the framework, construction safety indicators were analyzed to determine their level of significance and their relative effects on the safety performance of a construction project. The novelty and contributions of the presented framework lie in the provision of a systematic and statistical data collection and analysis approach for incidents prediction and prevention on construction sites. The framework provides a simplified model that can be easily incorporated into an existing safety program for the active monitoring and measurement of safety performance on construction sites.

Using an illustrative case study, safety indicators extracted from incidents data were used to develop a model (Poisson regression model in the case of this paper) for predicting the likelihood of having accidents (i.e. lagging indicators) on a construction site. The predictor variables chosen in the Poisson regression model for the estimation of the lagging indicator (i.e. first aid cases) recorded on the construction site were considered at a significant level of 0.05. The model is therefore considered good for predicting the lagging indicators (i.e. first aid cases) recorded on the construction site. The implication of this is that some of these leading indicators (such as unsafe behaviors or conditions) that can potentially result in lagging indicators can be controlled in order to prevent future accidents thereby enhancing safety performance. Because the data analysis and prediction portion of the framework was implemented using an illustrative case study, data used for the study considered a limited number of variables or cases. A detailed exploratory study is being undertaken to develop models including more variables that capture all the possible leading and lagging indicators that can be experienced on a typical construction site. The availability of a richer data would ensure that more robust models are developed for the analysis of safety indicators for the measurement of construction safety performance.

The unique contributions of this research include the provision of a safety performance monitoring and measuring framework that can be used to collect and analyze safety data to provide trends of safety performance, set improvement targets, and provide continuous feedback to enhance safety performance on construction sites. This research draws out the benefits of proactive and active monitoring to enhance safety performance on construction sites.

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