



Integration of hazard rectification efficiency in safety assessment for proactive management

Mei Liu, Pin-Chao Liao*

Tsinghua University, Department of Construction Management, rm 405, West Main Building, 100084, Beijing, China



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ABSTRACT

Objective: Safety assessment is crucial for the development of continuous improvement strategies. However, most studies assess construction safety with cross-sectional information and thus management tends to be passive. This study proposes an evidence-based methodology incorporating hazard rectification efficiency for project safety assessment.

Method: First, we theoretically introduced hazard rectification efficiency as a proxy for hazard exposure. Later, based on set-pair analysis, we proposed a safety assessment model that incorporates hazard occurrence and rectification efficiency. Subsequently, we collected site investigation records from seven building projects in Qingdao, Shandong. The data were used to develop a safety performance index (SPI) with the proposed model and a default model. The results were compared and discussed according to industrial practices for validation purposes.

Results: The proposed model provides conservative indications of project safety performance; more importantly, the index calculated with the model provides advance warning when necessary. In the proposed method, in terms of the SPI, hazard and rectification indicators provide actionable information to address failures and improve safety conditions.

Implications: This research describes a new perspective (rectification efficiency) for safety assessment, which supplements the current body of knowledge on safety assessment. The proposed index, SPI, promotes the adoption of proactive hazard identification, monitoring, and control in construction.

1. Introduction

Construction projects are often plagued by poor performance due to risk and uncertainty; to overcome these problems, available historical data is used to anticipate risk and uncertainty (Thompson et al., 2016). It is an internationally accepted practice for construction industries to rely on data such as fatality rates and lost time injury rates as safety performance measures (ACA, 2015; Fang et al., 2004). Physical evaluation of safety conditions and accident recording are the primary management practices in construction site safety. However, management factors influencing site safety are generally ignored (Fang et al., 2004; Wu et al., 2017). Traditionally, improvements in safety have been driven by historical data and thus site safety developments have been reactive and not proactive. For example, the occurrence of a serious injury/fatality or a high accident rate initiates an investigation to identify and prevent such incidents in future. While the frequency of injuries/fatalities is higher in construction than in other industries, the actual frequency of accidents is not high enough to accurately model

and make predictions based on historical data (Hopkins, 2009), particularly when assessing small-scale projects. Although monitoring this data is necessary and will continue to play a role in safety management, these recordable are defined as lagging indicators. The historic nature of a lagging indicator implies that it cannot accurately reflect the current status of safety management systems and environment (Grabowski et al., 2007; Hinze et al., 2013). Therefore, new proactive methods for risk management are needed and advance-warning systems should be developed for the construction industry. Currently, several researchers in the field of safety management are investigating the use of leading indicators for better risk assessment and predictions and to proactively drive safety improvements (Grabowski et al., 2007; Poh et al., 2018; Rajendran, 2013). While trends in safety management are shifting, for the most part, site-based risk management, monitoring, and control in the construction industry are limited to safety checklists and basic probabilistic hazard/risk assessment along with historical incident monitoring. Due to a lack of available statistical information, these evaluation techniques for hazard identification and risk quantification

* Corresponding author.

E-mail address: pinchao@tsinghua.edu.cn (P.-C. Liao).

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rely on expert opinion and subjective interpretation (Pinto et al., 2011). Temporal analysis of safety performance is limited to safety incident statistics, which may not reflect the current project environment and safety performance (Fang et al., 2004; Hinze et al., 2013). Proactive hazard control strategies are only rarely formally being employed to drive performance improvement (Hallowell et al., 2013).

To establish a proactive risk assessment methodology to address the above stated requirements, this study introduces a safety assessment model that incorporates hazard occurrence and hazard rectification as two new contributing elements to risk quantification. An entropy weight method is applied to evaluate risk occurrence for risk quantification. Rectification evaluation based on set-pair analysis (SPA) is considered both as an objective measure of duration of exposure to a given hazard and a leading indicator of safety management performance. Data from 7 construction projects was used to test the performance of the proposed model; further, temporal and safety performance analyses were conducted to validate and facilitate improved risk control and proactive safety management.

2. Literature review

A construction site is a dynamic system with many interactions occurring between resources and workers' activities in the workplace (Pereira et al., 2017). The construction site changes daily and is affected by uncertain factors, such as construction stages, management measures, and safety culture, which adds complexity to safety evaluation protocols in construction processes (Alruqi et al., 2018; Karimiazari et al., 2011; Nielsen, 2014; Yiu et al., 2018). Given the dynamic nature of construction projects, risk quantification, analysis, and mitigation are of utmost importance.

Typical risk evaluation methods in construction are based on the probability and severity of outcomes in a hazardous or dangerous situation (Hou and Zeng, 2016). Severity describes the potential loss incurred as a consequence of an accident while probability is the likelihood that the projected consequence will occur (Pinto et al., 2011). However, the constant weight evaluation of risk quantification taken for this parameter leads to a distortion in evaluation results and hence they cannot reflect the temporal characteristics of workplace conditions. Research into leading or proactive indicators is becoming increasingly popular in the area of construction safety given their potential to provide early warning signs and ability to proactively drive safety improvements (Fang et al., 2004; Grabowski et al., 2007). In light of this, studies in this area have investigated audit and organizational performance (Rajendran, 2013), frequency of safety control implementation (Lingard et al., 2017), safe and unsafe conditions, and hazard frequency and rectification (Awolusi et al., 2017; Hinze et al., 2013; Lingard et al., 2017). However, the assumptions being used currently cannot satisfactorily explain the safety performance of complex and nonlinear systems as they use simple linear causal relationships between indicators (Lingard et al., 2017; Wreathall, 2009). Lingard's study, as shown in Fig. 1, describes cyclical relationships between leading and lagging indicators over time. The evaluation score reflects dynamic relationships between injury frequency and

management actions in a temporal process (Stricoff, 2000).

Furthermore, the role of management as a leading indicator in the incident cycle indicates that workplace safety performance should focus on the outcomes of risk occurrence as well as dynamic management behavior. In this context, effective management strategies have a positive influence on workplace safety (Haadir and Panuwatwanich, 2011; Hon et al., 2010; Mohammadi et al., 2018a). Traditionally, safety level in a workplace is evaluated by lagging indicators and hence safety management is regarded as a fundamental part of tenders for future construction work (Guo and Yiu, 2016; Wu et al., 2017). Safety inspection and supervision are done on site to eliminate risks by checking the frequency of unsafe behavior, evaluating its consequences, and taking management measures (Jiang et al., 2015; Wachter and Yorio, 2014). The research on leading indicators highlights the role of management factors in safety monitoring practices and these have been incorporated in safety management through temporal analysis and monitoring of safety inspection, controls, management measures, and audit and organizational performance (Fang et al., 2004; Lingard et al., 2017; Rajendran, 2013). While risk factor causation analysis confirms that the physical site, humans, and management should all be considered in risk evaluation (Xia et al., 2018), some studies do not take a comprehensive approach to risk evaluation and ignore some of these elements (Awolusi et al., 2017; Hinze et al., 2013).

Furthermore, safety management studies have often focused on passive measures of performance. These include audit assessment of organizational culture and safety procedures and systems (Alruqi et al., 2018; Fang et al., 2004; Zhou et al., 2015). While these studies may facilitate revisions to management strategies and be predictive on a macro-scale, such measures provide little proactive value for monitoring and temporal analysis (Hinze et al., 2013; Mohammadi et al., 2018b). By adopting active or dynamic management variables and proactive construction management systems for assessment purposes, variability in safety throughout the lifecycle of a project may be analyzed, which facilitates the formulation of proactive safety strategies.

In construction, exposure, likelihood, and consequence are contributing factors to risk quantification and prediction (Zhou et al., 2009; Hou and Zeng, 2016). Exposure refers to the amount of time, number of cycles, and number of resources that may result in hazards to people (Chen and Yang, 2004; Zeng et al. (2015)). Risk exposure has also been shown to influence safety participation within an organization (Thurston and Glendon, 2018). Probability (likelihood) is mitigated through effective training, situational awareness, morale and attitude changes, and reducing employee exposure. Safety risk control and exposure both have a significant influence on the true risk levels of a project (Pinto et al., 2011; Thurston and Glendon, 2018). Rectification efficiency is defined as the performance of a management team in rectifying hazards, both physical and activity-based, identified at a given site. It is proposed as a positive indicator of management performance and a measure of the project's resistance to hazard occurrence (Lingard et al., 2017). A previous study (Lingard et al., 2017) incorporated rectification statistics as a monitorable indicator. However, it did not account for the efficiency of management but only monitored the number of hazards resolved in a given period. Therefore, in this study, we aim to develop an approach to evaluate rectification performance to reflect the actual effect of positive management. Our objective is to develop and analyze a performance-based safety evaluation method guided by the following research questions:

- 1 How should rectification performance be evaluated to reflect the actual effect of positive management?
- 2 How should the longitudinal influence of temporal effect to anticipate and overcome risks be evaluated?

3. Methodology

As shown in Fig. 2, this section outlines the evaluation framework

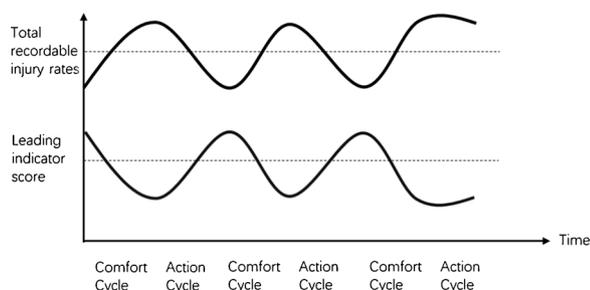


Fig. 1. A theoretical simplified cyclical relationship (Lingard et al., 2017).

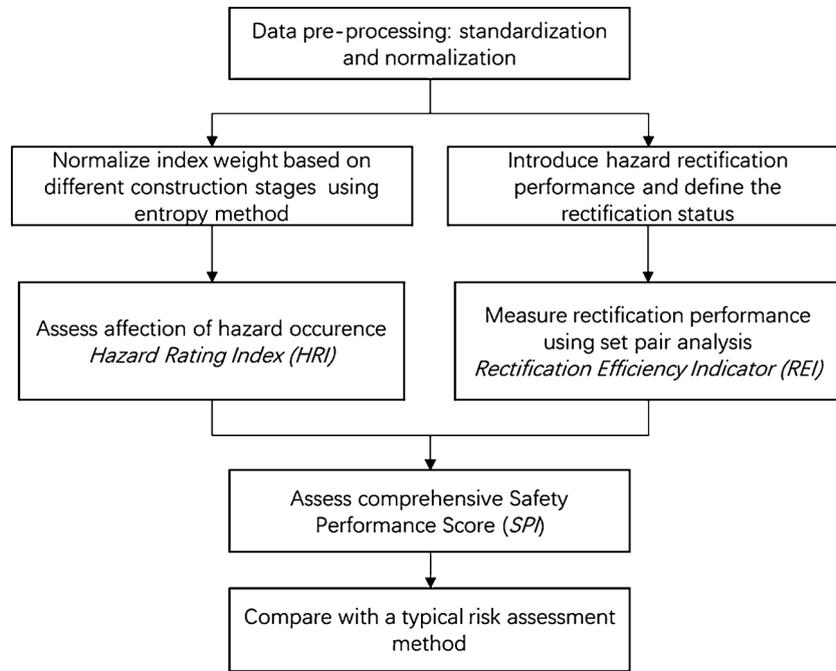


Fig. 2. Outline of the study.

and methodology for two safety performance indicators, Hazard Rating Index (HRI) and Rectification Efficiency Indicator (REI), as well as a comprehensive Safety Performance Index (SPI). The proposed methodology is then applied to a set of 7 building projects and the results are compared with those of a typical risk assessment method.

3.1. Data source

Data were collected from 7 building construction projects (case studies) in Shandong province, China, between June 2016 and January 2018. The 7 projects were almost simultaneously supervised by the same third-party company. Safety inspectors from the third-party company conducted 3–5 site inspections per month of each project and referred to the standard safety checklist JGJ59-2011 (China’s National Standard for Construction Safety Inspection). Inspectors identified both physical hazards and unsafe work practices. Based on the prescribed standard and their experience, inspectors prescribed site teams deadlines to rectify specific hazards (for e.g., 3 days or 5 days) or immediate rectification in the case of critical hazards. Further, the status of hazard rectification was monitored for compliance. Records with a standard list of safety performance indicators and non-conformance details include information on all the hazards identified, the date of occurrence, prescribed rectification deadlines, and rectification status. These scores are then collated for monthly evaluation. Inspection data was provided to the project owner through a safety management platform and shared with the academic research team.

3.2. Process for calculating hazard rating index

The HRI is a measure of the total risk level due to hazards identified on a site. First, the severity of specific hazards is obtained from the Chinese National Standard, Standard for Construction Safety Inspection JGJ59-2011. In this standard, hazard scores are allocated values in the range of 2–20; in this scenario, a large number corresponds to a hazard with greater consequences.

Next, this study applied the entropy weight method to measure hazard weights in different construction stages based on inspection records. It was selected based on its consistency and ability to reduce the bias and subjectivity of hazard weight associated with traditional

probabilistic risk assessment. In this case, a measure of uncertainty of safety hazard occurrence in the presence of a given risk factor, the greater the information and certainty of a given item, the smaller its entropy weight (Dunwen et al., 2012; Li et al., 2007; Wang and Chen, 2017; Yin and Deng, 2018). The process of calculating entropy weights is outlined here (Li et al., 2017).

Initially, the matrix X was established given m samples and n evaluated parameters. In this case, the matrix was constructed considering real hazard inspection data taken from m projects in n hazard categories:

$$X = \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \dots & x_{mn} \end{bmatrix} \tag{1}$$

Matrix X is then transformed into a standard-grade matrix Y:

$$Y = \begin{bmatrix} y_{11} & y_{12} & \dots & y_{1n} \\ y_{21} & y_{22} & \dots & y_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ y_{m1} & y_{m2} & \dots & y_{mn} \end{bmatrix} \tag{2}$$

This transformation was accomplished by constructing a normalization function.

$$y_{ij} = \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})} \tag{3}$$

Next, the ratio of the index value of each index (j) in i samples was calculated.

$$P_{ij} = y_{ij} / \sum_{i=1}^m y_{ij} \tag{4}$$

In the next step, information entropy, e_j, was generated as

$$e_j = \frac{-1}{\ln m} \sum_{i=1}^m P_{ij} \ln P_{ij} \tag{5}$$

Using the value of e_j, entropy weight was calculated according to the following relationship.

$$\omega_j = \frac{1 - e_j}{\sum_{i=1}^m (1 - e_j)} \tag{6}$$

Finally, considering the entropy weight of each hazard category and the severity rating of said hazard, a risk score, w_j , was determined for each risk category:

$$w_j = \frac{w_j^* S_j}{\sum_{j=1}^m \omega_j S_j} \tag{7}$$

where w_j^* is the entropy weight of hazard j adjusted for the number of inspections and S_j is the consequence rating of that hazard. Risk scores for each category may then be adopted in project hazard assessment to generate the HRI of the site.

HRI is standardized with respect to the project inspection area and is a measure of risk density on a construction site. It represents the summation of risk levels, w_i , with identified hazards ($h = 1, 2, 3, \dots, n$) with respect to the total project area, A .

$$HRI_i = \frac{\sum_{i=1}^n w_j}{nA} \tag{8}$$

3.3. Process for calculating rectification efficiency index

3.3.1. Hazard categories based on rectification

Rectification time is the time taken to eliminate hazards. Deadlines for hazard elimination are prescribed by inspectors based on the relevant standards and their experience (for e.g., 3 days or 5 days) or immediate rectification in the case of critical hazards. Considering the state and timeliness of rectification of the identified hazards, the rectification efficiency indicator in an evaluation period can be quantified and characterized into three categories, which are as follows. 1) On-time rectification, where rectification was completed within the prescribed deadline, 2) overdue rectification where rectification exceeded the prescribed deadline, and 3) overdue non-rectification, where risk is outstanding past the prescribed deadline for rectification. These three categories mutually oppose and unify each other for safety assessment, as the sum of their numbers is equal to the number of hazards.

Seven potential scenarios that can occur in a month's time have been identified based on the time for hazard rectification (Table 1).

During a monthly evaluation period, if a hazard is identified and rectified within the prescribed deadline, it would be allocated an “on-time rectification” rating (Scenario 1 and 4). If a hazard is rectified within the prescribed deadline, but it occurred in the preceding month and is rectified in the current month, its rating is allocated to the month when the hazard was identified (Scenario 5). If a hazard is rectified in this month, but rectification exceeded the prescribed deadline (Scenario 2 and 6), regardless of the month in which it was identified, it is allocated an “overdue rectification” rating. When a hazard is unresolved at the end of the monthly evaluation period (identified in the current month or at an earlier time) and is overdue, that item is allocated an “overdue non-rectification” rating.

Table 1
Classification of rectification scenarios in one month.

Scenario	Identified in this month	Rectified in this month	Rectified within the prescribed deadline	Hazard category based on rectification	Whether calculated in this month
1	Y	Y	Y	On-time rectification	Y
2	Y	Y	N	Overdue rectification	Y
3	Y	N	N	Overdue non-rectification	Y
4	Y	N	Y	On-time rectification	Y
5	N	Y	Y	On-time rectification	N
6	N	Y	N	Overdue rectification	Y
7	N	N	N	Overdue non-rectification	Y

Y – Yes; N – No.

3.3.2. Process for calculating rectification efficiency

To calculate rectification efficiency, set-pair analysis can be used to define the relationship between a set of hazards and their rectification states. SPA is an analytical game theory integrating certainties and uncertainties in a combined system; it is based on the concept of set pairs and their degree of connection. It has been used to address many practical problems, including enterprise performance assessment, forecasting, and risk assessment in multiple fields (Cai and Li, 2011; Chong et al., 2017; Li, 2013). In this study, SPA was adapted to generate a rectification efficiency indicator score for a given period based on the data collected by site assessment. The link between two or more sets is a function of the number of identical (S), discrepant (F), and contradictory (P) terms of these sets. The degree of connection equation is represented as follows

$$\mu = \frac{S}{N} + \frac{F}{N}i + \frac{P}{N}j = a + bi + cj \tag{9}$$

where μ is the degree of connection of a set pair and N is the total number of set characteristics. Further $a = \frac{S}{N}$, $b = \frac{F}{N}$, and $c = \frac{P}{N}$. Here, a is the identical degree, b is the discrepant degree, and c represents the contrary degree. The values of a , b , and c are in the range of $[0, 1]$ such that $a + b + c = 1$. i represents a difference coefficient and its value varies between -1 to 1 , while j is the opposition coefficient (-1). As the value of i approaches 1 , the uncertainty term b strongly supports a , while an i value close to -1 indicates opposition to a . In this case, a , b , and c are related to the rectification state of a given risk factor; a refers to on-time rectification, b refers to overdue rectification, and c refers to overdue non-rectification. The score of each category is the sum of products of hazard frequency and hazard severity. The scores of the three categories were later normalized to meet the requirement $a + b + c = 1$.

The discrepancy coefficient can be calculated using proportion, mean, probability, and function simulating methods using special value analysis techniques or computational techniques (Jiang et al., 2003; Li, 2013). In this study, we chose the proportion method to calculate i as follows:

$$i = \frac{a_i - a_{i-1}}{b_i} \tag{10}$$

Because the SPA function does not capture hazards identified beyond an evaluation period, two modifiers are applied to the indicator score generated by SPA to account for cross-period overdue non-rectification (Scenario 7) and overdue rectification for hazards identified in preceding periods (Scenario 6). Therefore, the final rectification performance indicator score (REI) is generated by:

$$REI = u_i - m_1 - m_2 \tag{11}$$

where u_i is the score generated by SPA considering only hazards identified during the evaluation period (i); m_1 is the penalty modifier for existing hazards from preceding periods which already exceeded the prescribed deadline and were rectified during the evaluation period; and m_2 is the penalty modifier for those hazards from preceding periods which were already outside the prescribed deadline but still remain

Table 2
REI penalty modifiers for cross period delayed rectification.

Evaluation period	b multiplier (M_b)	c multiplier (M_c)
Next month	2	3
2 months	3	4
3 months	4	5
4 months	5	6
5 months	6	7

unresolved during the evaluation period. m_1 and m_2 are determined using Eqs. (12) and (13), respectively.

$$m_{1i} = \frac{0.01}{I} \sum_{i=1}^n S_i M_{bi} \tag{12}$$

$$m_{2i} = \frac{0.01}{I} \sum_{i=1}^n S_i M_{ci} \tag{13}$$

Here, I is the number of inspections conducted in the evaluation period, S_i is the hazard weighting of each hazard, and M_{bi}/M_{ci} is the penalty multiplier for that specific hazard and is based on the duration of time between hazard identification and evaluation period. The values of the multipliers are listed in Table 2. Data normalization was also performed prior to modification and analysis.

3.4. Comprehensive safety performance

Finally, a comprehensive safety evaluation index is generated considering both the HRI and REI scores. A basic rectification efficiency to hazard rating ratio is adopted to generate a comprehensive SPI.

$$SPI_i = \frac{REI_i^*}{HRI_i} \tag{14}$$

Here, SPI_i is the comprehensive safety index for a given evaluation period and REI_i and HRI_i are the corresponding rectification efficiency indicator and hazard rating index, respectively. REI_i is a positive measure of management performance in rectifying site hazards and HRI_i is a measure of the total risk level due to the identified hazards, that is, it is a negative measure. Therefore, a high SPI_i value corresponds to a good safety performance for an evaluation period while a low score indicates that hazards have been poorly controlled relative to hazard development in that period. REI_i^* is equal to REI_i shifted by a constant ($= REI_{min}$), such that the influence of the negative numerator

Table 3
REI scores based on SPA (Project 1).

Month	Construction stage	On-time rectification	Overdue rectification	Overdue non-rectification	i	Score
2016/06	Foundation	38.33	0.00	0.00	0.00	1.00
2016/07	Foundation	31.40	8.60	0.00	1.00	0.57
2016/08	Foundation	25.80	4.60	0.00	0.29	0.80
2016/09	Foundation	17.25	0.75	0.00	0.68	0.99
2016/10	Foundation	14.25	5.00	1.75	0.22	0.65
2016/11	Structure	19.80	9.20	0.00	0.18	0.74
2016/12	Structure	20.50	0.00	0.00	0.32	1.00
2017/01	Structure	11.00	0.00	0.00	0.41	1.00
2017/02	Structure	8.00	8.00	0.00	0.24	0.62
2017/03	Structure	21.50	0.00	2.50	0.32	0.79
2017/04	Structure	26.00	0.00	0.00	0.39	1.00
2017/05	Structure	22.60	1.60	0.00	0.26	0.95
2017/06	Structure	21.00	0.00	0.00	0.32	1.00
2017/07	Fitting	16.75	2.75	0.00	0.22	0.89
2017/08	Fitting	18.80	1.80	0.00	0.25	0.93
2017/09	Fitting	16.00	2.25	0.00	0.21	0.90
2017/10	Fitting	6.25	4.50	0.75	0.15	0.54
2017/11	Fitting	0.00	11.33	1.00	0.10	0.01
2017/12	Fitting	7.00	6.25	12.75	0.16	-0.18

in the SPI computation is removed. Data shifting does not affect data distribution or standard deviation. Finally, the proposed safety evaluation methodology is compared to existing scoring methods often adopted by project safety inspection assessors. The established method (CSPI) is a product of hazard frequency and severity; hazard frequency is obtained from past records and hazard severity is obtained from the Chinese national standard, the Standard for Construction Safety Inspection JGJ59-2011. As the established method is a single-indicator risk-rating system, it is compared to SPI grading only. The results will be further compared and discussed with industrial practitioners for validation.

4. Results and analysis

The proposed methodology is applied to a set of 7 building projects and the results were compared with those of a typical risk assessment method. In this case study, quartiles were determined in all the projects for all indicators to differentiate scores in 4 distinct categories, viz. quartile 1 – Grade 4 (best), quartile 2 – Grade 3 (good), quartile 3 – Grade 2 (average/poor), and quartile 4 – Grade 1 (worst).

4.1. Rectification evaluation based on SPA

As shown in Table 3, in Project 1, the value of on-time rectification is greater than that of overdue rectification and overdue non-rectification, which indicates that most hazards could be rectified immediately. The highest score over five months showed that all the hazards were rectified in time due to active management. The worst month was December 2017, with a high score of overdue non-rectification. The value of i in June 2016 and July 2017 was negative, indicating that the efficiency of hazard rectification on the construction sites decreased. The efficiency of rectification reflects the attitude of contractors and construction units towards hazards and unsafe factors as well as safety conditions at a construction site. Therefore, when the value of REI is low, project managers are reminded to coordinate manpower and material resources as soon as possible to improve safety and avoid potential accidents.

When the frequency of inspection or evaluation duration changes, the scores of the corresponding three rectification categories change. However, normalized a , b , and c do not necessarily change as the range of a , b , and c is in the limits $[0,1]$ such that $a + b + c = 1$. For example, in December 2016 (4 inspections) and January 2017 (3 inspections), $a = 1$, $b = 0$, and $c = 0$ and REI score was the highest in these months. If a , b , or c changes, the value of i and REI score may experience a

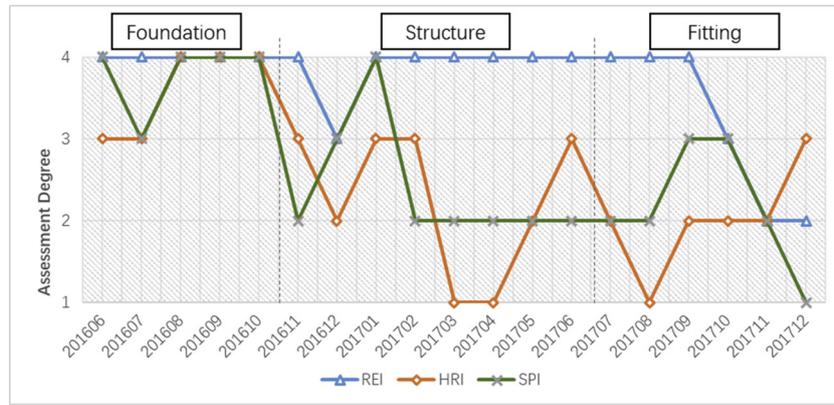


Fig. 3. Assessment degree of REI, HRI, and SPI.

corresponding change. This observation indicates that the frequency of inspection does not influence rectification efficiency when all hazards can be rectified in time. However, the REI is influenced when there are overdue rectification or overdue non-rectification hazards. These specific relationships will continue to be studied in the future.

4.2. Safety monitoring potential of REI, HRI, and SPI

After normalization, projects can be compared at different construction scales and stages.

4.2.1. Safety during the construction process

As shown in Fig. 3, for the first 5 months of a project, corresponding to the Foundation phase of construction, HRI scores of Project 1 lie in the range of Grade 3 and 4, indicating a relatively low risk due to the rectification of identified hazards. REI fluctuates between Grade 1 and 3 during these months, indicating varying performance in resolving identified hazards, but it never deteriorated to Grade 1 (poor). As a result, the SPI is consistently rated as good, except for July 2016 when the SPI was average (Grade 3).

In the Structure phase, REI falls to Grade 1 (poor) and the occurrence of new hazards increases, which is indicated by a rise in HRI, and consequently, the SPI is average/poor. As the second construction phase matures, REI recovers from the worst grade to oscillate between good and average/poor (Grade 1–Grade 3). HRI shows some fluctuations and continues to worsen, reaching the peak for hazard propagation in January 2017 (HRI = 0.213). Around this time, due to the high hazard propagation and average rectification performance, comprehensive SPI falls to Grade 1 (poor) between January and February 2017. HRI recovers to Grade 4 (good) in the final month of the Structure

phase of the project before exhibiting an average/poor performance during transition to the Fitting phase of construction. SPI follows a similar trend, improving to Grade 4 in the final month of construction. The performance of all 3 markers was observed to improve in the final months of each project phase.

In transition periods from Foundation to Structure and then on to Fitting, HRI tends to increase consistently for 2 months from the commencement of construction. In both these cases, a slight fall is observed in REI. This indicates that construction transition phases may be high-risk periods in which accidents can occur. Conversely, for this project, the performance of all 3 markers was observed to improve in the final months of each project phase.

In the final construction phase of the project (Fitting), rectification efficiency indicator illustrates a downward trend of management performance, and the REI deteriorates the final 3 months of observations substantially. This is due primarily to a failure to rectify multiple new hazards within the time allocated by safety guidelines in November and failure to rectify hazards from 2 months prior in December 2017. At the commencement of the period, HRI indicates a rise in overall hazard level. At this SPI and the previous HRI peak, hazards are identified across a range of hazard categories, while electricity and working at heights hazards are the most prevalent. This risk dissipates as the project matures but overall safety performance continues to fall, and the value of SPI indicates poor safety performance for the remaining months of construction and never recovering from Grade 1. At this point the project is ongoing.

4.2.2. Comparison of safety performance among different projects

In Fig. 4, the higher the score of HRI, the greater is the number of unsafe factors in the field. According to the average HRI values of

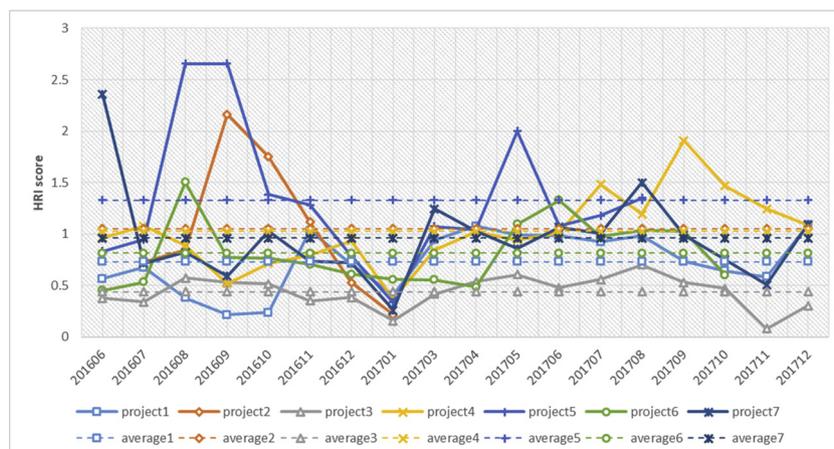


Fig. 4. HRI scores of 7 projects.

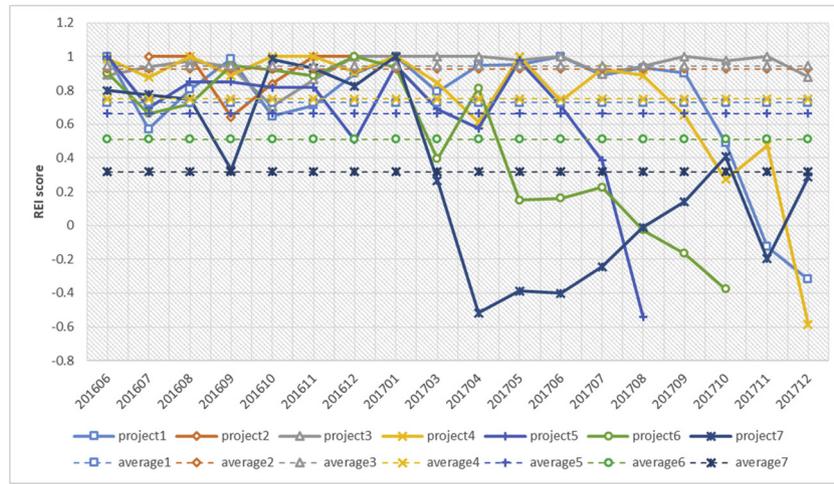


Fig. 5. REI scores of 7 projects.

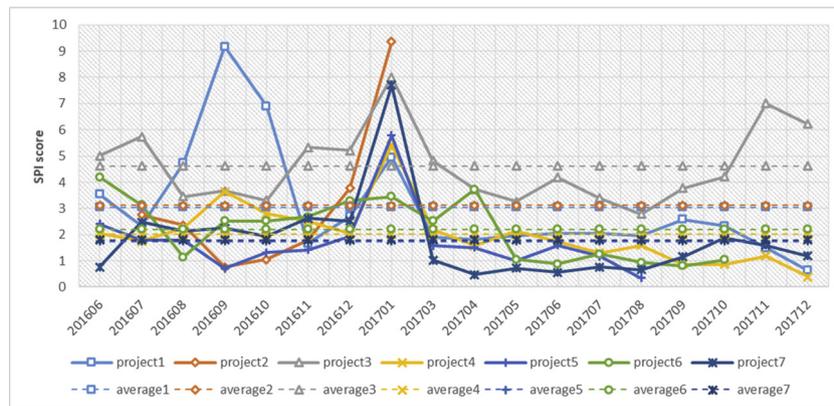


Fig. 6. SPI scores of 7 projects.

different projects, Project 2 is the best and Project 5 is the worst. These values indicate that in December 2017, hazards occurred frequently in the workplace of Project 5 and workers had little safety awareness. Therefore, personnel training should be taken up and inspection frequency should be increased. As can be seen from Fig. 5, the higher the REI score, the greater is the management efficiency. According to this metric, Project 3 is the best and Project 7 is the worst; this observation shows that there were long-term hazards in the workplace of Project 7. Workers were not serious about safety issues and hence inspectors should urge them to correct themselves or take punitive measures. As shown in Fig. 6, the higher the score of SPI, the higher is the comprehensive performance of the project. According to this parameter, Project 3 is the best and Project 5 and 7 are the worst. Hence, SPI evaluates the risk and safety management of a project; in addition, it can be stated that a project can be comprehensively evaluated and managed by combining HRI, REI, and SPI. However, none of the projects are always good or bad (even Project 3) and they show volatility. Therefore, if a project is in a transition state from a safe phase to an unsafe phase, the management strategy should be adjusted in a timely manner depending on the performance indicators to restore the safe state as soon as possible.

4.3. Temporal analysis of indicators

In this section, temporal analysis was conducted on the REI, HRI, and comprehensive SPI data to identify trends and phenomena as well as to establish and demonstrate predictive patterns, which may be used to develop proactive safety management strategies for future projects.

Firstly, studying the peaks and troughs of HRI, REI, and SPI across the 7 case study projects, patterns related to construction phases associated with the highest and lowest hazard propagation became evident. In 5 of the 7 projects studied, HRI is observed to reach a peak during the Fitting phase of construction. Further, low HRI scores for 5 of the 7 projects, which indicates a relatively low risk, are found during the Structure phase. Looking at the trends in rectification performance, similar trends are observed in poor performance. The absolute lowest REI scores are also found during the Fitting phase of construction for 6 of the 7 projects. However, unlike HRI, the absolute best evaluation months for REI appear to follow no pattern. Peak REI months are spread evenly across the 3 construction phases. As SPI represents the ratio of rectification performance to hazard development, similar trends are identified during the temporal analysis of this comprehensive indicator. For 6 of the 7 projects, peak SPI scores were found during structural work. The lowest absolute SPI scores occurred during the Fitting phase in 6 of the 7 projects. No seasonal- or month-related dependencies are apparent across the dataset for the three indicator ratings.

Later, we examined the periods of transition between the Foundation, Structure, and Fitting construction phases and performance trends were observed in the month leading up to and following these project milestones. Here, performance patterns are indications that these transitional periods may be associated with high safety risks for the construction team. Degradation is observed in all these indicators across the observed transitional periods in multiple projects. This trend is illustrated in Fig. 3 for Project 1, in which it can be observed that both REI and HRI decreased significantly at transition points. This indicates an increase in the development of new hazards

Table 4
Performance trends observed at transition stages.

	FOUNDATION - STRUCTURE			STRUCTURE - FITOUT		
	SPI falls	HRI rises	REI falls	SPI falls	HRI rises	REI falls
Project 1	✓	✓	✓	✓	✓	✓
Project 2				✓	✓	✓
Project 3	✓	✓		✓	✓	
Project 4			✓	✓	✓	✓
Project 5			✓	✓	✓	✓
Project 6				✓	✓	
Project 7	✓	✓		✓	✓	✓

during these periods and implies that the management team is unable to respond effectively to sudden increases in hazard propagation.

The transition phase between initial Foundation work and Structural work is associated with a reduction in indicator performance in more than 40% of the studied cases. As shown in Table 4, at this transition point, Projects 1, 3, and 7 experience a drop in HRI and SPI, while Projects 1, 4, and 5 exhibit a fall in REI. At the next transition point, stronger associations are identified. The transition from Structure to Fitting in all 7 projects is associated with a significant fall in HRI and SPI. Approximately 57% of the projects experienced a reduction in rectification performance at this transition point.

4.4. Comparison with established methods

In this section, the proposed safety evaluation methodology is compared with existing scoring methods employed by project safety inspection assessors. Upon comparing the 7 projects, 53% SPI scores lower than CSPI, 34% equal and only 13% of the time allocate better score; the proposed comprehensive SPI evaluation method appears to be more conservative than the established method (CSPI) used by assessors.

While the trends observed in both methods are generally similar, in some cases, the two methods produce different results. Hence, a closer look is necessary to explain atypical differences between SPI and CSPI. Taking Project 1 as an example (Fig. 7), in December 2017, CSPI rating was Grade 3 while the SPI rating was Grade 1. By checking records, 21 hazards were identified in Project 1 during this month; some of these were overdue and unresolved at the end of the evaluation month, owing to which the score of “rectify overtime” and “non-rectification overtime” is larger than that of hazards rectified in time. Thus, it can be concluded that the workplace was dangerous due to a number of neglected hazards. In this case, the SPI was better at predicting unsafe conditions.

Besides, we can observe that most project evaluations are jagged over time, but the fluctuations of the two evaluations are not entirely consistent. The results of SPI occasionally show a prior trend on some projects. For example, in the January to March 2017 in Fig. 7, the downward trend of SPI was ahead; we envisage that SPI will have the ability of predictive trend in some cases, which can identify the project unsafe conditions as early as possible. However, this conjecture is only derived from individual points and has not been widely applied in the safety assessment.

5. Discussion

5.1. Actionable information provided by HRI, REI, and SPI

The proposed Safety Performance Index, SPI, is a combination of 2 indicators, HRI and REI. Firstly, HRI provides an objective measure of site risk due to the propagation of new hazards by addressing flaws in risk assessment methods traditionally applied on construction sites. Meanwhile, REI, as a management performance indicator, uses SPA to quantify the hazard rectification performance of a project considering overdue and unresolved hazards in an evaluation period. Finally, SPI is treated as the ability of a project management team to eliminate hazards with respect to the development of new hazards. SPI results indicate that it is a conservative safety assessment parameter and provides actionable information as it is a combination of two indicators and introduces rectification performance as a new safety indicator.

Applying the proposed methodology to a set of case studies, it was found that this method reduced inconsistencies observed in traditional risk methods often adopted by third-party assessors. The observed SPI results indicate that it is a more conservative method of assessment. This can be attributed in part to the standardized risk allocation framework and also to the fact that it considers extended hazard exposure due to existing risks over a given evaluation period (Pinto et al., 2011; Thurston and Glendon, 2018). While the traditional method of risk assessment accounts for risk frequency and severity, it uses only a single indicator of risk level and consequently may serve only as a risk warning system for contractors (Awolusi et al., 2017; Lingard et al., 2017). Loss in data to single indicator use represents an unavoidable loss of information. As the SPI is, in fact, the ratio of two key indicators (HRI and REI), both may be analyzed independently, providing more information for users. While SPI itself may be a suitable warning mechanism for overall project risk, it does not highlight actionable areas for project improvement. According to Pereira et al. (2017), failure to identify hazards and neglecting them are the highest rated accident precursors. Using HRI and REI indicators, a contractor may identify if a project is experiencing too many new hazards or if the management

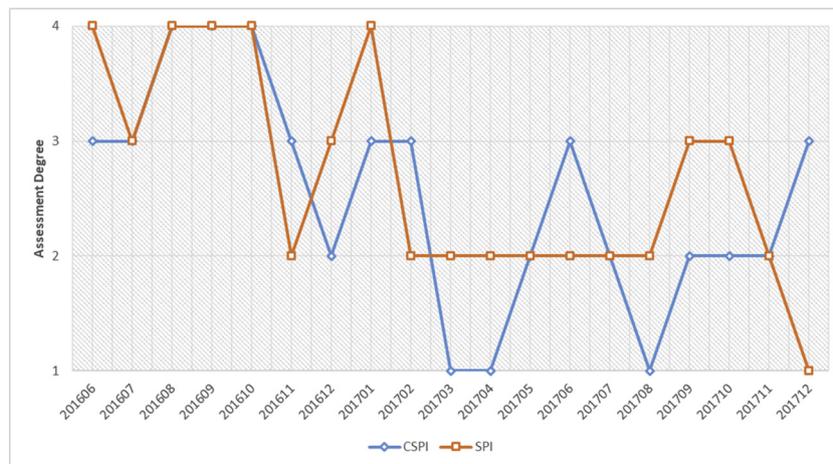


Fig. 7. Assessment degree of CSPI and SPI for Project 1.

team is not performing optimally in resolving existing hazards and mitigating exposure. This level of information then allows the contractor to efficiently direct resources to address safety management failures.

However, the conservative SPI indicator leads to excessive attention on safety, thus increasing the number and workload of on-site safety inspectors, training frequency of workers, and construction costs. Based on existing safety monitoring practices and safety inspection systems, the development and application of a new technology or system and its high costs presents researchers and practitioners with a challenge that is both practical and theoretical (Li et al., 2018). However, in the long run, although the adaptation period will induce an increase in expenses, using the comprehensive information provided by the three indicators, it is possible to reduce safety problems on-site, improve worker operational compliance, and reduce new hazard development. At the same time, rectification efficiency is improved and worker exposure to risks can be reduced. Finally, benign development of construction projects will also reduce risk cost to a certain extent.

Rectification efficiency reflects the attitude of contractors and construction units towards hazards and unsafe factors as well as safety at the construction site. For example, when the value of HEI is low (Grade 1 or 2), project managers are reminded to synthesize different values for the two indicators and coordinate manpower and material resources as soon as possible in order to improve safety conditions and avoid potential accidents. Previous studies used the probability of potential hazards and their consequences to assess project safety status (Chen and Yang, 2004). This is commonly referred to as HRI. According to the case study data, rectification performance is the best (Grade 4) when hazards occur frequently (Grade 1). It can be indicated that the worst environment irritates the inspectors and workers to restore safety as soon as possible. However, the same HRI grade can correspond to different rectification efficiencies. Even when the HRI is Grade 4, the efficiency of rectification may be extremely low, resulting in hazards left unresolved at the construction site. These hazards not only increase risk to humans, but also may trigger other hazards, with serious consequences.

5.2. The ability of predictive trend on project basis

Finally, the temporal analysis of the case project results using the proposed method highlights the effectiveness of proactive monitoring strategies in driving proactive safety measures at construction sites. General areas have been identified for all projects, where heightened attention to safety is required. For example, the Fitting phase of construction is typically associated with the worst average and absolute performance with respect to new hazard development and management rectification performance. This data is also supported by an analysis of construction accident frequency, which indicates that the highest accident frequency occurs during the Fitting stage that includes a number of mechanical and electrical tasks in addition to joining, roofing, and cladding tasks. Deterioration in performance metrics across some projects in the final months was supported by normalization of deviance in the complacency of the project team at project maturity (Pinto, 2014). It may also be supported by previous leading indicator studies, which suggest that project completion plays a role in overall risk level (Poh et al., 2018). Other factors may also play a role here such as deadline pressures as contractual completion dates draw near. Transitional periods are identified to be high risk, particularly between Structural and Fitting phases. Such knowledge can facilitate a management team in preplanning for additional resources and strategies in anticipation of increased safety workload during these high-risk periods. Furthermore, construction projects are unique and dynamic environments (Bavafa et al., 2018; Mohammadi et al., 2018a) requiring dynamic safety management strategies. Therefore, while collective analysis of these projects does provide some useful information for future projects, temporal analysis of safety performance is most beneficial when it is

implemented as part of a formal strategy on a project-by-project basis. Retroactive monitoring and analysis of case projects indicated that safety performance data provides an early warning system and predictive values for contractors and other stakeholders. This highlights how the observation of trends and performance patterns can be used to identify degeneration in project safety status and periods of high risk associated with accidents. The implementation of a formal monitoring plan will facilitate correction and strategy implementation in high-risk situations (Li et al., 2018), from the perspective of eventuating through proactive management rather than in reaction to risk or safety incidents.

6. Conclusion

In this study, a proactive safety performance evaluation methodology was developed, in which contractors and other stakeholders can apply temporal analysis and monitoring strategies; further, it addresses the inadequacies of traditional safety management practices within the construction industry. The framework adopts standard guidelines and an entropy-based approach to hazard rating and introduces rectification efficiency as a dynamic measure of management performance to provide comprehensive safety performance assessment.

The introduction of rectification efficiency facilitates dynamic and robust safety performance assessment that takes into consideration an active and objective measure of management performance. Application to case projects demonstrates that the proposed method is a conservative and reliable safety-performance assessment protocol, which is suitable for temporal analysis and formal monitoring. These strategies are expected to drive proactive safety management. In addition to providing a defined framework for comprehensive evaluation through SPI, HRI, and REI indicators, this research offers some general guidelines for the development of new proactive safety monitoring strategies and foundations for future studies. Its application to case projects highlights some general high-risk areas and periods at construction sites. Above all, the implementation of formal monitoring strategies incorporating project safety management measures may greatly benefit decision makers and improve safety management and performance in the construction industry.

However, this study has certain limitations. First of all, project safety is a complex subject and a multitude of factors influence the true safety level in construction projects. The proposed framework was developed using only existing project records and the management team's performance. Meanwhile, rectification performance may be an indication of a general attitude to safety and correlates with the overall performance of the management team; however, this does not directly consider a broader range of management factors, such as safety programming and planning, costs, and education training. In future research, the influence of frequency of inspection should also be considered. Furthermore, performance grades are determined relative to case data owing to which the proposed method considers the performance of a given project relative to baseline projects. A more extensive database of project data is required to improve the accuracy of this system and accident data is needed to establish potential safe/unsafe performance zones. Finally, the proposed method was validated through retroactive comparison with results generated by established methods and site inspection records, which may require further justification.

Declaration of interest

The authors declare no conflict of interest.

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References

- ACA, 2015. Lead Indicators Safety Measurement in the Construction Industry.
- Alruqi, W.M., Hallowell, M.R., Techera, U., 2018. Safety climate dimensions and their relationship to construction safety performance : a meta-analytic review. *Saf. Sci.* 109, 165–173. <https://doi.org/10.1016/j.ssci.2018.05.019>.
- Awolusi, I.G., Asce, A.M., Marks, E.D., Ph, D., Asce, S.M., 2017. Safety activity analysis framework to evaluate safety performance in construction. *J. Constr. Eng. Manag.* 143, 1–12. [https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0001265](https://doi.org/10.1061/(ASCE)CO.1943-7862.0001265).
- Bavafa, A., Mahdiyar, A., Kadir, A., 2018. Identifying and assessing the critical factors for effective implementation of safety programs in construction projects. *Saf. Sci.* 106, 47–56. <https://doi.org/10.1016/j.ssci.2018.02.025>.
- Cai, W.-L., Li, J.-S., 2011. Set pairs analysis model for synthetic performance appraisal. In: Zhou, M. (Ed.), *Education and Management*. Springer, Berlin Heidelberg, Berlin, Heidelberg, pp. 78–84.
- Chen, J.R., Yang, Y.T., 2004. A predictive risk index for safety performance in process industries. *J. Loss Prev. Process Ind.* 17, 233–242. <https://doi.org/10.1016/j.jlp.2004.03.001>.
- Chong, T., Yi, S., Heng, C., 2017. Application of set pair analysis method on occupational hazard of coal mining. *Saf. Sci.* 92, 10–16. <https://doi.org/10.1016/j.ssci.2016.09.005>.
- Dunwen, L., Lei, Y., Bo, L., 2012. Fuzzy-entropy theory comprehensive evaluation method and its application in building construction safety. *International Symposium on Safety Science and Engineering in China* 137–142. <https://doi.org/10.1016/j.proeng.2012.08.024>.
- Fang, D., Huang, X.Y., Hinze, J., 2004. Benchmarking studies on construction safety management in China. *J. Constr. Eng. Manag.* 130, 424–432. [https://doi.org/10.1061/\(ASCE\)0733-9364\(2004\)130](https://doi.org/10.1061/(ASCE)0733-9364(2004)130).
- Grabowski, M., Ayyalomasayajula, P., Merrick, J., Harrald, J.R., Roberts, K., 2007. Leading indicators of safety in virtual organizations. *Saf. Sci.* 45, 1013–1043. <https://doi.org/10.1016/j.ssci.2006.09.007>.
- Guo, B.H.W., Yiu, T.W., 2016. Developing leading indicators to monitor the safety conditions of construction projects. *J. Manag. Eng.* 32, 04015016. [https://doi.org/10.1061/\(ASCE\)ME.1943-5479.0000376](https://doi.org/10.1061/(ASCE)ME.1943-5479.0000376).
- Haadir, S.A.I., Panuwatwanich, K., 2011. Critical success factors for safety program implementation among construction companies in Saudi Arabia. *Procedia Eng.* 14, 148–155. <https://doi.org/10.1016/j.proeng.2011.07.017>.
- Hallowell, M.R., Asce, A.M., Hinze, J.W., Asce, M., Baud, K.C., Wehle, A., 2013. Proactive construction safety control : measuring, monitoring, and responding to safety leading indicators. *J. Constr. Eng. Manag.* 139, 1–8. [https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0000730](https://doi.org/10.1061/(ASCE)CO.1943-7862.0000730).
- Hinze, J., Thurman, S., Wehle, A., 2013. Leading indicators of construction safety performance. *Saf. Sci.* 51, 23–28. <https://doi.org/10.1016/j.ssci.2012.05.016>.
- Hon, C.K.H., Chan, A.P.C., Wong, F.K.W., 2010. An analysis for the causes of accidents of repair, maintenance, alteration and addition works in Hong Kong. *Saf. Sci.* 48, 894–901. <https://doi.org/10.1016/j.ssci.2010.03.013>.
- Hopkins, A., 2009. Thinking about process safety indicators. *Saf. Sci.* 47, 460–465.
- Hou, Z.Q., Zeng, Y.M., 2016. Research on risk assessment technology of the major hazard in harbor engineering. *Procedia Eng.* 137, 843–848. <https://doi.org/10.1016/j.proeng.2016.01.324>.
- Jiang, Y., Xu, C., Linz, Y., Zhao, K., 2003. A new approach for representing and processing uncertainty knowledge. *Fifth IEEE Workshop on Mobile Computing Systems and Applications*. pp. 466–470.
- Jiang, Z., Fang, D., Ph, D., Zhang, M., Ph, D., 2015. Understanding the causation of construction workers' unsafe behaviors based on system dynamics modeling. *J. Manag. Eng.* 04014099, 1–14. [https://doi.org/10.1061/\(ASCE\)ME.1943-5479.0000350](https://doi.org/10.1061/(ASCE)ME.1943-5479.0000350).
- Karimiazari, A., Mousavi, N., Mousavi, S.F., Hosseini, S., 2011. Risk assessment model selection in construction industry. *Expert Syst. Appl.* 38, 9105–9111. <https://doi.org/10.1016/j.eswa.2010.12.110>.
- Li, C.G.S., Wang, J., Peng, L.L., 2017. The risk assessment of tunnels based on grey correlation and entropy weight method. *Geotechnol. Geol. Eng.* <https://doi.org/10.1007/s10706-017-0415-5>.
- Li, F., 2013. Application of varying coefficient discrepancy degree in water quality evaluation of water supply networks. *Procedia Environ. Sci.* 18, 243–248. <https://doi.org/10.1016/j.proenv.2013.04.031>.
- Li, J.W., Li, L.Q., Yang, X.R., 2007. Interval entropy measurement method in risk analysis and its application to metro construction. *ISGSR2007 First International Symposium on Geotechnical Safety & Risk*. pp. 657–664.
- Li, Y., Hu, Y., Xia, B., Skitmore, M., Li, H., 2018. Proactive behavior-based system for controlling safety risks in urban highway construction megaprojects. *Autom. Constr.* 95, 118–128. <https://doi.org/10.1016/j.autcon.2018.07.021>.
- Lingard, H., Hallowell, M., Salas, R., Pirzadeh, P., 2017. Leading or lagging? Temporal analysis of safety indicators on a large infrastructure construction project. *Saf. Sci.* 91, 206–220. <https://doi.org/10.1016/j.ssci.2016.08.020>.
- Mohammadi, A., Tavakolan, M., Khosravi, Y., 2018a. Factors in influencing safety performance on construction projects : a review. *Saf. Sci.* 109, 382–397. <https://doi.org/10.1016/j.ssci.2018.06.017>.
- Mohammadi, A., Tavakolan, M., Khosravi, Y., 2018b. Developing safety archetypes of construction industry at project level using system dynamics. *J. Safety Res.* 67, 17–26. <https://doi.org/10.1016/j.jsr.2018.09.010>.
- Nielsen, K.J., 2014. Improving safety culture through the health and safety organization: a case study. *J. Safety Res.* 48, 7–17. <https://doi.org/10.1016/j.jsr.2013.10.003>.
- Pereira, E., Ahn, S., Han, S., Abourizk, S., 2017. Identification and association of high-priority safety management system factors and accident precursors for proactive safety assessment and control. *J. Manag. Eng.* 34, 04017041. [https://doi.org/10.1061/\(asce\)me.1943-5479.0000562](https://doi.org/10.1061/(asce)me.1943-5479.0000562).
- Pinto, A., Nunes, I.L., Ribeiro, R.A., 2011. Occupational risk assessment in construction industry - Overview and reflection. *Saf. Sci.* 49, 616–624. <https://doi.org/10.1016/j.ssci.2011.01.003>.
- Pinto, J., 2014. Project management, governance and the normalization of deviance. *Int. J. Proj. Manag.* 32, 376–387.
- Poh, C.Q.X., Ubeynarayana, C.U., Goh, Y.M., 2018. Safety leading indicators for construction sites: a machine learning approach. *Autom. Constr.* 93, 375–386. <https://doi.org/10.1016/j.autcon.2018.03.022>.
- Rajendran, S., 2013. Enhancing construction worker safety performance using leading indicators. *Pract. Period. Struct. Des. Constr.* 18, 45–51. [https://doi.org/10.1061/\(ASCE\)SC.1943-5576.0000137](https://doi.org/10.1061/(ASCE)SC.1943-5576.0000137).
- Stricoff, R.S., 2000. Safety performance measurement: identifying prospective indicators with high validity. *Prof. Saf.* 45, 36–39.
- Thompson, R.C., Gunnar, L., Su, Y., 2016. Reconsidering an appropriate probability distribution function for construction simulation. *Construction research congress 2016*. ASCE 2522–2531. <https://doi.org/10.1061/9780784479827.251>.
- Thurston, E., Glendon, A.I., 2018. Association of risk exposure, organizational identification, and empowerment, with safety participation, intention to quit, and absenteeism. *Saf. Sci.* 105, 212–221. <https://doi.org/10.1016/j.ssci.2018.02.012>.
- Wachter, J.K., Yorio, P.L., 2014. A system of safety management practices and worker engagement for reducing and preventing accidents : an empirical and theoretical investigation. *Accid. Anal. Prev.* 68, 117–130. <https://doi.org/10.1016/j.aap.2013.07.029>.
- Wang, Z.Z., Chen, C., 2017. Fuzzy comprehensive Bayesian network-based safety risk assessment for metro construction projects. *Tunn. Undergr. Sp. Technol.* 70, 330–342. <https://doi.org/10.1016/j.tust.2017.09.012>.
- Wreathall, J., 2009. Leading? Lagging? Whatever! *Saf. Sci.* 47, 493–494. <https://doi.org/10.1016/j.ssci.2008.07.031>.
- Wu, C., Li, N., Fang, D., 2017. Leadership improvement and its impact on workplace safety in construction projects: a conceptual model and action research. *Int. J. Proj. Manag.* 35, 1495–1511. <https://doi.org/10.1016/j.ijproman.2017.08.013>.
- Xia, N., Zou, P.X.W., Liu, X., Wang, X., Zhu, R., 2018. A hybrid BN-HFACS model for predicting safety performance in construction projects. *Saf. Sci.* 101, 332–343. <https://doi.org/10.1016/j.ssci.2017.09.025>.
- Yin, L., Deng, Y., 2018. Toward uncertainty of weighted networks: an entropy-based model. *Phys. A Stat. Mech. Appl.* 508, 176–186. <https://doi.org/10.1016/j.physa.2018.05.067>.
- Yiu, N.S.N., Sze, N.N., Chan, D.W.M., 2018. Implementation of safety management systems in Hong Kong construction industry – a safety practitioner's perspective. *J. Safety Res.* 64, 1–9. <https://doi.org/10.1016/j.jsr.2017.12.011>.
- Zeng, X., Yin, H., Li, Y., 2015. Application of modified LEC method in the large municipal bridge construction hazard evaluation. *Sci. World J.* 8–11. <https://doi.org/10.1109/ISCID.2015.79>.
- Zhou, J., Tang, D., Liu, X., Gong, S., 2009. A LEC-and-AHP based hazard assessment method in hydroelectric project construction. *Sixth Int. Symp. Neural Networks (IINN 2009)* 56, 81.
- Zhou, Z., Miang, Y., Li, Q., 2015. Overview and analysis of safety management studies in the construction industry. *Saf. Sci.* 72, 337–350. <https://doi.org/10.1016/j.ssci.2014.10.006>.