SAFETY SCIENCE

Safety leading indicators in construction: a systematic review

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Abstract

Safety leading indicators have been investigated as an emergent area in the construction industry. Yet the fundamental concepts of leading indicators, including definitions, viability and effectiveness, have not been commonly agreed. Despite this, various indicators have been proposed in construction management research. However, the findings are sporadic, and the relationships between proposed leading indicators and accident attributors remain unclear. This knowledge gap can hamper the implementation of safety leading indicators and proactive safety management in the construction industry. Based on a systematic literature review, the present study aims to: develop a common working definition of safety leading indicator for a better understanding of the current research in the construction sector; identify construction safety leading indicators; and create an integrated framework that fits in the complex and fragment structure of the construction industry for proactive safety management. The findings revealed sixteen indicators that were categorized into two dimensions to: 1) measure the safety performance of firms, projects or groups and individuals; and 2) identify potential incidents and injuries caused by organizational, operational or cognitive and behavioral issues. The findings call for researchers and practitioners to take an ecosystem perspective, consider the temporal effects, and combine qualitative and quantitative measurements in future research and implementing safety leading indicators in the construction industry.

Keywords

Construction safety; Proactive performance indicator; Safety leading indicators; Safety performance measurement; Systematic literature review

1. Introduction

Safety has risen up the construction industry agenda for reasons of culture (Al-Bayati et al., 2018), government (Eteifa and El-Adaway, 2018) and performance drivers (Choudhry et al., 2007). Despite these, safety performance in construction has been found to have plateaued in many developed countries such as Australia, the United Kingdom and the United States (Chen et al., 2018; Guo and Yiu, 2016; H C Lingard et al., 2010; Smyth et al., 2019). There are three main reasons for this phenomenon: 1) the lack of integrated systems between organizations, such as construction clients, designers and contractors, and hence a weak safety culture in projects (Guo and Yiu, 2016); 2) the transactional business model that prioritizes commercial considerations (Rowlinson and Jia, 2015) and treats safety improvement as something of a “bolt-on extra” in decision-making (Smyth et al., 2019); and 3) reactive safety management approaches in terms of both accident prevention and performance improvement (Lingard et al., 2017).

Strong evidence of reactive safety management in the construction industry is seen in the common usage of lagging indicators, such as lost time injury frequency rates (LTIFRs) and total recordable injury frequency rates (TRIFRs), to manage safety performance. Yet it is commonly recognized that lagging indicators are insufficient to indicate the current performance level due to their retrospective nature (Grabowski et al., 2007; Mengolini and Debarberis, 2008), and therefore are not able to predict or improve future performance. A low injury or accident rate in the past does not necessarily mean that management systems and processes are effective or undesirable incidents will not occur in the future (Hopkins, 2009). Moreover, most lagging indicators are not able to convey the reasons for negative outcomes. As a result, responses to lagging indicators tend to be a broad range of corrective actions that address possible weaknesses of safety management systems; yet they are not necessarily effective or efficient (Hinze et al., 2013). In addition, extant studies have questioned the reportability and recordability of lagging indicators in practice (Lingard et al., 2017; Oswald, 2019). Lagging indicators can be easily manipulated, especially when they are linked to performance evaluation and where the bonus systems of production and safety are imbalanced (Oswald et al., 2018; Toellner, 2001).

Against this background, researchers have proposed taking a more proactive approach by using leading indicators, such as organization commitment and safety training, as complementary measures of safety status (Lingard et al., 2011; Reiman and Pietikäinen, 2012; Zwetsloot et al., 2020). Such indicators are proactive in nature as they measure safety initiatives that provide an early indication of impending adverse events and drive preventive actions (Guo and Yiu, 2016). Further, the process of implementing and measuring proactive management activities provides knowledge beyond individual incidents, allowing for continuous learning and an adaptive safety system (Salas and Hallowell, 2016). Nevertheless, the growing interest in safety leading indicators in various areas (e.g., Grabowski et al. 2007 in energy transportation; Hopkins and Hale 2009 in process industries), including construction (e.g., Hinze et al. 2013), has led to a diversity of conceptualizations. This diversity renders it difficult to reconcile the findings of various pieces of research, which in turn can hamper the cumulative progress of theory development and the implementation of indicators in the construction industry (Guo et al., 2017). A working definition of safety leading indicators derived from different studies is therefore needed to build a shared understanding to guide practices.

While extant research has recognized a variety of leading indicators in construction (e.g., Guo et al. 2017; Hallowell et al. 2013), the specific contexts under investigation need attention because safety management is contextual and practices vary in different industries. Construction projects are embedded in multilevel ecosystems consisting of individuals and groups at the micro-level, projects and firms at the meso-level and institutions and institutional arrangements at the macro-level (Pryke et al., 2018; Rowlinson and Jia, 2015). In this vein, safety management, from the perspective of a firm or a project, occurs at the individual, project and firm levels. Different levels are interdependent and synergetic. Firms set up rules and resources that enable and constrain safety practices in projects, which in turn influence safety attitudes and actors' behaviors. On the other hand, individuals influence projects and firms in the form of habitualization and routinization (Bresnen et al., 2004; Manning, 2008). Yet, most research on safety leading indicators in construction have focused on a single level, such as the relationship between the frequency of toolbox meetings and the recordable injury rates (e.g., Lingard et al. 2017; Rajendran 2013; Salas and Hallowell 2016) while in other studies the level of analysis is ambiguous. In other words, these studies took a fragmented view on leading indicators and their effects on safety performance in construction. Furthermore, construction involves multiple stakeholders such as clients, designers, principal contractors and supply chain members. Each of them takes different roles and responsibilities in relation to construction safety (Hinze et al., 2013; Sakina and Omar, 2018). However, few studies, except Hallowell et al. (2013), explicitly consider the safety leading indicators of different stakeholders. In addition, although it is commonly recognized that safety leading indicators can provide early warning of potential accidents and injuries (Hinze et al., 2013), there is limited research addressing the connection between safety leading indicators and situations that might cause accidents and injuries (i.e. accident attributors).

In summary, despite the rich findings of extant research on safety leading indicators in the field of construction management, a synergy of various conceptualizations and an integrated framework of indicators are called for in improving proactive management and breaking the safety performance plateau in the construction industry. To fill this gap, the present study conducted a systematic literature review on safety leading indicators and accident causation in construction. Through reviewing peer-reviewed literature, the paper aims to: 1) develop a common working definition of safety leading indicators in construction; 2) generate an understanding of the current status of research on safety leading indicators in construction; 3) identify indicators based on the working definition; and 4) develop a systemic framework of safety leading indicators that can indicate the strengths and weaknesses of safety management processes and practices, and also identify situations that might cause construction accidents and injuries.

2. Review methodology

A systematic review enables researchers to integrate academic contributions and reveal central themes, gaps and prospective future directions in a given field of study (Petticrew and Roberts, 2006). Despite the traditional method used in positivistic and quantitative research in areas such as medicine, in the management field, where research is eclectic, a systematic review approach accounts for the different epistemologies and conceptualizations and uses qualitative reasoning of the studies reviewed (Petticrew and Roberts, 2006). This study followed such an approach and comprises three stages: 1) defining the concept; 2) identifying safety leading indicators; and 3) developing an integrated framework of safety leading indicators.

2.1. Stage one: defining the concept

The first stage was to generate a common understanding of safety leading indicators in construction by synergizing definitions given by various pieces of research (see Figure 1).

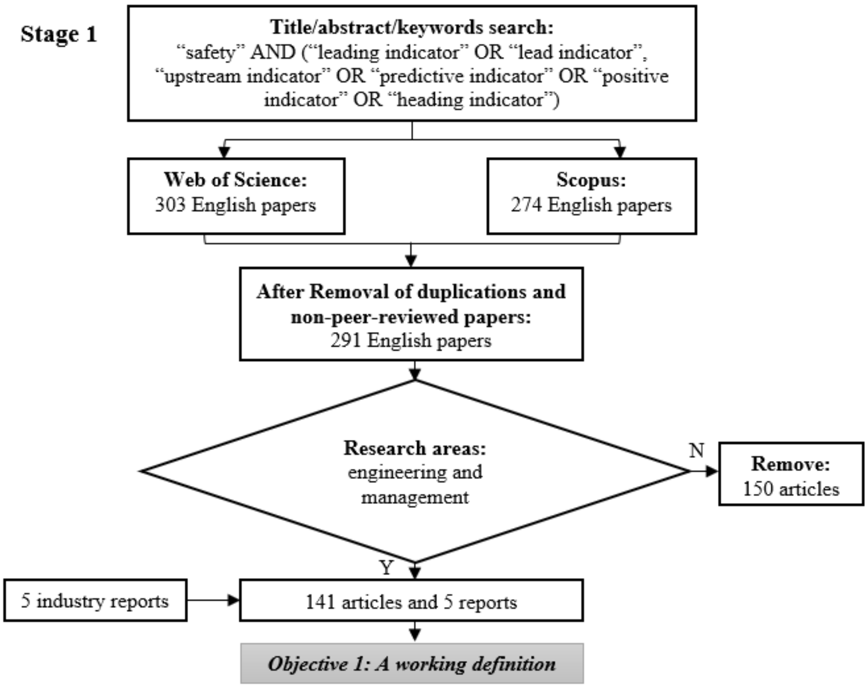

Figure 1 Stage one research process

Two databases were used as the starting point of the search, Scopus and Web of Science. These databases together provide complementary bibliographic information to most relevant academic journals. The search terms used were "safety" and "leading indicator" or "safety" and the synonyms of the latter ("lead indicator", "upstream indicator", "predictive indicator", "positive indicator" and "heading indicator"). The terms were mentioned in the title, abstract or keywords of journal papers written in English. After removing non-peer-reviewed papers (e.g., magazines) and duplications, the preliminary research resulted in 291 peer-reviewed journal papers. The initial sample was then manually screened to only include research in engineering and management areas, which eliminated 150 papers. In addition, five industry reports regarded as highly relevant (i.e., Autralian Constructors Association 2015; Campbell Institute 2015; Center for Chemical Process Safety 2019; eCompliance 2016; Health and Safety Executive 2006) were added to the review pool. A total of 141 journal papers and five reports were identified as relevant for analysis. The next step was to extract definitions of safety leading indicators from the review pool. By integrating the common characteristics and main functions, the first-stage study led to a working definition of safety leading indicator in construction.

2.2. Stage two: identifying indicators

The second stage was to identify safety leading indicators, particularly in construction (see Figure 2). For this purpose, the 141 articles were first checked to only include papers focusing on the construction industry, which removed 92 papers and four reports. The remaining articles were further checked based on two criteria, 1) related to the safety of people working in construction, and 2) focusing on the development, analysis or validation of indicators *per se*. The latter criterion helped exclude articles about the implementation of series of indicators to develop safety management systems or decision-making tools (e.g., Golovina et al. 2016; Kelm et al. 2013). This process identified 32 articles for further analysis.

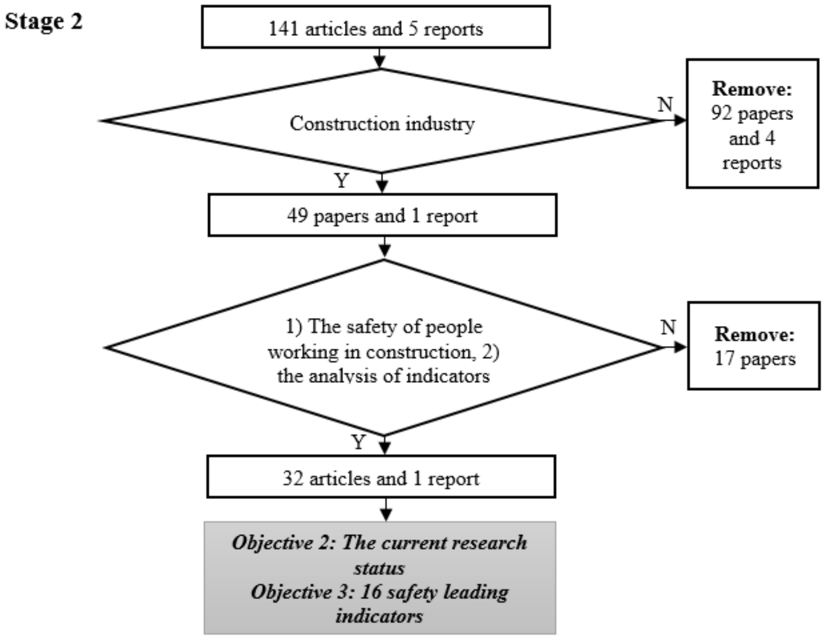

Figure 2 Stage two research process

Analysis of the 32 articles was facilitated by MAXQDA 2018, a software for qualitative data analysis. First, indicators and their descriptions were manually coded by the terms used in the original articles. Initial codes were then extracted across all articles to conduct in-depth analysis and make sense of the indicators in terms of what they were revealing about safety management and the level of measurement. In some cases, the original articles did not explicitly explain whether the indicators under investigation were for firms, projects, groups or individuals. The researchers inferred the information from research objectives and design, for instance, whether the research involved participants from different function units of organizations (firm-level analysis) or project representatives of clients, designers, principal contractors and subcontractors (project-level analysis). This process refined the initial findings by collating codes referring to the same safety management measures. Sixteen construction safety leading indicators were identified at this stage and categorized as firm level, project level, and group and individual level.

Table 1 List of 16 construction safety leading indicators

Safety leading indicator	Description	Examples of measures	Examples of literature sources
Firm level			

1. Organization commitment	Client, designer, principal contractor and subcontractor commitment to safety	- Total safety expenditures/total expenditures - Frequency of safety walk by senior management	Guo et al. (2017); Agumba and Haupt (2012);
2. Safety auditing	The process of collecting independent information on the efficiency, effectiveness and reliability of the safety management system and drawing up plans for preventive actions.	- Frequency of internal/external audits completed to schedule in a specific time frame - Number of action items suggested based on auditing - Percentage of action items that are closed on or before the target date	Hinze et al. (2013); Mitchell (2000)
3. Training and orientation	Improving skills, knowledge, attitudes and experiences of managers, supervisors and workers to effectively manage safety	- Hours of training received by workers in a specific time frame - Percentage of workers trained, including contracted workers	Alruqi and Hallowell (2019); Biggs and Biggs (2013)
Project level			
4. Client engagement	Client is engaged in construction safety throughout a project.	- Frequency of meetings between client's safety professional and designer teams in a specific time frame - Frequency of safety audits for contractors in a specific time frame - Frequency of qualified walkthroughs in a specific time frame	Alruqi and Hallowell (2019); Hinze et al. (2013)
5. Designer engagement	Principal designer and other designers (including designers of temporary works) is engaged in construction safety throughout a project.	- Number of meetings with main contractors per role (including designers of temporary works) in a specific time frame	Mitchell (2000)
6. Principal contractor engagement	Principal contractor is engaged in construction safety throughout a project.	- Frequency of a safety professional's onsite safety inspection in a specific time frame - Percentage of subcontractors audited monthly vs. total number	Hallowell et al. (2013); Rajendran (2013)
7. Supply chain and workforce engagement	Subcontractors, suppliers and self-employed workers are engaged in construction safety throughout a project.	- Number of safety inspection conducted by a subcontractor/supplier/self-employed worker in a specific time frame - Frequency of a crew's receiving notices of hazard removal	Guo et al. (2016); Hallowell et al. (2013)
8. Safety design	Preventing accidents during construction is regarded as one of the objectives of design.	- Number of hazards/risks highlighted and addressed in the design of structure, including temporary works	Mitchell (2000)

		- Number of hazards/risks eliminated by amending design	
9. Plan for safety	Safety in construction is considered in the planning process, including both preconstruction planning and short-term planning.	- Number of hazards and risks highlighted and addressed in site logistics and layout plans - Number of emergency plans, e.g., fires and explosion emergencies, established before construction	Agumba and Haupt (2012); Biggs and Biggs (2013)
10. Hazard identification and control	The process and outcome of identifying and controlling hazards and risks in workplace.	- Percentage of high-risk items identified in a specific time frame - Percentage of hazardous items actioned in the agreed time frame	Alruqi and Hallowell (2019); Hinze et al. (2013)
11. Safety learning	Learning from accidents, incidents and relevant experiences.	- Number of safety reports with actions implemented in a specific time frame	Biggs and Biggs (2013); Hinze et al. (2013)
12. Recognition and reward	Mechanisms to motivate workforce to comply with safety rules and actively participate in safety improvement activities	- Percentage of individuals or groups recognized e.g., employee of the month for excellent safety performance in a specific time frame - Percentage of individuals or groups who received safety bonus in a specific time frame	Guo et al. (2017); Biggs and Biggs (2013)
13. Site communication	Familiarizing operatives with a job, informing risks and improving task-specific competence to prevent accidents	- Percentage of operatives who receive induction prior to commencement of work - Frequency of toolbox meeting	Versteeg et al. (2019) Lingard et al. (2017);
Group and individual level			
14. Safety climate	Employees' perception of the priority an organisation and workgroup placed on safety-related policies, procedures and practices.	- Use of quantitative scales (e.g. a five-point scale) for measuring perceived management commitment, supervisor safety responses, co-worker safety response, client safety commitment, principal contractor safety commitment, and error management	Nadhim et al. (2018); Chen et al. (2017);
15. Worker involvement	Workers' level of involvement in establishing, operating, evaluating, and improving safety practices.	- Percentage of attendance of workers at safety events, e.g., training and induction/toolbox meeting	Agumba and Haupt (2012); Aksorn and Hadikusumo (2008)
16. Competence	Ensuring that employees have the skills, knowledge, attitudes and experience to safely carry out assigned tasks.	- Number of certification cards	Hinze et al. (2013); Aksorn and Hadikusumo (2008)

2.3. Stage three: developing the integrated framework

An effective framework of safety leading indicators needs to be able to highlight situations that might cause accidents or injuries. To do so, the theoretical construction of the framework should be linked with accident attributors, or causes of construction incidents or injuries (Toellner, 2001; Versteeg et al., 2019; Wreathall, 2009). This research explored whether the 16 indicators were associated with safety incidents and injuries by systematically reviewing literature related to construction accident attributors and then conceptually linking the leading indicators with accident attributors. It is notable that the research was not to reveal universal cause and effect as assumed by positivists; rather, it took a critical realist view (see Bhaskar, 1998; Danermark, Ekstrom and Jakobsen, 2001) and explored the tendencies that leading indicators can make a difference to safety incidents and injuries. Whether the causal powers of individual indicators are actualized depends on other conditions, such as the context and other indicators (cf. Lingard *et al.*, 2017).

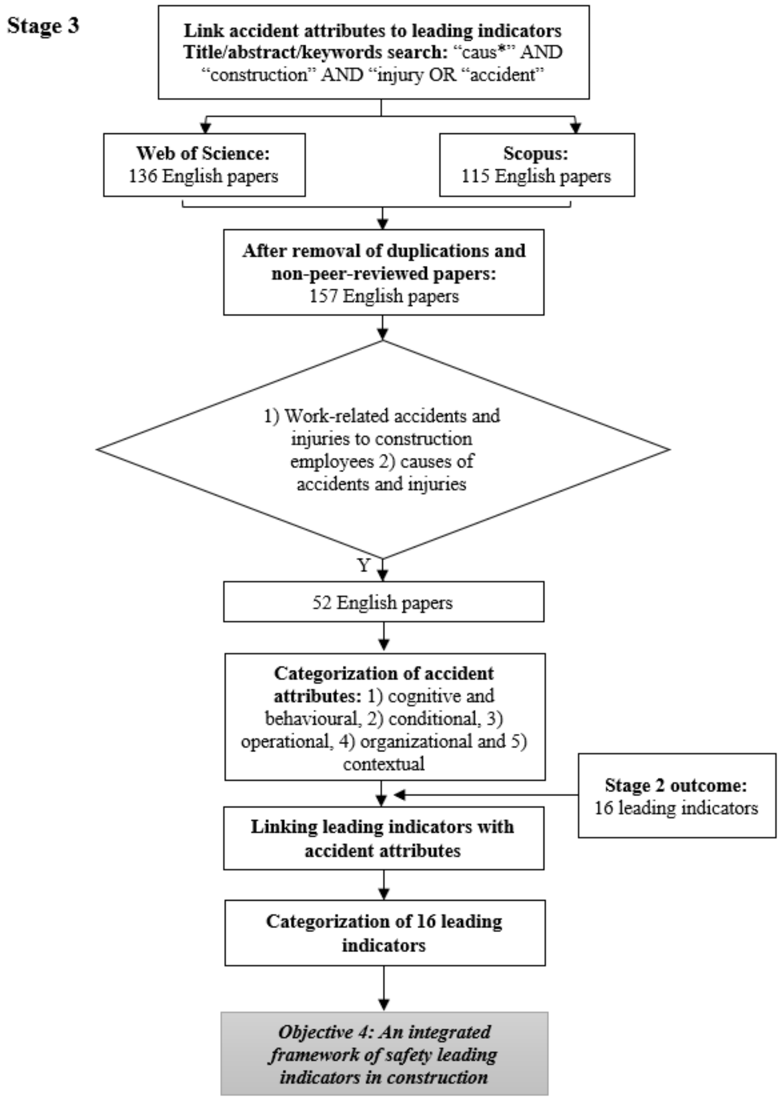

Figure 3 illustrated the research process of stage three.

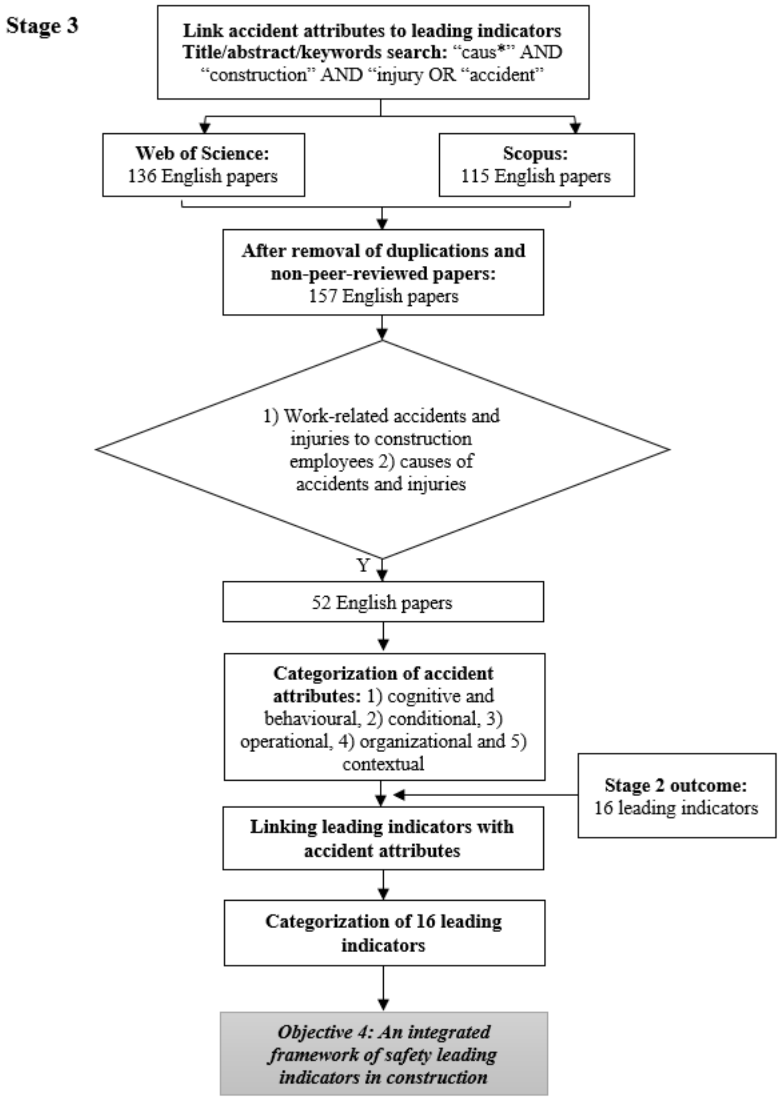

Figure 3 Stage three research process

Similar to the first-round review, the literature search was based on Scopus and Web of Science. The search terms used were "caus*" and "construction accident"; or "cause*" and "construction injury". The asterisk helped find words approximating to the word "cause", such as "causation" and "causality". The terms were mentioned in the title, abstract or keywords of peer-reviewed journal papers written in English. The preliminary research resulted in 157 articles. Each of the 157 articles was then checked to only include research that 1) focused on work-related accidents and injuries to construction employees and 2) identified causes of accidents or injuries (as opposed to, e.g., types of accidents or injuries).

Literature reviews were excluded to avoid duplication of interpretations. This process resulted in a set of 52 articles.

To analyze the 52 articles, various accident attributors were firstly indexed with original terms and phases, via MAXQDA 2018, and then aggregated on the basis of the same meanings. Meanwhile, the analysis identified various accident models (e.g., Suraji, Duff and Peckitt, 2001; Haslam *et al.*, 2005; Manu *et al.*, 2012), which enabled the accident attributors to be categorized into five groups, 1) cognitive and behavioral, 2) conditional, 3) operational, 4) organizational and 5) contextual. Figure 4 illustrates an extract from the data structure.

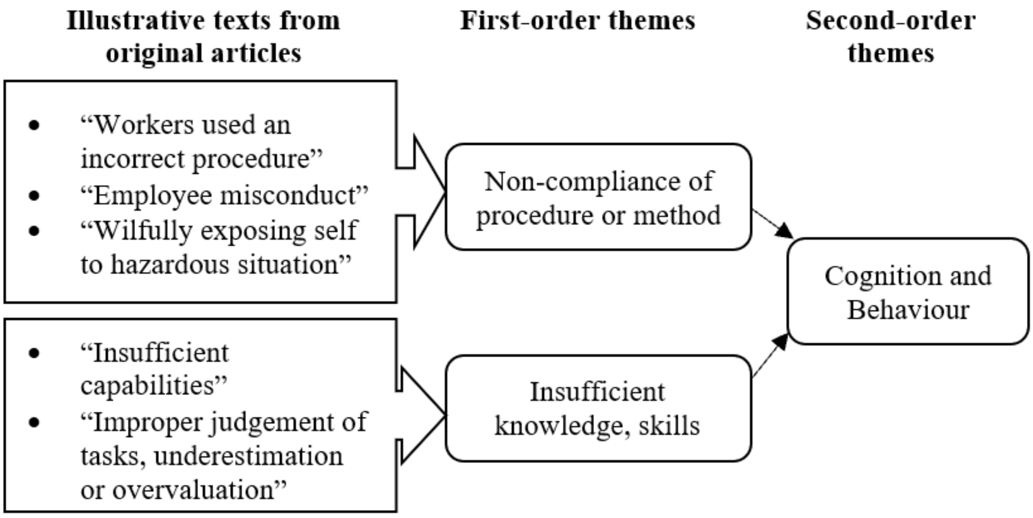

Figure 4 An extract from the data structure

Specifically, cognitive and behavioral attributors are related to human factors, including behaviors, attitudes and competences of individuals and groups. Conditional attributors include the conditions of the workplace, such as weather, lighting and stability of temporary structures. Operational attributors consist of the processes and practices of safety management, and organizational attributes are related to the key stakeholders of construction projects, including clients, designers, principal contractors and supply chain members. Lastly, contextual attributors are about the contexts in which projects and firms are embedded, including the industry and society.

The research conceptually linked the accident attributors with the 16 safety leading indicators as shown in Table 2. However, none of the safety leading indicators was aligned to the contextual accident attributors. As a result, the 16 leading indicators were categorized as cognitive and behavioral, operational or organizational indicators. Cognitive and behavioral indicators, for instance, can signal potential accidents or injuries that are caused by human factors such as non-compliance of procedures or methods. As Table 2 shows, operational and conditional attributors largely overlap and thus can be combined as one category. Operational indicators can identify potential accidents or injuries that are caused by the processes (operational) and the outcomes (conditional) of safety management activities. Organizational indicators can warn of unsafe situations due to key stakeholders' lack of engagement.

Table 2 Conceptual relationships between construction accident attributors and safety leading indicators

Categories	**Individual Attributes**	**References**	**Related Safety Leading indicators**
Cognition and Behavior	Non-compliance of procedure or method (e.g., material handling method and unsafe climbing)	E.g., Gharaie et al. (2015); Haslam et al. (2005)	Worker Involvement
	Co-worker's unsafe behavior	E.g., Eteifa and El-Adaway (2018); Abdelhamid and Everett (2000)	
	Economic incentives (e.g., workers are rewarded for higher production)	E.g., Rowlinson and Jia (2015); Choudhry and Fang (2008)	
	Attitudes (e.g., workers want to be "tough guys")	E.g., Harvey et al. (2018); Mitropoulos et al. (2005)	
	Work-related fatigue/pressure/stress	E.g., Eteifa and El-Adaway (2018); Rowlinson and Jia (2015); Choudhry and Fang (2008);	
	Improper use of personal protective equipment (PPE) or other equipment	E.g., Eteifa and El-Adaway (2018); Chi and Han (2013)	Competence
	Insufficient knowledge, skills and experience	E.g., Soltanzadeh et al. (2017); Behm and Schneller (2013)	
	Insufficient other competences (e.g., problem solving, decision making)	E.g., Harvey et al. (2018); Zhou et al. (2014)	
	Insufficient education level	E.g., Sakina and Omar (2018); Choudhry and Fang (2008)	
	Low safety awareness (e.g., workers often took an unsafe posture, such as standing with their back toward an unguarded opening)	E.g., Oswald et al. (2015); Rowlinson and Jia (2015)	
	Worker misjudgment/low risk perception	E.g., Lee and Lim (2017); Chi and Han (2013)	

	Team communication (e.g., language and culture barriers)	E.g., Behm and Schneller (2013); Haslam et al. (2005)	Safety Climate
	Team culture (e.g., chance-taking acts as a norm to boost productivity, blame culture)	E.g., Sakina and Omar (2018); Zhou et al. (2014)	
	Supervisors' lack of safety awareness	E.g., Sakina and Omar (2018); Haslam et al. (2005)	
	Peer pressure	E.g., Manu et al. (2012); Suraji et al. (2001)	
Conditional	Damaged or defective tools, machines, equipment, toxic material, PPE and other unexpected hazards	E.g., Winge et al. (2019); Mitropoulos et al. (2005)	Hazard Identification and Control, Safety Learning
	Insufficient prevention or protection devices and equipment (e.g., PPE, fall arrest system, securing and warning)	E.g., Chi and Han (2013); Suraji et al. (2001)	
	Poor site conditions (e.g., poor lighting, electrical apparatus or wiring, gases, storage, collapse of structure, height, and confined place)	E.g., Esmaeili et al. (2015); Behm and Schneller (2013);	Hazard Identification and Control, Safety Design, Plan for Safety
	Improper site layout (e.g., causing site congestion, and failure to properly locate utilities)	E.g., Sakina and Omar (2018); Manu et al. (2012);	Safety Design, Plan for Safety
	No safe access to site/scaffold/trench	E.g., Eteifa and El-Adaway (2018); Lee and Lim (2017);	
	Usability of equipment or material due to improper design or specification (e.g., design of equipment, specification, quality)	E.g., Harvey et al. (2018); Lee and Lim (2017)	
	Instability of temporary structure	E.g., Lee and Lim (2017); Suraji et al. (2001)	
	Natural environment (e.g., weather and temperature)	E.g., Lee and Lim (2017); Li and Xiang (2011)	
Operational	Insufficient hazard identification and communication (e.g., jobsite inspection and noticeboard)	E.g., Eteifa and El-Adaway (2018); Soltanzadeh et al. (2017)	Hazard Identification and Control, Safety Auditing
	Insufficient housekeeping	E.g., Chi and Han (2013); Haslam et al. (2005)	
	Inappropriate control of underground utilities	E.g., Lee and Lim (2017)	
	Insufficient maintenance of machinery, equipment, tools and PPE	E.g., Li and Xiang (2011); Haslam et al. (2005)	Hazard Identification and Control
	Inappropriate maintenance of temporary structure	E.g., Lee and Lim (2017); Suraji et al. (2001)	
	Insufficient safety procedures/method statement (e.g., method statement, lock-out/tag-out	E.g., Chua and Goh (2004); Suraji et al. (2001)	Safety Auditing

	procedure, and testing procedure for equipment)		
	Lack of first-aid training/first-aid personnel	E.g., Eteifa and El-Adaway (2018)	Training and Orientation
	Insufficient risk assessment and plans (e.g., resource needs such as human resources, machinery, equipment etc., consideration of project nature, duration and other risks)	E.g., Choudhry and Fang (2008); Manu et al. (2012)	Safety Design, Plan for Safety
	Lack of design specification for equipment and material	E.g., Behm and Schneller (2013); Haslam et al. (2005)	
	Lack of emergency preparedness	E.g., Zhou et al. (2014); Li and Xiang (2011)	
	Inappropriate design of permanent structure		
	Inappropriate design of temporary structure		
	Inappropriate installation plan for safety facilities	E.g., Lee and Lim (2017)	
	Lack of training and orientation (e.g., both on-the-job training and pre-job training)	E.g., Soltanzadeh et al. (2017); Choudhry and Fang (2008)	Training and Orientation, Site Communication
	Lack of award system for workers who are committed to safety standards, both monetary and non-monetary	E.g., Sakina and Omar (2018); Rowlinson and Jia (2015)	Recognition and Reward
	Lack of incident reporting, investigation and analysis	E.g., Soltanzadeh et al. (2017); Mitropoulos et al. (2005)	Safety Learning
Organizational	Insufficient investment in safety management improvement (e.g., safer construction method, and innovation, technology, staff, budgets for equipment, PPE and tools)	E.g., Rowlinson and Jia (2015); Haslam et al. (2005)	Organization Commitment
	Lack of understanding of safety regulations/standards (e.g., gross negligence, non-compliance, and not using safer/sustainable material)	E.g., Eteifa and El-Adaway (2018); Zhou et al. (2014)	
	Insufficient risk management systems	E.g., Winge et al. (2019); Gibb et al. (2014)	
	Insufficient project management systems	E.g., Gharaie et al. (2015); Suraji et al. (2001)	
	Insufficient change management systems (e.g., to deal with unpredictability in projects)	E.g., Mitropoulos et al. (2005); Manu et al. (2012)	
	Lack of safety management systems	E.g., Soltanzadeh et al. (2017); Zhou et al. (2014)	
	Lack of knowledge management systems (e.g.,	E.g., Eteifa and El-Adaway (2018); Sakina and Omar (2018)	

	learning from errors and incidents)		
	Lack of/inappropriate safe working policy and procedures	E.g., Lee and Lim (2017); Li and Xiang (2011)	
	Inappropriate management instruction	E.g., Sakina and Omar (2018); Lee and Lim (2017)	
	Lack of integration of safety and production (e.g., prioritizing production)	E.g., Rowlinson and Jia (2015)	
	Lack of senior management/client involvement in safety activities (e.g., regular meetings, and changing requirements without considering impacts on safety)	E.g., Eteifa and El-Adaway (2018); Sakina and Omar (2018)	Organization Commitment, Client Engagement
	Designer lack of experience (e.g., practice CDM, and deal with complex design requirements)	E.g., Manu et al. (2012); Haslam et al. (2005)	Designer Engagement
	Designer changing designs during construction without considering impacts on safety	Suraji et al. (2001)	
	Lack of enforcement of safety regulations/standards in projects	E.g., Sakina and Omar (2018); Zhou et al. (2014)	Client Engagement, Principal Contractor Engagement, Supply Chain and Workforce Engagement
	Principal contractor lack of coordination of site activities	E.g., Harvey et al. (2018); Sakina and Omar (2018)	Principal Contractor Engagement
	Principal contractors' lack of control of construction process (e.g., deviation of the construction operations from the plan), which increases the risk or undesired events	E.g., Gharaie et al. (2015); Gibb et al. (2014)	
	Inappropriate environmental management of workplace	Lee and Lim (2017)	Principal Contractor Engagement, Supply Chain and Workforce Engagement
	Lack of management of transient workforce	Harvey et al. (2018)	
	Insufficient provision of supervision	E.g., Winge et al. (2019); Suraji et al. (2001)	
	Contractor/subcontractor lacking awareness regarding health and safety	Sakina and Omar (2018)	
	Lack of communication between various stakeholders	Sakina and Omar (2018)	Client Engagement, Designer Engagement, Principal Contractor Engagement, Supply Chain and Workforce Engagement

	Principal contractors not understanding the design	Lee and Lim (2017)	Principal Contractor Engagement, Designer Engagement
	Lack of management of contractors/sub-contractors	E.g., Sakina and Omar (2018); Li and Xiang (2011)	Client Engagement, Principal Contractor Engagement
Contextual	Subcontracting system	E.g., Harvey et al. (2018); Manu et al. (2012)	N/A
	Low-profit margins of the industry	Harvey et al. (2018)	
	Procurement system	E.g., Sakina and Omar (2018); Manu et al. (2012)	
	Lack of safety monitoring by the government	E.g., Sakina and Omar (2018); Rowlinson and Jia (2015)	
	Others (e.g., workload and working hour, training and licensing system; norms of occupation, market, union, social cultures)	Rowlinson and Jia (2015)	

Based on the two-round literature review, the integrated safety leading indicators framework was developed. It consists of 16 indicators and has two dimensions. The first dimension, which is the level of measurement, represents the safety management performance at the firm, project, or group and individual level. The second dimension categorizes indicators as cognitive and behavioral, operational or organizational indicators that can identify different accident and injury situations in construction.

3. Findings

This section reports three major findings from the study: the present status of safety leading indicator research in construction; a working definition building upon various conceptualizations; and a framework of safety leading indicators in construction.

3.1. Safety leading indicator research: current status

Bibliographic information from the 141 articles in engineering management fields reveals that the construction and process industries are the most dominant areas for safety leading indicator research (see Figure 5). However, studies in these two industries had distinct units of analysis. Safety leading indicators in construction research focused on the safety of construction employees and therefore investigated incidents that injure or might injure people. Research in the process industry emphasized the safety of the working process, which might not be harmful to people. Interestingly, the nuclear industry, which is commonly regarded as a high-hazard industry, used the term "safety leading indicator" much less frequently than the construction and process industries. This might be due to the prevalence of alternative terms, notably "safety culture", in the industry, particularly after the Chernobyl accident that led to the introduction of the term safety culture.

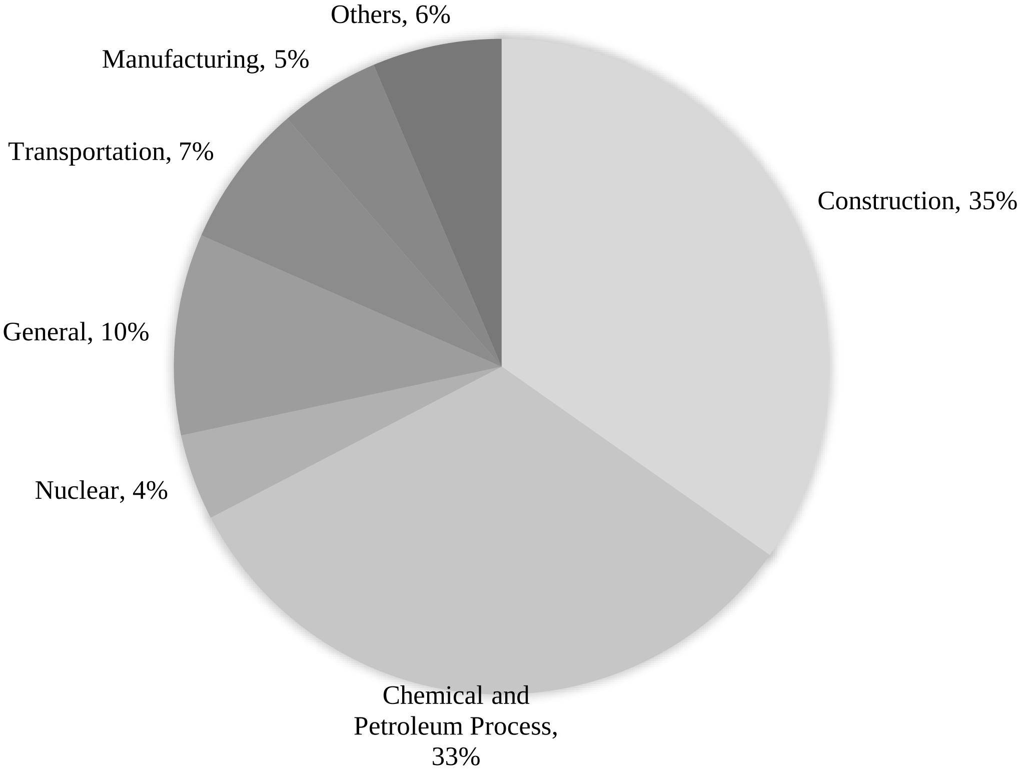

Figure 5 Overview of the safety leading indicator research in engineering management by industries (n=141)

In stage two of the review process, 32 key articles were identified based on the set of criteria illustrated in the method section. For the 32 key articles, their research methods, level of analysis and research topics were systematically documented.

3.1.1. Research method

Figure 6 reported the research methods used in safety leading indicator research in construction. Results indicate that the field of research is dominated by quantitative approaches (51% of all contributions). Most studies used primary data collected through questionnaires, in which one or several safety indicators were quantified. Four studies used secondary data from other research (i.e., Alexander, Hallowell and Gambatese, 2017; Lingard *et al.*, 2017; Alruqi and Hallowell, 2019) or enterprise database (i.e., Salas and Hallowell, 2016). Multivariate methods, such as multiple regression and structural equitation modelling, were then used to explore or validate the relationships between indicators.

For qualitative studies (19%), researchers conducted focus group discussion, interview or Delphi methods to identify and prioritize leading indicators in the context of construction. Key indicators were also identified by investigating procurement prequalification documents used by clients, principal contractors and consultants (i.e., Liu *et al.*, 2019). Three studies (9%) combined qualitative and quantitative approaches (i.e., Mitchell, 2000; Biggs and Biggs, 2013; Guo *et al.*, 2017). Finally, seven conceptual articles (22%) were identified, which reviewed the concepts of leading and lagging indicators and pointed out current issues and future directions for the research community.

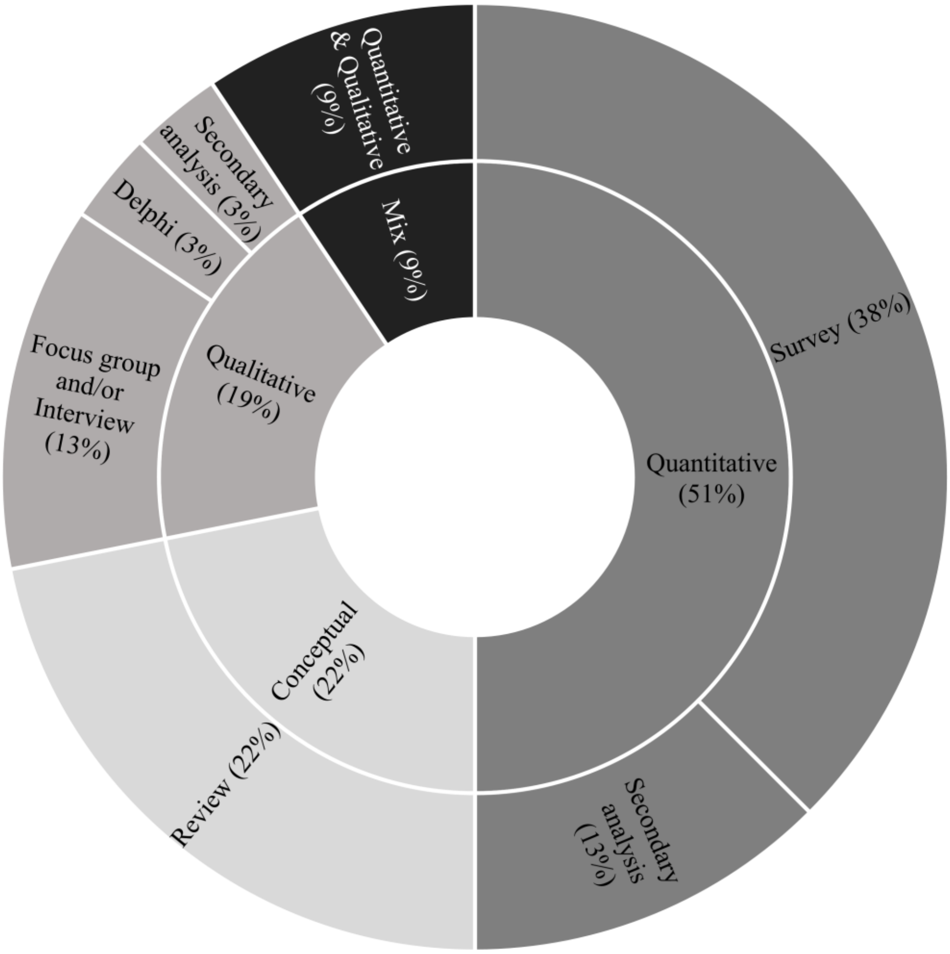

Figure 6 Segmentation of construction safety leading indicator research database (n=32) by research methods

3.1.2. Level of analysis

Figure 7 illustrates that the majority of the research focused on project-level indicators such as the frequency of safety inspections and site inductions, whereas firm-level indicators such as organization strategies and management commitment received less attention. At the group and individual levels, safety climate in general and in minority groups has been investigated as a safety leading indicator. Five cross-level studies combined indicators from firm, project, group and individual levels to evaluate construction safety performance. The interactions between multiple levels of ecosystems that bring about the phenomenon of safety in construction were largely ignored by extant studies.

Figure 7 Segmentation of construction safety leading indicator research database (n=32) by levels of analysis

3.1.3. Research Topics

The research revealed five main research topics in the construction safety leading indicator studies (see Figure 8). The first topic is the identification of safety leading indicators in construction. Various research methods were employed to explore this topic. For example, Mitchell (2000) and Hallowell *et al.* (2013) combined different research methods, such as focus group discussion and case study, and generated comprehensive lists of safety leading indicators in construction. In addition, Hallowell *et al.* (2013) categorized indicators identified based on the organizations' roles in projects, which were owner-, contractor- and vendor-led indicators. Agumba and Haupt (2012) conducted four successive rounds of Delphi method among 20 experts in eight countries and identified 32 indicators that can improve the health and safety performance of small and medium enterprises (SMEs). Akroush and El-adaway (2017) surveyed the safety leading indicators that were implemented in the Tennessee construction industry and compared the indicators used by large firms and SMEs. They identified 48 indicators used by Tennessee construction firms, with housekeeping, use of PPE and substance abuse programs being the most widely used. Moreover, larger companies were more likely to use safety policies and programs than smaller companies. By analyzing 52 contractor prequalification surveys, Liu *et al.* (2019) found that safety management leadership and worker training were the mostly used safety leading indicators in contractor selection to evaluate contractors' safety performance.

The second topic concerns the effectiveness of safety leading indicators in terms of predicting safety incidents and injuries. Alruqi and Hallowell (2019) categorized leading indicators as active and passive indicators and conducted a meta-analysis of 114 studies on the relationship between nine safety leading indicators and injury rate in construction. It was revealed that pre-task safety meeting and safety inspections, when treated as active indicators and measured regularly, could significantly improve future performance. Positive effects were also found among eight passive safety leading indicators, which are safety record, safety resource, staffing for safety, owner involvement, safety training and orientation, personal protective equipment, safety incentives program, and safety inspections. Nevertheless, the effectiveness of safety leading indicators on safety performance varies in empirical studies. Some researchers pointed out the positive effects of safety monitoring and inspections, control of subcontractors and pre-job risk analysis and plans for reducing accident or injury rates (Aksorn and Hadikusumo, 2008; Rajendran, 2013; Salas and Hallowell, 2016). However, a recent study (Versteeg et al., 2019) investigated 47 construction projects of a construction firm and did not find significant relationships between the number of inspections and toolbox talks and 'lost time' injuries or medical injuries. The authors further explained that the reason for the insignificant relationship might be the small number of injuries in the period of investigation.

The study by Lingard *et al.* (2017) is especially worthy of note here. It took into account temporal effects on the relationship between leading indicators (e.g., frequency of toolbox meetings, pre-brief meetings, audits and drug tests) and total recordable injury frequency rates (TRIFRs). No consistent relationships were established between individual indicators and TRIFRs, pointing to the need to consider the complex interactions between indicators and their collective effects on safety performance. In summary, findings of studies on the effectiveness of safety leading indicators on safety performance are inconsistent and difficult to reconcile with each other. It was observed that researchers frequently selected three to five leading indicators that fit the purpose of their studies, but it was unclear why these indicators were chosen while others were not. Furthermore, extant studies focused on the relationship between individual leading indicators and lagging indicators (e.g., the relationship between safety inspections and injury rate). The temporally dynamic interrelationship among multiple leading indicators and the collective effects on safety performance were largely neglected.

The third topic is about the development of safety indicator frameworks. Whereas some frameworks consisted of both leading and lagging indicators to evaluate the safety performance of construction firms or projects (i.e., Liang et al. 2018; Lingard et al. 2011), others comprised only leading indicators (i.e., Biggs and Biggs 2013; Guo et al. 2016, 2017). Guo et al. (2016) proposed a framework based on Rasmussen's two safety models and included 32 leading indicators to maintain and improve project safety conditions. Based on systems theory, Guo et al. (2017) developed a pressure-state-practice model of safety leading indicators to measure and compare the safety levels of three projects. Although the safe levels of one project, as indicated by the scores of individual leading indicators, were demonstrated in relation to total recordable injury frequency rate (TRIFR), the authors did not explicate the relationships between the selected safety constructs and the lagging indicator. Similarly, in their recent literature review, Shaikh et al (2020) identified 48 safety performance indicators, including both leading and lagging indicators, and employed Leavitt's (1965) organizational model to classify the indicators as structure, task, technology and people. Yet it is not clear whether and how these frameworks can help identify safety incidents and injuries. In other words, the effectiveness of the framework in terms of preventing negative outcomes remains unexplored.

Safety climate is the fourth topic in the construction safety leading indicator research. Nine studies were found that explicitly acknowledged safety climate as a leading indicator in construction. The main areas of interest for this topic were identified as: (1) dimensions of safety climate in the context of construction (Newaz et al., 2019; Niu et al., 2017); (2) antecedents of safety climate such as the management of cultural and cognitive differences (Al-Bayati et al., 2017; Liao et al., 2017) and open communication (Liao et al., 2015); and (3) the effects of safety climate on employees' risk perceptions (Pandit et al., 2019). The concept of safety climate as a safety leading indicator is developing largely in a silo and is weakly linked with other types of safety leading indicators in construction.

The last topic, concepts and issues, consists of studies that contributed to the conceptual development of safety leading indicators in construction (Forteza et al., 2020; Hinze et al., 2013) and differentiation and integration of safety leading indicators and other proactive management methods (Hallowell et al., 2019; Teizer, 2016). Particularly, in their review on safety prediction methods, Hallowell et al. (2019) differentiated safety leading indicators from safety climate. They argued that safety leading indicators as quantitative measures that directly and empirically measure the strength of safety management systems, whereas the measure of safety climate that encompasses individual perceptions can only indirectly indicate the status of safety management systems. However, other studies (e.g., Forteza et al., 2020; Lingard et al., 2011; Shaikh et al., 2020) regarded safety climate score as a leading indicator. The role of regulations and law in structuring proactive safety management and the needs for reducing bureaucratization were explicitly discussed by Forteza et al. (2020). In addition, Oswald (2019) criticized the dominated quantitative measures of indicators and put forward the usefulness of adding qualitative information in terms of informing the safety management performance in construction.

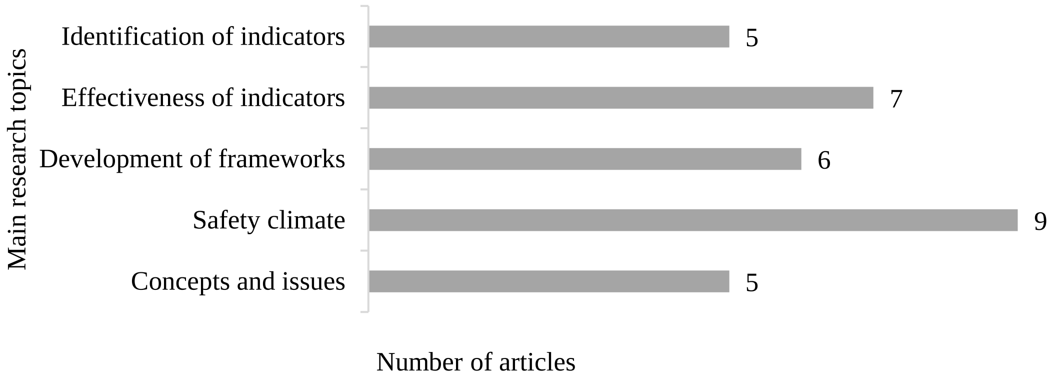

Figure 8 Segmentation of construction safety leading indicator research database (n=32) by research topics

3.2. A working definition

Table 3 lists a selection of extracted definitions along with fields of study and the characteristics and functions stressed in each article. It was found that, across industries, safety leading indicators were commonly recognized as measures of the safety management system. A safety management system consists of safety rules and resources as well as actors with the aim of creating and sustaining the safety of a workplace (Guo et al., 2017). In the context of construction, safety management systems are at both the firm and project levels. Safety leading indicators, therefore, measure safety management processes and practices of firms and projects. Such measurements precede the occurrence of an incident, accident or injury (Grabowski et al., 2007; Kjellén, 2009). They can provide early warning of situations that might increase risk levels or cause negative safety outcomes (Leveson, 2015; Sinelnikov et al., 2015). Moreover, leading indicators trigger proactive actions in response to the current state in order to correct the deficiencies or further develop the system (Hallowell et al., 2013; Hinze et al., 2013). The predictive value of safety leading indicators is built upon their ability to monitor the system's performance over time, providing early warnings of potential changes that might cause accidents or injuries, and driving actions to avoid unwanted outcomes and achieve continuous improvement. Safety leading indicators do not only seek to mitigate errors but also recognize the positive side so that systems can be strengthened. In this vein, leading indicators are not precursors to harm but signs of changing vulnerabilities or improvements (Reiman and Pietikäinen, 2012), which can be measured throughout project lifecycles (cf. Hallowell et al., 2013). Apart from the process of safety management, leading indicators measure outcomes of activities such as workforce engagement, competence and safety climate.

Table 3 Examples of safety leading indicator definitions

References	Definitions	Characteristics	Functions	Industry
Toellner (2001, p. 42)	Measurements linked to preventive or proactive actions	Preventive or proactive	N/A	Chemical and petroleum process
HSE (2006)	"The leading indicator identifies failings or 'holes' in vital aspects of the risk control system discovered during routine checks on the operation of a critical activity within the risk control system."	N/A	Identifying the weakness of the system	Chemical and petroleum process
Hopkins (2009, p. 460)	"Lead indicators are those that directly measure aspects of the safety management system, such as the frequency or timeliness of audits."	Measures of the safety management system	N/A	Chemical and petroleum process
Kjellén (2009, p. 486)	"An indicator that changes before the actual risk level of the organization has changed."	Preceding changes of the risk level of the organization	N/A	General
Reiman and Pietikäinen (2012, pp. 1994–1995)	"Lead safety indicators indicate either the current state or the development of key organizational functions, processes and the technical infrastructure of the system."	N/A	- Indicating the current state of the system - Developing the system	General
Shea *et al.* (2016, p. 293)	"…precursors to harm that provide early warning signs of potential failure."	Precursors to harm	Providing early warning of potential failure	General
Navarro *et al.* (2013, p. 21)	"characteristics that foment safety behavior, such as safety culture or safety climate."	N/A	Driving safety behavior, culture or climate	Nuclear

Grabowski *et al.* (2007, p. 1017)	"Leading indicators, one type of accident precursor, are conditions, events or measures that precede an undesirable event and that have some value in predicting the arrival of the event, whether it is an accident, incident, near miss, or undesirable safety state… are associated with proactive activities that identify hazards and assess, eliminate, minimize and control risk."	- Preceding an incident - Predictive	N/A	Energy transportation
Agumba and Haupt (2012, p. 546)	Leading indicators that allow a weakness to be addressed before there is an accident	Preceding an accident	Addressing the weakness	Construction
Hinze, Thurman and Wehle (2013, p. 24)	"Leading indicators are measures which are not necessarily historical in nature but rather can be used as predictors of future levels of safety performance… are selected measures that describe the level of effectiveness of the safety process. Leading indicators measure the building blocks of the safety culture of a project or company."	Not historical	- Predicting future safety performance - Indicating the effectiveness of safety process - Indicating the safety culture of a project or company	Construction
Hallowell *et al.* (2013, pp. 4013010–1)	"Leading indicators are safety-related practices or observations that can be measured during the construction phase, which can trigger positive responses."	- Safety-related practices - Construction phase	Triggering positive responses	Construction
Guo et al. (2016, pp. 04015016-2)	"…leading safety indicators as a set of quantitative and/or qualitative measurements that can describe and monitor validly and reliably the safety conditions of a construction project."	Quantitative and/or qualitative	Describing and monitoring the safety conditions	Construction
Karakhan *et al.* (2018, pp. 04018054–3)	"Safety leading indicators are proactive, pre-incident measurements consisting of multiple levels of safety protections carried out before the start of (or during) the construction phase, at both the organization and project levels."	- Proactive and pre-incident - Used before or during construction - At organization and project levels	N/A	Construction

Alruqi *et al.* (2019, pp. 04019005–1)	"Safety leading indicators are measures of the safety management system that correlate with injury rate."	- Measures of the management system - Correlate with injury rate	N/A	Construction

By summarizing all the definitions listed in Table 3 the present study puts forward a definition of safety leading indicators in construction as:

Safety leading indicators are measures that indicate the current performance of a safety management system of a project or firm. They can: 1) identify the system's weaknesses and strengths, 2) identify situations that might cause incidents and injuries, and 3) drive proactive actions to prevent an incident or injury before it occurs and achieve continuous improvement.

3.3. An integrated framework of safety leading indicators

The processes of identifying the measurement levels of safety leading indicators and linking leading indicators with accident attributors, which were illustrated in the methodology section, enabled the study to develop an integrated framework (see Table 4).

Table 4 An integrated framework of safety leading indicators in construction

	Organizational	**Operational**	**Cognitive and Behavioral**
Firm level	• Organization commitment	• Safety auditing • Training and orientation	
Project level	• Client engagement • Designer engagement • Principal contractor engagement • Supply chain and workforce engagement	• Safety design • Plan for safety • Hazard identification and control • Safety learning • Recognition and reward • Site communication	
Group and individual level			• Safety climate • Worker involvement • Competence

3.3.1. Dimensions of the framework

The integrated framework is consisted of two dimensions. The first dimension, the level of measurement, evaluates the safety management performance at the levels of firms, projects, groups and individuals. Firm-level indicators are linked to the safety management systems of clients, designers, principal contractors and supply chain members, which include organization commitment, safety auditing, and training and orientation. Project-level indicators are linked to the safety management systems of construction projects, which are temporary organizations constituted by project stakeholders. Group-and individual-level indicators are linked to cognitive and behavioral improvement including four indictors (i.e., safety climate, worker involvement and competence).

The second dimension provides early warns of potential accident and injury situations caused by organizational, operational or cognitive, and behavioral issues. Specifically, the indicators that measure the performance of organizations monitor the safety-related practices of construction stakeholders, particularly clients, designers, principal contractors and supply chain members. The lack of or insufficient organization commitment and engagement can lead to unsafe operations or actions that cause accidents. Operations indicators evaluate the processes and outcomes of safety management activities, which can be conducted within individual firms or collaboratively between various organizations involved in a project. Cognition and behavior indicators measure the performance of construction actors as well as their working groups, including their supervisors and co-workers, hence preventing safety incidents and injuries due to human factors.

3.3.2. Firm-level organizational indicator

Organization commitment has been argued to be the foundation for effective safety management (Abudayyeh et al., 2006; Hallowell et al., 2013; Ng et al., 2005) as it creates and sustains the safety culture within the organization that can influence employees' attitudes and behavior toward safety (Choudhry et al., 2007). The level of commitment is reflected in the organization's strategies and policies, which specify the safety-related goals and imply the relevant importance of safety in relation to other functional priorities such as revenue and production (Mahmoudi et al., 2014). The implementation of safety policies and the realization of goals require sufficient investment and resources such as PPE, competent personnel and well-maintained equipment (Feng, 2013; Rajendran and Gambatese, 2009; Teo and Feng, 2011). Whether the level of commitment can be sustained over time, especially under cultural and organizational changes (see Smyth et al. 2019), can be implied by the extent to which safety management and other key functions are integrated with each other (Mohamed, 2003). For instance, operatives' safety competence and performance are considered in human resource management and as an integral part of career development. Senior management engagement gauges the senior management's awareness of safety issues as well as their involvement in safety activities, for example, the frequency of site walkthroughs, communicating with operatives and participation in safety management training (Agumba and Haupt, 2012; Toellner, 2001).

3.3.3. Firm-level operational indicator

Operationally, safety auditing assesses whether the safety management system performs as planned, including the sufficiency of safety resources and flow of information (Hallowell et al., 2013; Lingard et al., 2017; Teo and Ling, 2006). Moreover, the process of auditing enables management to reflect on whether the original plans and indicators are still effective, especially after changes or possible changes, monitor the impacts of corrective and improvement actions, and analyze the root causes of non-compliance mentioned in audit reports (Choudhry et al., 2007; Mohamed, 2003; Trethewy and Gardner, 2003). In other words, safety auditing measures the compliance and integrity of the safety management system.

Training and orientation is another operational indicator at the firm level. It indicates the organization's efforts to enrich managers' and operatives' knowledge, skills and ability to effectively manage safety. The capability is not only technical, such as identifying and controlling hazards (Albert et al., 2017), but also "soft" in the sense that employees' care about each other's safety and recognize their own competence or incompetence in risky situations (Wen Lim et al., 2018). In addition, firm-specific orientations provide opportunities for increasing operatives' understanding of the company's safety initiatives and programs so that they can better comply with policies and engage with safety activities (Hallowell and Gambatese, 2009; Liu et al., 2019). The frequency of training and percentage of employees trained reflect the organization's investment in safety. Yet they cannot ensure the effectiveness of activities (Oswald, 2019), pointing to the importance of evaluating the quality of training, such as the extent to which training is conducted according to the objectives, the engagement of employees and the transfer behavior after the training. More consideration needs to be taken in selecting leading indicator measures in order to reflect the effectiveness of the safety management systems.

3.3.4. Project-level organizational indicators

Four organization-related indicators (i.e., client engagement, designer engagement, principal contractor engagement, supply chain and workforce engagement) indicate each project actor's level of involvement in safety activities and also their interactions to improve project safety. The role of clients can be both functional and symbolic. Functionally, clients' engagement with designers can mitigate safety risks early in design. Selection and early involvement of competent contractors can ensure that risks recognized in design are acknowledged in execution and sufficient preventive measures have been put in place (Suraji et al., 2006). Establishing a project safety committee consisting of designers, contractors and supply chain partners and regular site walkthroughs by the client can align divergent interests and build a mutual understanding of safety issues among various stakeholders (Evans, 2008). Sufficient safety budget can provide quality resources for site operatives. Symbolically, clients' proactive involvement communicates the message that safety is valued in daily operations, hence promoting a safety culture within projects (Hallowell et al., 2013).

The designer's level of engagement determines the level of risk before project execution on site and the level of prevention to address residual design risks during execution (Hallowell et al., 2013). The designer's knowledge and skills affect the client's and contractors' ability to manage safety (Suraji et al., 2006; Toole and Gambatese, 2008), which in turn are enriched by the experience of learning with other parties, particularly about the underlying accident causes that include the effects of design and the design process (Evans, 2008; Suraji et al., 2006).

Principal contractor engagement influences the level of prevention and control in construction. Through early involvement in projects, principal contractors can help identify safety risks in design so that potential incidents can be mitigated through changing unsafe structures, layout or materials at the early phase of a project (Saurin, 2016). Formal and informal control of subcontractors and suppliers, such as auditing subcontractors' management systems and rewarding safety behavior, can help improve the performance during execution (Hallowell et al., 2013; Hinze et al., 2013). The effectiveness of the client's and principal contractor's management, moreover, depends on supply chain members' engagement in safety activities, the quality of their risk assessment and the level of compliance to the documented safe work method statement, for example (Trethewy and Gardner, 2003).

3.3.5. Project-level operational indicators

The engagement of and interactions between key stakeholders help ensure the safety of operations, through safety design, planning, hazard identification and control, safety learning, site communication, recognition and rewarding. Specifically, the practice of prevention through design can recognize and address potential hazards by amending design, adding facilities for fixing of temporary works, for instance, as well as providing early warning about outstanding hazards that cannot be rectified at the design stage (Gangolells et al., 2010; Toole and Gambatese, 2008; Trethewy and Gardner, 2003). Plans for safety set responsibilities among various trades and embed safety measures into the project schedule to avoid conflicts between safety and production (Liang et al., 2018; Mitchell, 2000). Furthermore, design documents and plans facilitate the practice of identifying and controlling hazards during execution (Hinze et al., 2013; Lingard et al., 2017). They can be used to create formal inspection plans, stressing high-risk areas, for instance, and guide the method for controlling identified hazards (Hallowell and Gambatese, 2009; Liu et al., 2019; Mahmoudi et al., 2014). Apart from regular inspections, continuous monitoring of work environment and taking remedial actions help to measure the safety level on site (Mahmoudi et al., 2014; Teo et al., 2005). Although safety learning might be based on unwanted outcomes, such as through incident reporting and investigation, this practice leads to learning from the past that is beneficial to future performance (Hinze et al., 2013; Li et al., 2018; Oswald, 2019). Moreover, reporting can include positive non-conformities and performance adjustments where knowledge and experience of successfully managing safety can be learned and generalized to strengthen the system. Reporting both positive and negative events tends to generate more learning in daily works, especially where the accident or injury rate is low (Saurin et al., 2015; Versteeg et al., 2019).

The effectiveness of identifying and controlling hazards, prioritizing and reporting incidents, and investigating and learning from incidents, however, relies on the knowledge and experience of operatives who assume the responsibility (Saurin et al., 2015). Site communication, such as inductions, on-the-job training and toolbox meetings provide opportunities to enrich task-specific skills to prevent accidents (Hallowell and Gambatese, 2009; Hinze et al., 2013). Rewarding mechanisms are measures that sustain safe operations as they motivate the workforce to continuously comply with safety rules and actively participate in safety improvement (Mohamed, 2003). Whereas monetary rewards offer extrinsic incentives, social recognition and identity based on good safety performance help generate norms of practice, hence the emergence of a safety climate (Choi et al., 2017; Liang et al., 2018).

3.3.6. Group- and individual-level cognitive and behavioral indicators

Group-and individual-level indicators are linked to cognitive and behavioral improvement including three indictors (i.e., safety climate, worker involvement and competence). Lingard et al. (2010) revealed that workgroups with stronger and positive safety climates had lower rates of reportable injury. Despite different views on conceptualizing safety climate as a leading indicator (cf. Hallowell et al., 2019), the proposed framework considers safety climate as a group-level measure that indicates employees' perception of the priority an organization and workgroup places on safety-related policies, procedures and practices (Zhang et al., 2015). From an ecosystem's viewpoint, a safety management system consists of safety rules and resources at multi-level organizations as well as actors who are able to make sense, reinforce but also adapt the rules and resources (Dekker, 2005; Guo et al., 2017; Hollnagel, 2014). While written procedures and formal routines, hence the monitoring of rule compliance by quantitative measures can indicate the strength of a safety management system from a top-down perspective, rule users' attitudes and particularly the gap between perceptions and quantitative measures reflect the effectiveness of rule implementations in a bottom-up way. Furthermore, safety climate measures imply informal norms and routines that emerge and are internalized in day-to-day interactions (Mohamed, 2002; Saunders et al., 2017). It has been pointed out that safety climate can influence individuals' attitudes and behavior toward workplace safety (Chen et al., 2018; Fang et al., 2004), hence safety management performance (Pandit et al., 2019). In this vein, safety climate indicates the strength of social control at the group level and predicts the system's capability of sustaining safety performance especially during unexpected incidents (Weick and Sutcliffe, 2015).

Worker involvement monitors whether workers comply with policies and procedures and whether they actively participate in safety programs and improve safety performance (Hallowell and Gambatese, 2009; Liu et al., 2019; Mohamed, 2003). The competence indicator ensures that employees have the knowledge, skills and experience to safely carry out assigned jobs, which can be regularly improved through firm- and project-specific training (cf. Hinze et al. 2013). As mentioned, the competence is not only technical but includes the ability to recognize others' needs, challenging unsafe yet normative practices, acknowledging one's own incompetence and seeking advice.

4. Conclusion

Leading indicators are an emergent area in safety research in engineering management fields. The concepts of safety leading indicators have not been commonly agreed. Despite this, in construction, a wide range of leading indicators have been suggested. The present study conducted a systematic literature review and generated a shared understanding of the concept among various areas. It also identified 16 safety leading indicators in the construction industry and streamed the indicators into different levels of construction context. Moreover, this study systematically reviewed 52 studies on construction accident causes and linked leading indicators with accident attributors. By doing so, the 16 safety leading indicators were categorized as organizational, operational or cognitive, and behavioral indicators. The combined findings of the literature review led to the integrated framework, which has two dimensions. The first dimension, the level of measurement, indicates the safety performance of firms, projects or groups, and individuals. The second dimension identifies potential incidents and injuries caused by organizational, operational or cognitive, and behavioral issues. The two-dimensional framework can enable both researchers and practitioners to know what safety leading indicators should be measured and monitored at different entity levels (i.e., firms, projects, and groups and individuals). Furthermore, the framework helps identify and monitor processes and activities that are related to different types of accident attributors in construction. The two-dimensional integrated framework is a pioneering first step in construction safety research. Another contribution is the systematic approach used in this research. It conceptualized, identified and validated the indicators; linked the indicators with accident attributes; and developed the framework related to situations that might cause incidents or injuries in construction. Although this study focused on the construction industry, this approach can be generalized to safety leading indicator research in other engineering management areas.

4.1. Limitations and future directions

This systematic literature review was designed to generate a shared understanding of the concept of safety leading indicator and identify indicators, particularly in the construction industry. Also, the proposed theoretical framework requires validation in practice. The limitations and findings, however, shed light on some prospective directions for future research.

4.1.1. An ecosystem perspective

Construction projects are embedded in multilevel ecosystems consisting of individuals and groups at the micro-level, firms and projects at the meso-level and institutions at the macro-level (Pryke et al., 2018; Rowlinson and Jia, 2015). Yet, the review found that the majority of safety leading indicator research focused on micro and meso levels. Higher-level factors such as safety regulations (Forteza et al., 2020), the competitive tendering system and precarious employment arrangements in the construction industry received less attention. Future studies are needed to extend the scope of the integrated framework. The relationships between safety leading indicators across multiple levels require further investigation, which can be supported by an ecosystem perspective. For instance, a firm's investment in safety resources can influence the quality of safety design and planning, whereas the effectiveness of safety practices within projects can affect the continuity of the firm's investment in such practices. Across levels, safety management is influenced by micro-level indicators such as individuals' wellbeing and competence (Eteifa and El-Adaway, 2018; Lingard et al., 2017), as well as industrial norms and cultures at the macro-level (Al-Bayati et al., 2017; Harvey et al., 2018). Furthermore, the ecosystem perspective promotes a systemic view in investigating the relationship between leading and lagging indicators. Most studies have focused on quantifiable indicators and explored the cause-effect relationships between individual leading and lagging indicators. For example, an increase in the frequency of toolbox meetings leads to a decrease in accident rates. However, measuring fragmented safety practices and activities has led to inconsistent statistical findings (e.g., Lingard *et al.*, 2017). From an ecosystem perspective, individual leading indicators could have the causal power to positively influence the safety outcomes, hence reducing lagging indicators. Yet the actualization depends on the conditions of other indicators as well as the context, which calls for a systemic view in investigation (Guo et al., 2017).

4.1.2. A matter of time

Future studies on validating the framework need to consider the temporal effects on the implementation of leading indicators in practice. Extant studies on validating the predictability of leading indicators have usually taken a "snapshot" view of the effects of safety practices (e.g., Salas and Hallowell, 2016; Versteeg *et al.*, 2019). However, like Zeno's arrow, the status at one moment does not necessarily represent the whole picture. One-off studies report the causes and effects at the time of surveying. However, it requires time for leading indicators to take effect (see Lingard *et al.*, 2017). It has been recognized that some leading indicators tend to be more effective in terms of predicting future performance when they were implemented over time and measured regularly than implemented only once (Alruqi and Hallowell, 2019). Longitudinal approaches are needed to take a "longshot" view of safety management systems, including the effects of but also interactions between indicators.

4.1.3. A combination: quantitative and qualitative measurements

Figure 6 shows that current studies on safety leading indicators in construction have been dominated by quantitative approaches. Many researchers have stressed the quantifiable aspect of indicators and conceptualized safety leading indicators as quantitative measures such as frequency of managerial practices and activities (e.g., Rajendran, 2013; Hallowell, Bhandari and Alruqi, 2019). The value of quantitative-only approaches has been questioned in terms of their usefulness to reflect the effectiveness of the safety management systems (Hopkins and Hale, 2009; Oswald et al., 2018). The measurement of an indicator can be qualitative or quantitative (Guo and Yiu, 2016; Oswald, 2019; Reiman and Pietikäinen, 2012). Whereas quantitative indicators can measure management efforts to some extent, the number on its own can be interpreted in different ways. For example, an increase in near-miss reports might suggest that there are many hazards and incidents of non-compliance on site. Alternatively, it might indicate an open culture of reporting and effective communication systems. Moreover, frequent safety walks or training do not mean that these activities are effective, and might lead to tick-box behavior (Oswald et al., 2018). Future study on indicator measurements needs to combine qualitative information and quantitative measures so that measurements can explain how and why an indicator is at the level it is quantitatively assessed and drives proactive actions (Oswald, 2019).

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