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A comprehensive systematic review of safety leading indicators in construction

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ABSTRACT

Safety leading indicators have gained attention as an emerging field within the construction industry. However, there is a lack of consensus regarding the fundamental aspects of leading indicators, including their definitions, effectiveness, and implementation. This study aims to extract the evolved definition of safety leading indicators, identify trends, and shifts in their context, investigate the relationship between these indicators and safety management factors, and evaluate the effectiveness of their implementation in construction projects. A total of 728 journal articles were selected using preferred reporting items for systematic reviews and *meta*-analyses (PRISMA) guidelines. These articles were analyzed to present a comprehensive overview of the body of knowledge on safety leading indicators. The analysis focused on identifying key themes, trends, and insights related to these indicators in the construction industry. The research findings emphasized the continuous development and refinement of the definition of safety leading indicators over time. Moreover, the study identified four emerging trends, revealing the evolving nature of safety management practices. Furthermore, it underscored the challenge of establishing direct links between these indicators and other safety management elements due to the intricacy of factors contributing to safety performance. Lastly, the study assessed the effectiveness of implementing safety leading indicators in construction projects, providing valuable insights on their actual impact. This study contributes to the field by providing a comprehensive review of safety leading indicators in the construction industry. This knowledge adds value by offering guidance for future research endeavors related to safety leading indicators in the construction industry.

1. Introduction

The construction industry plays a significant role in the economic development of all countries (Mahmoud et al., 2020). While its impact on a country's progress is inevitable, it has always been admonished with high injury and fatality rates (Alexander et al., 2017; Moradi et al., 2022; Sunindijo and Zou, 2012). The construction industry ranks first in terms of preventable injury-related fatalities caused by incidents (OHSA, 2019). The high mortality rate can be attributed to the characteristic of the industry, with its dynamic and decentralized working conditions (Karakhan et al., 2023; Reis et al., 2020; Schwatka et al., 2016). Moreover, the construction sector is known for its labor-intensive nature and heavy reliance on equipment (Golovina et al., 2016). Therefore, it is crucial to implement safety management systems to mitigate hazards and incidents during construction projects. Safety-related indicators are a key component of these systems (Alruqi and Hallowell, 2019). Due to the dangers of the construction industry, safety indicators have been developed to measure safety performance and prevent injury (Versteeg et al., 2019). Safety indicators are typically categorized as "leading" or "lagging" (Hinze et al., 2013). The terms leading and lagging were originally borrowed from the field of economics, where leading indicators are used to predict changes in the economy before they occur (Oswald, 2020).

Measuring and evaluating safety performance on construction projects is challenging (Oswald et al., 2018). Traditionally, safety management systems have focused on reactive measures, such as lagging

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indicators, which respond to trends in injuries (Gondia et al., 2023; Neamat, 2019). However, proactive safety indicators, known as leading indicators, can be measured before incidents occur to trigger positive responses (Xu et al., 2021). Despite the potential benefits of leading indicators, there is limited research exploring their implementation alongside traditional reactive measures, and their inter-relationships have yet to be investigated and organized approach need to be codified (Hallowell et al., 2013; Pereira et al., 2018).

Originally the initial idea of safety leading indicators was introduced as a clear contrast to the concept of lagging indicators (Hinze et al., 2013). Leading indicators evaluate construction processes prior to the occurrence of safety hazards. These leading indicators have emerged as a more effective alternative to traditional safety metrics in the construction field (Akroush and El-Adaway, 2017). Leading indicators are meant to produce foresight, inspire individuals to work on safety and contribute to resolving safety concerns, and maintain high safety standards (Xu et al., 2021). This proactive and dynamic perspective towards safety management defines the core concept of leading indicators (Guo et al., 2017). However, the context of this specific subject still lacks clarity in terms of its definition, governance, and measurement (Neamat, 2019; Rajendran, 2013).

Although there have been rich findings in existing research on safety indicators in construction management, there is a limited number of studies that outline the relationship between the leading and lagging indicators and the factors that contribute to incidents and injuries (Neamat, 2019; Pereira et al., 2020; Xu et al., 2021). To bridge this gap, the present study conducts a systematic literature review on safety leading indicators in construction. Through reviewing peer-reviewed literature, this paper aims to: (1) extract the evolved definition of safety leading indicators over the years in construction research; (2) identify trends and shifts in the context of safety leading indicators in construction; (3) investigate the relationship between safety leading indicators and safety management factors; and (4) evaluate the effectiveness of implementing safety leading indicators in construction projects.

2. Methodology

A systematic literature review integrates findings about a given field of study, provides key insights, themes, and research gaps and elaborates potential steps that can been implemented in future studies (Zhou et al., 2015). This study has conducted a systematic literature review to explore safety leading indicators in construction research. The methodology employed in this review follows the approach used in previous systematic literature reviews (Golabchi et al., 2022; Newaz et al., 2021), which involves three stages: (1) implementing a systematic review protocol, (2) employing the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) approach for study screening (Moher et al., 2016), and (3) summarizing the extracted findings from the eligible studies.

2.1. The search process

The current review contains relevant research which have explored safety leading indicators in the construction industry. To gather relevant studies, generic databases such as Web of Science and Scopus were utilized. These databases offer comprehensive search options and access to a wide range of relevant work (Harzing and Alakangas, 2016). Keywords such as “safety”, “construction”, and “leading indicators” were looked up to highlight studies that have focused on leading indicators that are utilized for construction safety. The databases were searched using the defined keywords and the Boolean “AND” and “OR” operators. Since terms should be looked up in the fields of title, abstract, and keywords, the search string was formulated as follows: Title/Abstract/Keyword ((safety management OR safety*) AND (construction) AND (leading indicator OR performance indicator)). This ensured that the search results encompassed all terminologies associated with safety leading indicators in the construction context. The retrieved articles were managed using EndNote X20 to maintain and organize the full text for further analysis. This review concentrated on peer-reviewed safety studies to ensure the credibility and validity of the findings. The following is the eligibility requirements for choosing the representative articles: (1) English papers published by June 2023, (2) papers related to construction safety, and (3) papers published in peer-review journals. Exclusion criteria encompass: (1) duplicate records and (2) studies on technological aspects of safety, such as building information modelling, simulation, and technical site experiments.

2.2. Screening records to determine eligible studies

A total of 728 entries were retrieved from Web of Science and Scopus using the search string, and filtering the search results to include those that were published in peer-reviewed papers between 2010 and 2023 and in English. After eliminating 78 duplicate records, the remaining studies were imported into EndNote for initial screening based on their title, abstract, and keywords to ascertain their relevance to construction safety management. Following this screening phase, a subset of studies that met the inclusion requirements (650 articles) was manually reviewed in detail. As a result, 487 studies which were not aligned with the specific topic were excluded. For the purpose of selecting studies that particularly discuss construction safety leading indicators, the full text of 163 remaining articles were examined more carefully. Accordingly, a set of 112 studies were eliminated, including a total of 51 studies for content review and analysis (Fig. 1).

2.3. Data extraction and analysis

The extracted content from the eligible studies includes various elements such as title, authors, journal, year of publication and country, keywords, research goal, safety leading indicators, key findings, and research gaps. The retrieved data was compiled, sorted, and analysed using Excel. The steps for content analysis are as follows: (1) gathering the relevant content from the selected studies and organizing it in an Excel sheet, (2) investigating the primary findings of each study to identify trends in safety leading indicators and potential contrast between conclusions, and (3) discussing and categorizing similarities and differences in concepts and findings of selected studies. It is important to note that while a comprehensive list of leading indicators proposed by previous studies exists (Neamat, 2019; Xu et al., 2021), this review aims to focus on current research gaps and build upon past research instead of duplicating what has already been done. Therefore, a recent review paper (Xu et al., 2021) was used as a foundational reference for extracting a comprehensive list of leading indicators, forming the basis for the current analysis. Notably, this study extended beyond the indicators identified by Xu et al. (2021), ensuring a more exhaustive exploration of safety leading indicators in the construction safety literature. Going beyond mere identification, the current study aims to extract the evolving definition of safety leading indicators over time, identify trends, explore the relationship between leading indicators and safety performance, and assess their effectiveness in construction projects.

3. Findings

3.1. Descriptive analysis

The descriptive analysis serves as the foundational framework upon which subsequent key findings are constructed. Through a meticulous examination of publishing sources, trends, and keyword frequencies, this section not only reveals the present state of construction safety research but also establishes the groundwork for a profound understanding of emerging themes and critical patterns. This contextual

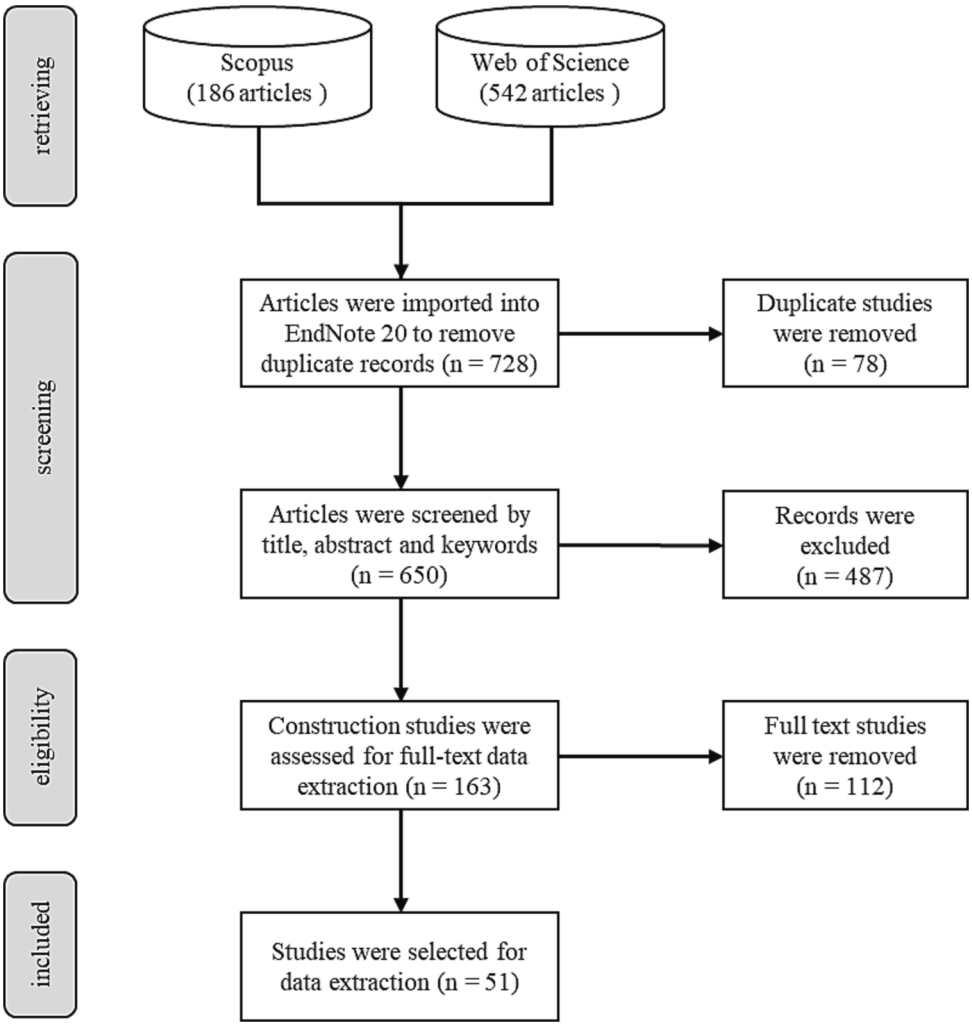


Fig. 1. The process based on PRISMA protocol.

comprehension proves fundamental in appreciating the temporal evolution of safety leading indicators in construction.

Examining the publishing source reveals that Safety Science has made the most significant contributions to the topic. A notable proportion of the selected papers, totaling 7 articles, finds its place in this journal. Following closely behind is the Journal of Construction Engineering and Management, contributing 6 articles. Over the years, there has been a noticeable increase in the number of publications, reaching a peak in 2020. In terms of research on construction safety management, USA has emerged as the leading country, followed by Australia. The observed increase in articles on safety leading indicators aligns with the broader rise in research activities across various domains, suggesting that this trend may be influenced by the overall expansion of research endeavors over the years.

The identified studies brought to light a set of keywords that featured prominently in their content. Noteworthy among these were "leading indicator," constituting 47 % of the studies, followed by "construction safety" at 31.4 %, and "safety" and "safety performance measurement" at 17.6 %. Additionally, the term "construction" had a prevalence of 13.7 % (Fig. 2). These insightful analyses, drawn from the descriptive assessment, sets the stage for a more nuanced exploration of key themes and trends in subsequent sections.

The data obtained in this study showcases the increasing attention given to leading and lagging indicators of construction safety performance, ultimately reflecting the safety performance of the construction projects (Shaikh et al., 2020). Additionally, the data supports the assertion that safety leading indicators gained significant attention among researchers after 2013. Between 2010 and 2013, only four publications were found on safety leading indicators in the construction sector, indicating a relatively early stage of development and a lower emphasis on proactive safety management. However, from 2013 to 2023, there was a notable increase, with 47 articles published on construction safety leading indicators. This increase underscores a growing trend and a heightened acknowledgment of the importance of proactive safety measurements, aligning with the overall escalation in research activity during this timeframe. It is essential to note that this observed increase aligns with a broader trend in research output expansion, reflecting a surge in scholarly endeavors over the years.

The existing review identified four key research topics related to safety leading indicators in construction studies. The first research topic aims to identify and understand leading indicators in construction safety. Studies in this area employ various approaches, methodologies, or techniques to identify and define these leading indicators. These approaches include statistical analysis of historical data and qualitative assessments through interviews or surveys. The second research topic focuses on exploring the trends in safety indicators within the construction industry. This involves analyzing existing data and research to identify patterns and changes in the use of safety indicators over time. The third research topic investigates the relationship between safety leading indicators and safety performance in construction projects. Studies in this area may involve analyzing data from construction projects, evaluating the correlation between leading indicators and safety

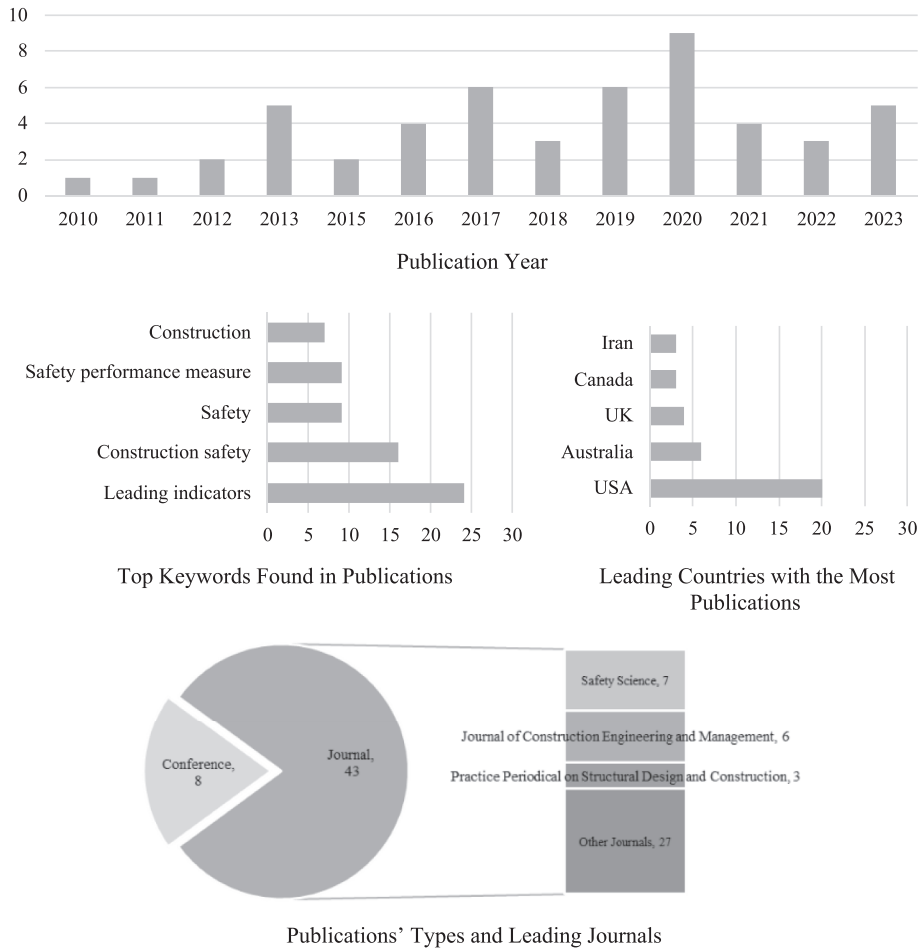


Fig. 2. Descriptive analysis of the included studies.

performance, and conducting statistical analyses to establish the strength of the relationship. The fourth research topic focuses on evaluating the effectiveness of safety leading indicators in construction projects. This involves assessing the practicality, reliability, and applicability of different leading indicators in real-world construction projects. Researchers may examine case studies, conduct field experiments, or analyze data from ongoing projects to evaluate the impact of leading indicators on safety performance. These four key research topics contribute to the advancement of knowledge in construction safety by exploring different aspects of safety leading indicators. They help enhance the understanding of leading indicators, track trends in their usage, establish their relationship with safety performance, and evaluate their effectiveness in practical construction settings. Each of these topics will be further explored in the subsequent sections.

3.2. *Understanding safety leading indicators*

The definition of safety leading indicators has evolved over the years, reflecting changing attitudes and approaches towards safety in the construction industry. This section aims to discuss the definition of safety leading indicators in the construction and its changes based on published papers. There have been ongoing discussions on the definition of safety leading and lagging indicators (Hinze et al., 2013; Versteeg et al., 2019). Particularly in recent years, an increasing number of studies have debated the definitions and measurement of safety indicators in the construction industry (Lingard et al., 2017; Wehle and Issa, 2016). The diversity in definitions can be attributed to several reasons: (1) The initial concept of indicators was borrowed from the field of economics (Oswald, 2020) and may not have been fully applicable to the construction industry. (2) Although there is a general agreement on the importance of leading indicators for safety performance, a lack of standardization or consensus among researchers and practitioners has resulted in the absence of a universally accepted definition or set of indicators (Rajendran, 2013; Xu et al., 2021). (3) Construction practices, processes, and technologies are constantly evolving, introducing new safety risks and challenges that may require different or additional safety indicators (Golabchi and Hammad, 2023). (4) Cultural and organizational differences among companies and projects can influence the selection and interpretation of safety indicators, as priorities may vary (Akroush and El-Adaway, 2018).

To better understand how different studies define safety leading indicators and how these definitions have changed over time, an analysis was conducted by investigating various resources. The resulting set of extracted definitions of leading indicators is summarized in Fig. 3. Safety indicators have been recognized as "measures of safety management systems" (Xu et al., 2021), with leading indicators being proactive measures that help prevent incidents and lagging indicators being reactive measures that respond to incidents after they have occurred. However, these definitions have evolved over the years and may differ across different fields of study (Oswald, 2020; Xu et al., 2021). The changes in the definition of leading indicators over time reflect a deeper understanding of the specific factors and practices that influence safety performance in construction.

Leading indicators in construction were initially associated with general safety activities such as safety training (Abas et al., 2021; Versteeg et al., 2019) and safety meetings (Alruqi and Hallowell, 2019). While these indicators are still considered important, there has been a shift towards identifying more specific and tailored leading indicators



Fig. 3. The evolution of the safety leading indicators definition in years.

that are relevant to different construction activities, project types, and work environments (Hollaway and Johnson, 2014; Shaikh et al., 2020). For example, leading indicators could include the frequency and quality of safety inspections (Rajendran, 2013), the implementation of safety protocols and procedures (Akroush and El-Adaway, 2017), the level of worker engagement in safety activities (Bhagwat et al., 2022; Karakhan et al., 2023), the presence of effective communication among workers (Liu et al., 2019), and the utilization of hazard identification and risk assessment tools (Oguz Erkal et al., 2021). In fact, there is a growing recognition that leading indicators should be measurable, actionable, and context-specific to be effective in predicting and preventing safety incidents (Oswald et al., 2018; Xu et al., 2021).

While the core concept of being proactive and predictive remains consistent, the emphasis and scope differ among studies. Some researchers focus on quantifiable measurements and observable behaviors (Sinelnikov et al., 2015), while others highlight the behavioral aspects (Lefsrud et al., 2021; Oswald, 2020), emphasizing the importance of individual and collective actions in creating a safe work environment (Xu et al., 2021). Furthermore, some definitions encompass a broader range of factors, such as organizational processes (Janackovic et al., 2013) and safety culture (Biggs et al., 2010; Loosemore et al., 2019), while others emphasize the real-time monitoring and predictive nature of leading indicators (Teizer, 2016; Versteeg et al., 2019). In line with the diverse perspectives on leading indicators, researchers have also explored various classification frameworks that shed light on their distinct characteristics and measurement approaches.

For instance, Hinze et al. (2013) classify leading indicators into passive and active measures. Passive measures can predict trends over an extended period, while active measures initiate corrective actions within a shorter timeframe (Alruqi and Hallowell, 2019; Falahati et al., 2020). Wehle and Issa (2016) have put forth a recommendation to replace the terms passive and active with consistent and dynamic, respectively, in order to accurately characterize these indicators in practical applications. Additionally, Lingard et al. (2017) suggest that the conventional approach of categorizing indicators as leading or lagging may not fully capture their true nature. They propose an alternative approach of labeling indicators as positive and negative indicators, rather than strictly considering them as leading or lagging. Positive indicators signify positive safety performance or improvement, while negative indicators indicate safety concerns or deteriorating performance. This shift in terminology focuses on the direction of change and allows for a more accurate representation of the indicators' impact on safety outcomes.

These alternative terminologies and categorizations reflect the ongoing discussions and refinements in the field of safety indicators. It is important to note that these definitions are not mutually exclusive; rather, they collectively embody a shared common-sense understanding characterized by three fundamental components: proactivity, predictiveness, and measurability. Researchers may adapt and refine their definitions and classifications in response to evolving knowledge and the changing demands of construction safety. These variations reflect the multidimensional nature of leading indicators and the different perspectives and research emphases within the construction safety field (Sattari et al., 2022; Singh et al., 2022).

3.2.1. Identification of safety leading indicators

The current state of the leading indicators in the construction industry is that there is still ongoing research and discussion on their definition, implementation, and effectiveness (Xu et al., 2021). The importance of leading indicators in proactively managing safety in construction is widely acknowledged by organizations and researchers (Hallowell et al., 2013; Marks et al., 2013; Rajendran, 2013). Many studies have been conducted to explore different approaches, methodologies, and data sources to determine leading indicators for proactive safety management (Table 1). However, a consensus has not been reached on the most effective indicators or their practical application (Neamat, 2019; Rajendran, 2013; Versteeg et al., 2019). While some organizations have developed standardized sets of leading indicators, their adoption and effectiveness in improving safety performance vary among companies (Akroush and El-Adaway, 2018; Hinze et al., 2013).

Elsebaei et al. (2020) discussed different elements of safety management systems including safety indicators. They explored contractors' perception on safety through questionnaire and the result emphasized the importance of safety measurement methods and their role in accurate performance assessment. In another study, Ng et al. (2012) explored leading indicators, their use, and the challenges of implementation in construction companies from a lean perspective. They indicated that a clear understanding and tracking of leading indicators would enable construction companies to achieve safer and more efficient task execution. Interestingly, Phinias (2023) conducted a comprehensive review paper aiming to examine the advantages and challenges associated with the implementation of leading indicators. The study identified eight benefits that arise from the use of leading indicators, including the ability to identify construction incidents, facilitate measurement and monitoring, prevent incidents, establish an early warning system, enhance compliance with health and safety legislations, ensure anonymity and confidentiality, enable predictions, and enable the implementation of control measures. Additionally, the study highlighted eight challenges, which encompassed aspects such as training and communication, leadership and commitment, time and cost considerations, effectiveness and uncertainty, varying definitions, the prevalence of quantitative indicators, convenience, and worker involvement and

Table 1
Summary of construction safety leading indicators.

Leading indicator	Description	References
Organizational indicators		
Management commitment to safety/Safety policy	Organizational leaders commitment to safety aspects of construction projects/Outlining the organization's overall approach, principles, and objectives regarding safety management	Agumba and Haupt, 2012; Akroush and El-Adaway, 2017; Falahati et al., 2017; Guo et al., 2017; Hallowell et al., 2013; Janackovic et al., 2013; Karakhan et al., 2023; Lingard et al., 2011; Liu et al., 2019; Mahmoud et al., 2020; Oguz Erkal et al., 2021; Schwatka et al., 2016; Singh et al., 2022; Sunindijo and Zou, 2012; Xu et al., 2021
Stakeholders engagement (client, owner, designer, etc.)	Client, owner, designer, principal contractor, and subcontractor involvement in safety throughout a construction project	Alruqi and Hallowell, 2019; Hallowell et al., 2013; Hinze et al., 2013; Mahmoud et al., 2020; Rajendran, 2013; Salas and Hallowell, 2016; Xu et al., 2021
Subcontractor selection/Site safety policy for subcontractor	Assessment of the safety performance and qualifications of subcontractors prior to a project through evaluating their safety records, safety plans, training, certifications, and other safety-related documentation/Evaluating the extent to which subcontractors adhere to safety expectations, regulations, and site-specific safety policies	Agumba and Haupt, 2012; Alruqi and Hallowell, 2019; Hallowell et al., 2013; Liu et al., 2019; Mahmoud et al., 2020; Oguz Erkal et al., 2021; Salas and Hallowell, 2016
Operational indicators		
Safety Inspection/ Jobsite audits	Identifying hazards or safety violations through safety inspections or observations by collecting information on the efficiency, effectiveness, and reliability of the safety management system	Agumba and Haupt, 2012; Alruqi and Hallowell, 2019; Falahati et al., 2017; Hinze et al., 2013; Lingard et al., 2017; Liu et al., 2019; Mahmoud et al., 2020; Xu et al., 2021
Safety orientation and training	Providing training and orientation of jobsite hazards to improve skills, knowledge, attitudes and experiences of supervisors and workers	Agumba and Haupt, 2012; Akroush and El-Adaway, 2017; Alruqi and Hallowell, 2019; Falahati et al., 2017; Hinze et al., 2013; Janackovic et al., 2013; Lingard et al., 2017; Liu et al., 2019; Mahmoud et al., 2020; Niu et al., 2017; Oguz Erkal et al., 2021; Singh et al., 2022; Xu et al., 2021
Safety review in design phase	Considering incidents prevention during construction as one of the objectives of design	Alruqi and Hallowell, 2019; Mahmoud et al., 2020
Hazard identification/ Safety risk assessment	Identifying and controlling hazards and risks in jobsites	Alruqi and Hallowell, 2019; Falahati et al., 2017; Hinze et al., 2013; Oguz Erkal et al., 2021; Salas and Hallowell, 2016; Xu et al., 2021
Incentives (recognition and reward)	The safety promotions and motivations for workers who comply with safety	Alruqi and Hallowell, 2019; Guo et al., 2017; Hallowell et al., 2013;

(*continued on next page*)

Table 1 (*continued*)

Leading indicator	Description	References
	rules and actively participate in safety improvement activities	Karakhan et al., 2023; Mahmoud et al., 2020; Oguz Erkal et al., 2021; Xu et al., 2021
Communication and consultation	Promoting a culture of open communication, knowledge sharing, active involvement, and shared responsibility for safety	Agumba and Haupt, 2012; Falahati et al., 2017; Lingard et al., 2017; Mahmoud et al., 2020; Versteeg et al., 2019; Xu et al., 2021
Safety walk throughs	Assessments conducted by individuals or teams to ensure and evaluate the safety conditions and practices	Hallowell et al., 2013; Lingard et al., 2011; Salas and Hallowell, 2016
Working at height/Fall protection	The implementation of measures and equipment to prevent falls or mitigate the impact in case of a fall	Akroush and El-Adaway, 2017; Manjourides and Dennerlein, 2019; Ng et al., 2010
Safety rules and procedures	Outlining the necessary precautions, actions, and behaviors to prevent incidents, injuries, and risks	Alruqi and Hallowell, 2019; Janackovic et al., 2013; Mahmoud et al., 2020; Schwatka et al., 2016
Substance abuse and drug tests	Conducting random drug and alcohol tests to prevent substance abuse among workers	Hallowell et al., 2013; Lingard et al., 2017; Manjourides and Dennerlein, 2019
Housekeeping program	The practice of maintaining cleanliness, order, and organization in the working spaces free from hazards	Akroush and El-Adaway, 2017; Alruqi and Hallowell, 2019; Hallowell et al., 2013; Niu et al., 2017
Personal Protective Equipment (PPE)	The provision of the required PPE for all workers	Alruqi and Hallowell, 2019; Guo and Yiu, 2016; Mahmoud et al., 2020; Manjourides and Dennerlein, 2019
Safety resources	The efforts of the safety committee, which may include supervisory personnel, owner safety representatives, and project managers, in providing required safety resources	Agumba and Haupt, 2012; Hallowell et al., 2013; Karakhan et al., 2023; Schwatka et al., 2016; Singh et al., 2022
Near miss reporting	Reporting and documenting incidents or events that had the potential to cause harm, injury, or damage but did not result in any immediate consequences	Alexander et al., 2017; Alruqi and Hallowell, 2019; Hallowell et al., 2013; Hinze et al., 2013; Lingard et al., 2011; Liu et al., 2019; Mahmoud et al., 2020; Salas and Hallowell, 2016; Schwatka et al., 2016; Versteeg et al., 2019
Toolbox meetings	Gathering of workers and supervisors (typically short and informal) to discuss specific safety topics and address potential hazards before starting work	Karakhan et al., 2023; Salas and Hallowell, 2016; Versteeg et al., 2019
Pre task safety plans	Safety planning or meeting conducted by both supervisors and workers as daily tasks to ensure that day-to-day activities are performed safely	Agumba and Haupt, 2012; Alruqi and Hallowell, 2019; Hallowell et al., 2013; Lingard et al., 2017; Versteeg et al., 2019
Safety record	Reporting and maintaining incident records and safety performance records	Alruqi and Hallowell, 2019; Falahati et al., 2017
Safety corrections	Actions taken to address identified safety hazards, risks, or deficiencies in order to ensure a safe working environment	Falahati et al., 2017; Lingard et al., 2017; Oguz Erkal et al., 2021; Salas and Hallowell, 2016

Table 1 (*continued*)

Leading indicator	Description	References
Cognitive and behavioral indicators		
Safety climate	The perception of workers regarding the priority that an organization assign to safety-related policies, procedures, and practices	Alruqi and Hallowell, 2019; Hinze et al., 2013; Liu et al., 2019; Niu et al., 2017; Pandit et al., 2019; Poh et al., 2018; Schwatka et al., 2016; Sunindijo and Zou, 2012; Versteeg et al., 2019; Xu et al., 2021
Worker involvement	The degree of worker participation in establishing, implementing, evaluating, and enhancing safety practices	Agumba and Haupt, 2012; Hallowell et al., 2013; Liu et al., 2019; Niu et al., 2017; Schwatka et al., 2016; Xu et al., 2021
Worker safe behavior observation (WSBO)	Observing and assessing workers' behaviors related to safety on construction sites	Liu et al., 2019; Mahmoud et al., 2020; Niu et al., 2017; Schwatka et al., 2016; Singh et al., 2022

participation.

Hallowell et al. (2013) identified over 50 leading indicators through case studies, content analysis and discussions with safety experts. Among these, 13 leading indicators were selected as top priority. They suggested that using these leading indicators as proactive safety metrics would significantly enhance safety performance in construction projects. Later, Salas and Hallowell (2016) aimed to identify and validate leading indicators and their predictive capabilities. They tested the hypothesis that variability in safety leading indicators predicts variability in lagging indicators, using regression models. The results confirmed a strong correlation between predicted and actual values, supporting the predictive validity of the identified leading indicators. Accordingly, they suggested that their developed models can be used as new leading indicators providing warning signs in safety performance. In a recent study, Xu et al. (2021) found sixteen leading indicators through a systematic review and streamed the indicators into different levels of construction context. They also reviewed studies on construction incident causes and linked leading indicators with incident attributors. They suggested taking an ecosystem perspective and combining qualitative and quantitative measures for implementing safety leading indicators in the construction industry.

Various studies have utilized focus groups, expert panels, and interviews to identify leading indicators that affect safety performance. For instance, Agumba and Haupt (2012) conducted four rounds of Delphi to identify and validate a set of leading indicators suitable for small and medium construction enterprises (SMEs). They identified 32 leading indicators with major impacts on safety performance at the project level. Oguz Erkal et al. (2021) identified a list of potential predictors of injuries in construction and prioritized them though an expert panel to determine the predictors with the greatest practical potential for injury prediction. They aimed to establish a unified model including leading indicators, precursor analysis and risk assessment, addressing the limitation of previous research that focused on singular safety prediction approaches. Mahmoud et al. (2020) identified 137 Key Performance Indicators (KPIs) and rank their importance through interviews and focus groups with safety experts. The most crucial KPIs identified included communicating safety requirements to designers, incorporating safety performance in contractor selection criteria, accessibility of relevant insurance policies, and issuance of motivational directives by top management. Niu et al. (2017) explored indicators affecting safety climate through focus groups, identifying 25 indicators which influence safety performance while can address the dynamic environment of construction projects. In a recent study, Karakhan et al. (2023) focused

on identifying leading indicators that reflect the health and well-being of the construction workers. To gather insights, the researchers conducted a survey questionnaire targeting industry experts. Their findings revealed six significant leading indicators that contribute to the health and well-being of construction workers. These indicators include: (1) toolbox talks, (2) company social events, (3) safety, health care, and wellness programs, (4) employee assistance programs, (5) employee benefits and perks, and (6) annual medical checkups.

Some studies employed fuzzy methods to investigate safety indicators. Janackovic et al. (2013) identified and ranked safety indicators based on expert evaluations using fuzzy Analytic Hierarchy Process (AHP). They found that organizational factors have a significant impact on the quality of safety management systems. Falahati et al. (2017) determined leading indicators based on OHS management system along with the main incidents and risks of the projects. Bayesian network and AHP were used to identify 29 leading indicators for the management system and 33 leading indicators for operations. Later, Falahati et al. (2020) indicated that the leading indicators extracted from the components of the OHS management system deployed in an organization are often passive and cannot show the changes in the safety status of a workplace in a short period. In a recent study, Singh et al. (2022) proposed a framework to measure safety performance, identifying safety KPIs through literature review and expert opinions. These KPIs were then ranked using the fuzzy TOPSIS method, highlighting their relative importance. The results emphasized the importance of management's role in informing workers about safety rules and ensuring compliance with safety measures. The study highlighted several specific KPIs that emerged as highly important in driving safety performance. These included the implementation of comprehensive safety training programs, monitoring and managing absenteeism rates to address potential safety risks, fostering a culture of safe behavior, implementing well-documented safety guidelines, and conducting periodic safety drills.

Moreover, several studies aimed to develop new leading indicators and novel methods for safety evaluation. For example, Leveson (2015) described a new approach to identify system-specific leading indicators based on incident causation and processes incorporating system theory rather than traditional reliability theory. Orogun and Issa (2018) developed a set of metrics for safety performance. They proposed 35 metrics that were validated through expert judgment via questionnaire surveys. Lingard et al. (2011) developed leading indicators and measurement tools to assess safety performance in construction projects. They tested two measurement tools: a monthly weighted safety index and a quarterly safety climate survey. They found that combining measurement techniques with traditional lagging indicators provided more comprehensive data for early detection of safety hazards. Guo and Yiu (2016) proposed a conceptual framework for developing leading indicators by clarifying the definition, purpose, and attributes. Their approach emphasized the informative and decision-aiding functions of leading indicators. They suggest that leading indicators could be able to provide information about safety state and help decision makers take remedial actions. Accordingly, Guo et al. (2017) developed a set of leading indicators to assess safety performance at the project level based on their framework.

Bhagwat et al. (2022) introduced a new leading indicator-based safety inspection method. They highlighted the improvement of safety performance by reducing unsafe behavior and conditions. Al-Kasasbeh et al. (2021) proposed a new safety assessment methodology based on leading and lagging indicators, consisting of 20 criteria. They suggested that the proposed method could replace the current approaches. Hallowell et al. (2020) noted that preventive approaches are often modeled independently from one another and proposed a unified model that incorporates risk assessment, precursor analysis, leading indicators, and safety climate assessment. They believed that such a model could make robust predictions by considering the interconnections between work attributes, human resources, and management strategies.

3.3. Trends in safety indicators in construction

Similar to the definition changes, there have been some shifts and trends regarding the safety indicators in construction. Safety research topics in construction vary over time to focus on the most recent safety challenges and concerns in the construction industry (Zhou et al., 2015). During this review some research trends on safety leading indicators were identified. These research trends are discussed as follows:

3.3.1. Transition from lagging to leading indicators

Traditionally, safety performance in construction was measured using lagging indicators, which offered a retrospective view of safety performance and were easy to measure and obtain (Hallowell et al., 2013). These indicators gained considerable attention as they served as metrics for assessing the safety performance of construction projects (Hinze et al., 2013). However, in recent years there has been a shift toward leading indicators despite the conveniences in tracking lagging indicators. Leading indicators were developed to enhance preventive safety measures and proactively avoid injuries (Hallowell et al., 2020). This shift is further supported by the growing interest in proactive safety management approaches, such as behavior-based safety and safety climate, which emphasize hazard identification and mitigation before incidents occur (Neamat, 2019).

Instead of solely focusing on indicators that reflect safety outcomes like injuries, researchers and practitioners have redirected their attention to indicators that contribute to injury prevention, such as site inspections (Biggs et al., 2010; Janackovic et al., 2013; Phinias, 2023; Rajendran, 2013). The idea behind this shift is that leading indicators facilitate proactive investigation, as opposed to the reactive nature of lagging indicators. Recent research suggests that leading indications are more influential than lagging ones (Salas and Hallowell, 2016; Versteeg et al., 2019). According to studies, concentrating on leading indicators provides more efficient insight into safety performance since they are proactive measures for measuring project safety (Guo and Yiu, 2016; Wehle and Issa, 2016).

3.3.2. Integration of safety with other aspects of construction

Safety is no longer considered a separate entity, but an integral part of construction (Sattari et al., 2022). There is a growing trend towards integrating safety with other aspects of construction, including quality management (Singh et al., 2022) and project management (Pereira et al., 2018). This holistic approach ensures that safety considerations are embedded throughout the entire project life cycle as safety is among the most important aspects that highly contribute to the project success (Moradi et al., 2022; Golabchi et al., 2018a,b).

Although notable work has been undertaken on the indicators affecting the safety performance of construction projects and involved individuals, recent research argues for a more systematic approach by exploring the link between such indicators in order to produce realistic models (Hallowell et al., 2020). Recent studies have investigated the role of stakeholders, such as contractors (Votano and Sunindijo, 2014) and supervisors (Martin and Lewis, 2014) in establishing safety practices and promoting a learning culture in safety behavior. Additionally, significant emphasis has been placed on leading indicators like worksite characteristics, communications, and collaborations, which play a crucial role in shaping safety performance outcomes (Alruqi and Hallowell, 2019; Lingard et al., 2019; Newaz et al., 2021). Bhagwat et al. (2022) asserted that adopting a leading indicator-based approach positively impacts the safety culture of construction projects, leading to increased worker involvement and improved communication among stakeholders, thereby establishing a bidirectional correlation between safety and other aspects of construction projects. Forteza et al. (2020) conducted a critical review of proactive safety approaches, including precursors and leading indicators, suggesting the need for the development and validation of new integrated proactive measures.

3.3.3. Emphasis on behavior-based safety

Within the realm of safety leading indicators, there has been a shift towards behavior-based indicators (Neamat, 2019). Behavior-based safety approach focuses on the behaviors and actions of workers and supervisors, going beyond the physical conditions of the worksite (Chen et al., 2021). This approach encourages workers to take responsibility for their own safety and that of their colleagues (Shi, 2020). It involves identifying and addressing unsafe behaviors while encouraging safe behaviors through positive reinforcement. Oswald (2020) highlighted focusing on quantity while overlooking qualitative indicators can lead to a missed opportunity to gain valuable insights into safety conditions.

Akroush and El-Adaway (2018) found that among the indicators studied, those related to simple safety tasks and routine practices such as housekeeping, use of Personal Protective Equipment (PPE), and substance abuse programs were most popular. Conversely, more complex indicators related to strategic and policy-making programs, such as contractual safety obligations and the evaluation of safety meetings and reporting systems, were less popular. However, recent studies show that despite the current approach which is relying more on the physical aspects, focusing on behavior and culture can more efficiently enhance the safety performance in construction projects (Lefsrud et al., 2021; Neamat, 2019). For instance, Versteeg et al. (2019) indicated that prioritizing safety training and safety culture among workers has a greater impact than conducting numerous site investigations during projects. Proper safety training for workers (Golabchi et al., 2018a,b) and equipping them with advanced safety equipment (Dale et al., 2020) are perceived crucial for ensuring a safe workplace environment. Controlling absenteeism rates reduces the burden of extra work on employees, thereby encouraging safe behavior (Singh et al., 2022). Rajendran (2013) found that pre-task plan review and worker safe behavior observation can serve as insightful leading indicators for companies as part of their safety program. The research conducted by Ghosh et al. (2023) centered around measuring workers' perceptions of safety in construction projects using three leading indicators: safety climate, safety control, and risk perception. While previous studies have examined the connection between safety performance and these indicators separately, this study aimed to explore the interrelationships among them. Through correlation analysis, the study revealed a positive correlation between workers' perceptions of safety control and safety climate, indicating a mutually reinforcing relationship between the two indicators.

3.3.4. Development of safety culture and safety climate in construction organizations

In recent years, "safety culture" and "safety climate" have been embraced as significant leading indicators in construction safety research (Alghamdi et al., 2019; Chen et al., 2021). Many studies have focused extensively on understanding safety culture and safety climate, often using these concepts interchangeably (Berry et al., 2020). In a comprehensive review conducted by Shaikh et al. (2020), an analysis of construction safety indicators spanning from 2000 to 2019 was performed. The result of their study revealed that safety climate is considered as one of the most frequently reported indicators, highlighting its significant importance in the construction industry. Moreover, researchers have examined how safety culture is established in construction firms (Adzivor et al., 2022; Lefsrud et al., 2021; Loosemore et al., 2019), highlighting the variability and changes in safety culture at different levels within the construction project environment (Cheung et al., 2022).

Recent studies have stressed the need for a more comprehensive investigation of the factors influencing safety culture (Pandit et al., 2019; Zahoor et al., 2017). This understanding is essential for designing effective strategies tailored to various types of construction companies, considering factors such as size, scope, complexity, and market position (Chen et al., 2018). Safety climate, particularly at the organizational level, has also gained attention as an aggregate of psychological climates, reflecting individuals' perceptions of safety (Berberoglu, 2018; Ghosh et al., 2023; Lefsrud et al., 2021).

Biggs et al. (2010) highlighted the lack of a reliable standard leading indicator for safety culture. They proposed the need for accurate measures of safety culture to assess safety effectively as there is no standard safety effectiveness indicator accepted by the construction industry. However, quantitative surveys employed to measure safety culture and climate have limitations and may not yield reliable results. Combining quantitative and qualitative approaches is necessary to provide clear utility for safety indicators (Xu et al., 2021). On construction sites, significant attention has been placed on skills essential for crews to detect and respond proactively to safety hazards. Particularly, Sunindijo and Zou (2012) emphasize that SMEs, such as subcontractors, are extensively involved in construction operations, necessitating an increase in safety knowledge and skills among their workforces. In order to successfully contribute to improving safety outcomes, stakeholders and workers should be involved not only in safety trainings but also in operational safety initiatives (Ghosh et al., 2023; Martin and Lewis, 2014).

In conclusion, the evolving trends in safety indicators in construction research (summarised in Table 2) reflect changing attitudes and approaches towards safety. The focus is shifting towards preventing incidents and injuries by utilizing leading indicators and implementing safety culture. Safety is now integrated with oher aspects of construction, fostering a more holistic approach to safety. Furthermore, behavior-based safety is increasingly being recognized as an essential aspect of construction safety and organizations are providing resources and support for workers to manage safety conditions. These shifts represent a positive transformation towards a proactive and comprehensive approach to safety in the construction industry.

3.4. Relationship between safety leading indicators and safety performance

The present study also investigated how safety data including leading and lagging indicators are correlated with each other and how they affect safety performance in construction projects. Despite numerous studies investigating leading and lagging indicators in the construction industry, limited research has investigated their relationship (Neamat, 2019; Pereira et al., 2017). In a recent study, Oguz Erkal et al. (2023) highlighted the common practice of studying safety indicators in isolation, without thoroughly discussing potential weaknesses. To address this gap, the researchers evaluated existing safety indicators against a predefined set of criteria and investigated how multiple indicators could be used collectively to maximize their strengths. The findings of the study indicated that no single safety indicator excelled in all evaluation criteria. However, it was demonstrated that combining multiple indicators can lead to a more comprehensive evaluation, thereby enhancing the overall assessment of safety performance.

Several studies have explored the relationship between various data sources and safety data. For instance, Mohamed et al. (2019) investigated the association between project performance data and safety. They utilized project-related data along with safety data to more accurately assess proactive safety performance. Their findings indicated that project performance data were linked to safety performance, demonstrating that project data in addition to traditional leading indicators, can contribute to building a safety management system. In another study, Dale et al. (2020) evaluated the relationship between safety management programs, safety climate, and safety behavior. Interestingly, they observed a weak relationship between safety management programs scales and safety climate scores. Contractor size did not significantly affect reported safety climate and safety behavior, but there were notable differences in the quality and content of safety management programs. The authors concluded that it is crucial to understand how best to measure safety performance in construction companies with different sizes.

Table 2
Summary of identified research trends.

Research Trend	Key Characteristics	Primary Findings	Examples of Literature
Transition from Lagging to Leading Indicators	- Shift from retrospective lagging indicators to proactive leading indicators	- Emphasis on indicators contributing to injury prevention, such as site inspections - Growing interest in proactive safety management approaches	Neamat (2019); Versteeg et al. (2019); Salas and Hallowell (2016); Hallowell et al. (2013); Hinze et al. (2013)
Integration of Safety with Other Aspects of Construction	- Safety considered integral to construction - Integration with quality management and project management	- Systematic exploration of the link between safety indicators, stakeholders' roles, and worksite characteristics - Emphasis on safety's contribution to overall project success	Bhagwat et al. (2022); Newaz et al. (2021); Forteza et al. (2020); Lingard et al. (2019); Pereira et al. (2018)
Emphasis on Behavior-Based Safety	- Increasing focus on indicators centered around behavior of workers - Encouraging workers' responsibility for their safety and that of colleagues	- Recognition of the effectiveness of prioritizing safety training, culture, and behavior observation over traditional site investigations - Specific studies highlighting the impact of behavior-based indicators on safety outcomes	Ghosh et al. (2023); Lefsrud et al. (2021); Oswald (2020); Shi (2020); Versteeg et al. (2019)
Development of Safety Culture and Safety Climate in Construction Organizations	- Embrace of safety culture and safety climate as significant leading indicators	- Comprehensive investigation of factors influencing safety culture - Lack of a standardized leading indicator for safety culture - Combined quantitative and qualitative approaches advocated for clear utilization - Involvement of stakeholders and workers in both safety training and operational safety initiatives	Cheung et al. (2022); Adzivor et al. (2022); Shaikh et al. (2020); Pandit et al. (2019); Zahoor et al. (2017)

In the past, leading indicators were classified based on their reflection of proactive or preventive safety actions, while lagging indicators were associated with metrics indicating harm or injury (Versteeg et al., 2019). These classifications were primarily based on the descriptive nature of the indicators, without necessarily establishing a causal relationship (Kjellén, 2009). However, there is a growing consensus among scholars to label leading and lagging indicators based on findings of causality rather than mere description (Versteeg et al., 2019). It is important for leading indicators to be developed in accordance with incident causation frameworks and should present measurable procedures (Xu et al., 2021). This approach ensures that the indicators are aligned with the underlying causes of incidents and can provide meaningful insights into safety performance and potential risks (Pereira et al., 2020).

In a review paper, Neamat (2019) investigated common indicators and outlined gaps in indicators research. They also explored the relationship between leading and lagging indicators through previous studies. The review analyzed eighteen papers from 2010 to 2019 to identify common leading and lagging indicators and understand their correlations. The results outlined that the leading indicators can be used to discriminate variations in project safety performance. However, the relationship between indicators is challenging, and there is a limited number of studies exploring the correlation between safety indicators. Among these studies, Manjourides and Dennerlein (2019) attempted to investigate the connection between leading and lagging indicators. They found that higher safety management system scores were associated with lower injury rates. Interestingly, safety programs did not consistently correlate with injury outcomes. The result also indicated that safety measurements related to drug and alcohol programs were linked to lower injury outcomes, while indicators related to return to work showed no consistent association with injury.

Lingard et al. (2017) examined the relationship between safety indicators over time, revealing time-dependent relationships and exploring causal links between them. They discovered complex interactions among indicators over time. The expected leading indicators exhibited characteristics of both leading and lagging indicators in relation to total recordable injury frequency rate. The authors proposed that leading and lagging indicators have a bidirectional relationship. Moreover, the lagging indicators were not derived solely from the leading indicators; instead, the whole recordable injury rate was approximated using predictive technique. The expected leading indicators were also interrelated with each other in complex ways. This indicates that the theory underlying leading and lagging indicators is relatively simple compared to the inherent complexity of the construction projects. The authors suggested reconsidering the original assumptions about leading indicators, as their findings challenged the notion that leading indicators measured at one point in time can predict safety at a subsequent point in time.

In another study, Alruqi and Hallowell (2019) conducted a *meta*-analysis to study the association between active and passive leading indicators in construction safety projects. Nine safety leading indicators were examined through this study. According to the result of the analyzing software, it was found that the effect sizes of leading and lagging indicators' correlations are drastically different. Significant effect sizes were observed between safety inspection and injury, as well as between pre-task safety meetings and injury. Injury rate had a significant effect size in its relationship with safety record and safety resources. Owner involvement, staffing for safety, safety training, PPE, and incentive programs had moderate effect sizes. Safety inspections had the lowest effect size compared to the other indicators. They suggested that safety inspections should not be used so much as a leading indicator, and better indicators around climate and the quality of hazard response should be considered.

The study indicated that the pre-task safety meetings could be a potential key predictor for safety performance evaluation if they are tracked and perceived as active leading indicators, although they may not be efficient predictors of safety performance. Findings supported other studies that causality between leading and lagging indicators is not as simple as once suggested.

Also, the relationship between lead/lag indicators, when based on a single company, had "minimal to no prevention effect when examined within the entire project period rather than segments of time within the project". They suggest a challenge is that the indicators used by companies may not allow them to see the positive effect of injury prevention in their workplace. They offer that this may be because the metrics used to evaluate safety prevention aren't effectively showing the strengths of the prevention, the methods to examine the effects are too complex for a construction contractor to measure, or maybe the prevention methods just aren't effective.

They concluded that although active leading indicators are rare and recent, inspections and pre-task safety meetings are correlated with

near-term safety performance. Passive leading indicators are common, and its research has been done for decades. The result of their analysis showed that safety recordkeeping, incentive programs, safety inspections and observations improve long-term safety performance.

In a *meta*-analysis conducted by Alruqi and Hallowell (2019), the association between active and passive leading indicators in construction safety projects was investigated. The study examined nine safety leading indicators and found notable differences in the effect sizes of leading and lagging indicators' correlations. Notably, significant effect sizes were observed between safety inspection and injury, as well as between pre-task safety meetings and injury. The relationship between injury rate and safety record, as well as safety resources, also exhibited significant effect sizes. On the other hand, owner involvement, staffing for safety, safety training, PPE, and incentive programs had moderate effect sizes. Among the indicators, safety inspections had the lowest effect size, indicating that they should not be overly relied upon as leading indicators. Instead, the study suggested considering better indicators related to climate and the quality of hazard response. The study highlighted that although pre-task safety meetings may not be efficient predictors of safety performance, they could serve as potential key predictors if they are tracked and perceived as active leading indicators. The study emphasized that although active leading indicators are relatively uncommon and more recent, they are correlated with near-term safety performance. On the other hand, passive leading indicators, such as safety recordkeeping, were found to improve long-term safety performance based on the analysis conducted.

Furthermore, the study found that examining the relationship between leading and lagging indicators based on a single company throughout the entire project period, rather than segmented time periods, showed minimal to no prevention effect. This poses a challenge because it suggests that the indicators used by companies may not effectively capture the positive effects of injury prevention in the workplace. Possible reasons for this discrepancy include the metrics used for safety prevention evaluation not adequately showcasing the strengths of prevention efforts, the complexity of methods used to examine effects being impractical for construction contractors, or the ineffectiveness of the prevention methods themselves. These findings supported previous studies indicating that the causality between leading and lagging indicators is more complex than initially thought.

Versteeg et al. (2019) examined the relationship between safety leading and lagging indicators at the project level using the company administrative data. They found the expected relationship between higher site inspection and toolbox talks and lower injury and first aid injuries, although these findings were only significant for first aid outcomes. However, the estimated effect sizes of the models were very small, and the limited number of injuries prevents adequate data analysis. The authors anticipated to find significant correlations with negative estimates since the nature of leading and lagging indicators implies that increase in leading indicators would lead lagging indicators decrease. They concluded that their findings revealed that the causal relationship between leading and lagging indicators is not as simple as previously assumed. The authors challenged the traditional assumption that safety leading indicators are associated with lower injury rates and should be the focus of programs aiming for safety performance enhancement. Many scholars recognize that the causal relationship between leading and lagging indicators is understudied (Lingard et al., 2017; Neamat, 2019; Oswald et al., 2018; Xu et al., 2021). Therefore, research on leading and lagging indicators has focused on further defining what a leading and lagging indicator is (Kjellén, 2009) and exploring their causality (Salas and Hallowell, 2016).

Due to the complexity of injury causation factors, it becomes more challenging to establish a clear link between a leading indication and a lagging indicator (Versteeg et al., 2019). Additionally, comparing project-level data with the timing and sequencing of leading and lagging indicators may produce different findings (Lingard et al., 2017). Moreover, the observation of statistically significant connections in safety research is complicated by the decreasing injury rates observed in many jurisdictions over the years (Mustard et al., 2003). This poses a challenge in terms of the sample size required for research, particularly when analyzing indicators at the project level and within individual companies. As injury rates decline, larger sample sizes are needed to detect significant relationships and draw meaningful conclusions. Versteeg et al. (2019) highlight these are some of the possible explanations for why some studies are concluding that there is little to no correlation between leading and lagging indicators.

Lastly, Versteeg et al. (2019) believe that academics and industries may not be utilizing the most effective leading indicators for leading and lagging indicator analyses. As an illustration, Lingard et al. (2017) and Rajendran (2013) have employed site inspections as a leading indicator. However, none of the studies provided solid evidence supporting their effectiveness. Although count data offer simplicity of acquisition and reliability, they have limitations in terms of their validity as metrics of safety performance (Versteeg et al., 2019). Counts of inspections and safety talks provide an indication of the efforts made by firms to improve safety. But they are rather coarse metrics that are sometimes far distant from incident events on the causation path. Versteeg et al. (2019) suggest that instead of relying on counts of site inspections, more reliable indicators such as safety climate and indicators related to the quality of hazard response processes should be considered. Construction companies need to integrate the measurement of accurate and valid leading indicators into their project management strategies. Advances in methods for collecting, evaluating, and sharing safety performance data (Oguz Erkal et al., 2023; Xu et al., 2021) may assist researchers and companies in evaluating and refining leading indicators.

3.5. *Evaluating the effectiveness of safety leading indicators in construction projects*

Lagging indicators have been widely utilized in construction projects to measure safety performance due to their easy measurability (Lingard et al., 2017). However, in recent years, the construction industry has recognized the value of safety leading indicators as proactive measures, alongside traditional lagging indicators (Cheung et al., 2020). Despite their potential, the use and effectiveness of leading indicators in construction projects are still in their early stages, and few studies have been conducted to evaluate their implementation (Hallowell et al., 2013; Xu et al., 2023). This limited adoption can be attributed to several factors. Firstly, there is insufficient guidance available to the industry on the appropriate selection and utilization of indicators at different organizational levels and stages of construction projects (Cheung et al., 2020). Secondly, there is a lack of familiarity with the concept of leading indicators within the local construction industry (Akroush and El-Adaway, 2017).

In a study by Alexander et al. (2017), a hypothesis was tested suggesting that a small number of precursors identified prior to an incident could predict the probability of fatal events. Using a mathematical predictive model, the researchers identified 16 precursors that outperformed random chance in predicting the outcome of new cases. Their initial theory was based on the assertion that observable leading conditions could serve as predictors for high-impact events such as fatalities. Marks et al. (2013) evaluated the effect of leading indicators to foresee hazards and incidents on construction sites. The result of their experiment indicated that the data generated by leading indicators could be processed and analyzed effectively for this purpose. Teizer (2016) investigated the critical time window for incident prevention and response. They developed a roadmap focusing on automated safety data gathering, analysis, and reporting. (Xu et al., 2023) examined the potential implementation of leading indicators to enhance safety performance in construction projects. The study identified several key factors that significantly influenced safety performance, including organization commitment; engagement of clients, designers, and contractors; training and orientation programs; as well as safety climate and competence. The

findings emphasized the necessity of active engagement from clients, contractors, designers, and supply chains to foster the development of organizational capabilities for the successful deployment of leading indicators.

Oswald et al. (2018) conducted 32 interviews with industry safety experts and employed safety climate surveys to explore the utilization of leading indicators in the construction industry. The findings elaborated the limitations of the measurement approaches commonly employed in construction projects, which tend to prioritize indicators that are easily quantifiable. However, the study also indicated that there is potential value in measuring indicators that are more challenging to accurately assess. Specifically, indicators that capture the cultural aspects of an organization were deemed highly valuable. The study emphasized that relying solely on easily measurable indicators is not advisable for construction companies. This includes placing excessive focus on the frequency of common and low severity lagging indicators or treating ordinary day-to-day actions as leading indicators. Instead, there should be a greater emphasis on the effectiveness of selected leading indicators, understanding the root causes of lagging indicators, and recognizing that certain aspects of safety are inherently difficult to measure and may not be adequately captured by the current measurement approaches. Furthermore, the researchers concluded that commonly used indicators are susceptible to manipulation and misinterpretation. It is crucial to consider the limitations and deficiencies of indicators, as they do not encompass the entirety of factors influencing safety performance. They also highlighted that there will always be disagreements regarding what should be included in the measurements and how they should be assessed.

A study by Akroush and El-Adaway (2017) examined the usage trends of leading indicators in local construction firms. The findings revealed that many companies were utilizing leading indicators without a clear understanding of their benefits to safety performance. Among the companies reviewed, more than 60 % had implemented a safety indicator system. Interestingly, even companies that did not have a formal system still employed many indicators, with some using up to 75 % of the indicators investigated. The most popular leading indicators were related to simple safety tasks and routine practices such as housekeeping, use of PPE, and substance abuse programs. More complex indicators related to strategic and policy making programs such as evaluation of safety meetings were less popular. These more complex indicators were more likely to be used by larger companies, as smaller companies often had limited safety budgets to implement such policies, programs, and procedures. Liu et al. (2019) conducted a study investigating safety prequalification surveys in the construction industry to identify approaches that include leading and lagging indicators, 52 surveys were identified including 112 unique questions. The surveys incorporated a mixture of leading and lagging indicators. Most of the questions were related to lagging indicators, safety management leadership and worker training. Only two surveys included most of the important leading indicators recommended in best practice guidelines. Safety management system elements, such as hazard prevention program evaluation and communication, were notably absent in most surveys. Furthermore, there was little consistency among the surveys concerning safety leading indicators.

In a recent study, Bhagwat et al. (2022) developed a leading indicator-based jobsite safety inspection technique to evaluate the project safety performance. The findings demonstrated that reducing unsafe behavior and conditions resulted in increased safe behavior and conditions. The safety performance index of the case study significantly increased from 39.07 % to 67.47 %. Wehle and Issa (2016) found that safety performance would increase with the implementation of more safety policies and guidelines. The data indicated a cumulative effect, where projects using more passive leading indicators tended to exhibit better safety performance. However, evaluating the direct effectiveness of some leading indicators was more challenging, as they are influenced by variables such as communication, leadership, and management.

In another study, Cheung et al. (2020) utilized a two-round Delphi technique to determine the relative importance of leading indicators according to safety professionals. Based on the result, they concluded that organizational commitment, client engagement, main contractor engagement, supply chain engagement, and designer engagement are perceived by industry experts as among the most important indicators for safety management performance. Abas et al. (2021) investigated the significant factors affecting the safety performance of construction projects based on the perceptions of safety personnel. The findings revealed that safety training, safety rules and induction, and performance monitoring as significant factors at both the project and organizational levels. Rajendran (2013) evaluated leading indicators under real projects conditions and provided recommendations for their use by construction contractors. The study identified three types of leading indicators: pre-task plan (PTP) review, worker safe behavior observation (WSBO), and site safety audits. It was found that PTP reviews and worker safe behavior observations could be effective leading indicators, while site safety audits were not suitable. A well-executed PTP not only resulted in fewer injuries and incidents but also had a significant impact on worker behavior. WSBOs were deemed better leading indicators than PTP reviews. To be effective, a minimum of 20 PTP reviews and 30 observations per week on a construction site were recommended.

The essence of the findings, synthesized from an in-depth analysis of the research papers discussed and their alignment with the data presented in Table 1, highlights the critical importance of integrating all three categories of leading indicators, namely Organizational indicators, Operational indicators, and Cognitive and Behavioral indicators. This comprehensive approach enhances safety performance and contributes to robust safety management in the construction industry (Pereira et al., 2020). It is evident that relying solely on one or two categories of leading indicators (Akroush and El-Adaway, 2017; Liu et al., 2019) falls short of achieving the same level of effectiveness as the triangulated approach (Abas et al., 2021; Cheung et al., 2020). The synergy created by this triangular methodology provides a more holistic perspective of safety management in construction, ultimately yielding superior safety outcomes (Oswald et al., 2018; Wehle and Issa, 2016).

In conclusion, the utilization of leading indicators in construction safety management is still in its early stages, with limited studies evaluating their implementation. While lagging indicators have traditionally been favored due to their ease of measurement, there is a growing recognition of the benefits of incorporating leading indicators as proactive measures. Research studies have demonstrated the potential effectiveness of leading indicators in improving safety performance. The relative importance of leading indicators has been identified through expert opinions, emphasizing factors such as organizational commitment and stakeholder engagement. However, the lack of consistency in the use of leading indicators and the absence of comprehensive safety management system elements in existing surveys highlight the need for further development and standardization in the industry. Continued research, industry-wide awareness, and the development of best practices are essential to fully leveraging the benefits of leading indicators and improving construction safety outcomes.

4. Conclusion

Leading indicators have gained recognition as an important area of study in the field of construction safety. However, there is still a lack of consensus regarding their definition, governance, and effectiveness. Nevertheless, the construction industry has seen a multitude of leading indicators being proposed. In light of this, the aim of this systematic literature review was to establish a shared understanding of the concept and to bridge the gap in our limited knowledge of safety leading indicators in construction. By scrutinizing a diverse range of studies, this research successfully establishes a shared understanding of safety leading indicators, contributing to the ongoing challenge of achieving consensus on their definition and governance. By taking this pioneering

step, this study serves as a cornerstone for subsequent research and practice, providing a roadmap for researchers and industry experts alike on what safety leading indicators should be measured and tracked across different levels. Through a comprehensive analysis of various studies on construction safety, this research not only identified changes in the definition of leading indicators over time but also explored prominent trends within the field. This temporal analysis provides valuable insights for practitioners and researchers to stay abreast of emerging themes and adapt their strategies accordingly.

This study also investigated connections between these indicators and safety performance. This comprehensive approach emphasizes the need for a continuous focus on safety indicators in the construction industry, encompassing indicators related to people, culture, and processes. This nuanced understanding is crucial for industry practitioners and policymakers, as it provides actionable insights into the effectiveness of various indicators in enhancing safety outcomes. This knowledge can guide the selection and implementation of indicators for improved safety management. A notable contribution of this research lies in its systematic approach, which not only envisioned and identified safety leading indicators but also validated their efficiency. Furthermore, the study discerned trends within the realm of safety leading indicators and delved deep into the interrelationships and implementation of these indicators in construction projects. These findings serve as a foundation for future research endeavors, helping to advance our understanding of safety performance and contribute to the ongoing efforts in improving construction safety management.

As with any review study, this research has inherent limitations that may impact the generalization of the findings. This study is limited by its reliance on knowledge synthesis and evidence analysis from other studies, rather than conducting an empirical examination of theories in real-world practice. Another limitation is the restricted pool of publications that were included and reviewed. It is possible that relevant findings from other sources were not captured, which could introduce bias. However, the results obtained in this study still provide valuable insights and serve as a foundation for future guidance and research. It is important to note that the aim of this research was not to encompass the entire population of safety indicators but rather to highlight the key aspects of safety leading indicators that are relevant to construction projects.

Future research directions in the field of safety leading indicators could focus on exploring the concept of psychological safety. Psychological safety is a crucial aspect of safety culture and is characterized by an environment where individuals would share concerns and engage in open communication regarding safety issues. Investigating the impact of psychological safety on safety management and its relationship with other leading indicators would contribute to a more comprehensive understanding of safety performance in the construction industry. Additionally, considering the dynamic nature of the construction industry, future research could explore the integration of leading indicators with emerging technologies, such as artificial intelligence, Internet of Things (IoT), and data analytics. Leveraging these technologies can enhance the collection, analysis, and utilization of safety data, leading to more proactive and effective safety management practices.

CRediT authorship contribution statement

Hamidreza Golabchi: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Abbey Dale Abellanosa:** Writing – review & editing, Methodology, Conceptualization. **Lianne Lefsrud:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Estacio Pereira:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Conceptualization. **Yasser Mohamed:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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