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Constructs of leading indicators: A synthesis of safety literature

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ABSTRACT

Introduction: Leading indicators represent an invaluable tool that offer organizations the capability to: track health and safety performance, not just failures and accidents; measure effectiveness of safety efforts adopted; and focus on undesired precursors, rather than undesired occurred events. Despite these palpable advantages associated with their adoption, leading indicator's definition, application, and function are mostly ambiguous and inconsistent within literature. Therefore, this study systematically reviews pertinent literature to identify the constructs of leading indicators and generates guidance for leading indicator implementation (as a conceptual model). *Method:* The overarching epistemological design adopted interpretivism and critical realism philosophical stances together with inductive reasoning to analyze 80 articles retrieved from the Scopus database, plus 13 more publications supplemented by the snowballing technique. Analysis of the safety discourse within literature (as secondary data) was undertaken in two stages, namely: (1) a cross-componential analysis identified the main features of leading indicators in comparison to lagging indicators; and (2) content analysis revealed prominent constructs of leading indicators. *Results and conclusion:* Analysis results identify that the definition, types, and development methods represent the main constructs for understanding the concept of leading indicators. The study identifies that ambiguity around the definition and function of leading indicators is due to the lack of differentiation of its types, namely passive leading indicators and active leading indicators. *Practical application:* As a practical contribution, the conceptual model, which introduces continuous learning through a perpetual loop of development and application of leading indicators, will help adopters create a knowledge repository of leading indicators and to continuously learn and improve their safety and safety performance. Specifically, the work clarifies their difference in terms of the timeframe passive leading indicators and active leading indicators take to measure different safety aspects, the functions they serve, the target they measure and their stage of development.

1. Introduction

> *"You cannot teach a man anything, you can only help him find it in himself"- Galileo Galilei CE: 1564 -1642*

The introduction of Safety-I and Safety-II concepts in safety science has changed conventional understanding of safety, its metrics, measured elements, and approach to preventative measures accordingly (Patriarca et al., 2019). Safety-I defines safety as an absence of failure (or negative outcomes) and attempts to minimize accident occurrence (Sujan et al., 2019), whereas Safety-II describes safety as the presence of positive outcomes and strives to sustain safety by measuring and learning from '*what went right*' (Hollnagel, 2014). Scholars in safety management literature might disagree on one unequivocal definition of safety (namely, the absence of failure or presence of success), however all safety management theorists and practitioners agree that measuring and maintaining safety is intrinsically important for all stakeholders in safety practice (Floyd, 2021). Hence, various prominent scholars (cf. Hallowell et al., 2020; Elsebaei et al., 2020; Erkal et al., 2021; Schwatka et al., 2016) offer a plethora of indicators and metrics that are designed to inform the status of safety at a given time (either before or after an accident) to enable prevention of unfavorable events' occurrence or reoccurrence. Measuring safety of the past is achieved through investigation and analysis of factors in historical incidents, also known as lagging indicators (Almost et al., 2019; Jazayeri & Dadi, 2017). Studying lagging indicators

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enables the identification of '*what went wrong*' in the system, so that past failures, errors, and mistakes can be prevented in the future (Erkal et al., 2021). Examples of lagging indicators include: recordable injury rate (Floyd, 2021); employers' liability compensation costs (Costin et al., 2019); lost work day rate (LWDR) (Falahati et al., 2020); experience modification rate (EMR) (Jazayeri & Dadi, 2017); and fatality rate (Hinze et al., 2013). Outcomes derived from analyzing lagging indicators serve as a foundation for developing preventative measures for future projects (Elsebaei et al., 2020; Sinelnikov et al., 2015).

However, numerous academics (mostly Safety-II proponents) question the efficiency or accuracy of lagging indicators to measure safety or indeed to predict future safety performances (cf. Grabowski et al., 2007; Alruqi & Hallowell, 2019; Yorio et al., 2020; Xu et al., 2021). This growing notoriety of lagging indicators is ascribed to their erroneous external (outside the company) misuse in the form of benchmarking indicators or contractors' selection criteria (Elsebaei et al., 2020). Such practices change the organizational psychology from using lagging indicators for introspection, learning and prevention purposes, towards exercising record-keeping for performance demonstration purposes only, which in turn triggers the manipulation of recording and generation of spurious accident events reporting (Xu et al., 2021). In contrast to measuring safety in/of the past (using lagging indicators), there is a range of proactive safety metrics used to measure current safety status in a timely manner (e.g., safety culture, safety risk analysis, leading indicators, safety climate) (Elsebaei et al., 2020; Tang et al., 2018) - amongst which leading indicators are commonly contrasted with lagging indicators (cf. Alruqi & Hallowell, 2019; Xu et al., 2021). In recent literature, this duo of lagging and leading indicators is also referred to as reactive and proactive, trailing and leading, downstream and upstream, historical and predictive, trailing and heading, negative and positive indicators, respectively (cf. Sinelnikov et al., 2015; Haas & Yorio, 2016; Xu et al., 2021). Leading indicators are defined as the predictive and proactive measurement of safety that enable safety status monitoring without waiting for a system to fail and reveal its weaknesses (Eaton et al., 2013). Leading indicators seek to measure organization's safety status by monitoring its long term, safety related practices and short-term, current (negative or positive) manifestation of such practices in real time (Falahati et al., 2020). This ensures that relevant actions can be undertaken to prevent negative outcomes or continue positive actions leading to success (Patriarca et al., 2019). However, despite the popularity and potential advantages of leading indicators, its definition, types, applications, functions, and elements (i.e., measurements adopted to be a leading indicators) described in extant literature are mostly equivocal and inconsistent (cf. Alruqi & Hallowell, 2019; Guo & Yiu, 2016; Sinelnikov et al., 2015; Sheehan et al., 2016). Moreover, the distinctiveness of every organization's safety management system(s), safety culture maturity level, as well as different capacity and resources allocated to develop, measure, and record the leading indicators make the elements and application of leading indicators non-generalizable and unique to every organization and individual project (Xu et al., 2021).

Hence, the following research question is framed *viz.,* what are the main leading indicator constructs that enable clear explanation of such concept and facilitate their wider adoption for proactive safety management? Therefore, this study systematically reviews the prevailing academic discourse within pertinent literature on safety leading indicators to determine their constructs, that is, components that define them. Moreover, the work presents a conceptual model of leading indicator development and application that serves as essential theoretical guidance for organizations to develop, adopt, and implement leading indicators as their proactive safety monitoring practice. Such a model will augment organizations' transformation into continuous learning entities by collecting and recording the data about safety status and safety performance in their knowledge repository. Associated objectives are to: identify the main features of safety leading indicators in contrast to safety lagging indicators using a cross-componential analysis; and generate a new theory-based guidance note of leading indicator implementation that will clarify the definition, function, development process, and potential use of leading indicators in safety management. Cumulatively, this work provides an invaluable contribution to contemporary academic discourse on proactive safety management by clarifying the complexities of leading indicators and paves the way for future studies to focus on the differences of active leading indicators (ALIs) and passive leading indicators (PLIs) and their prospective use in proactive safety management.

2. Methodology

To determine the main features of leading indicators and generate a conceptual model for leading indicators' development, a comprehensive review of pertinent literature is undertaken, where each publication represents a unit of analysis and secondary data source (Posillico et al., 2021). An overarching epistemological stance that combines critical realism and interpretivism (augmented by inductive reasoning) is adopted for successful achievement of the study's objectives (Burton et al., 2021; Edwards et al., 2021; Roberts et al., 2019). Interpretivism explains and interprets a phenomenon under investigation from different perspectives in a subjective way, whereas critical realism entails using objectivity to enhance critique and appraisal of analysis undertaken (Clark et al., 2021). At stage one, a cross-componential analysis of leading and lagging indicators was performed utilizing critical realism to reveal distinctive features of both indicators by comparison. Cross componential analysis is a process of dividing the sense of a word or concept into its minimal distinctive features (i.e., semantic components) in contrast to another word or concept (Widyastuti, 2016). Componential analysis strives to dissect the inferential, implicational, and core meaning of two or more words and concepts (or lexemes) being analyzed, by identifying and comparing their semantically related common and distinctive components (Widyastuti, 2016).

Data for the analysis is sourced from the Scopus database with the search rules of TITLE-ABS-KEY ("leading indicators") AND TITLE-ABS-KEY ("safety management") to remain consistent with the study's aim and objectives. These specific search keywords were selected and no filter or exclusion criteria were applied in order to study the current status of leading indicators literature. The Scopus database was utilized for this research primarily because it has a broader coverage of literature when compared to alternative databases (i.e., Web of Science, PubMed and Google Scholar) (cf. Kukah et al., 2022). Moreover, Scopus was also chosen because it: contains automated analytical tools for summary analysis of search results; allows comma-separated value (CSV) file download of bibliometric details of publications; and has been extensively utilized in similar studies (Li et al., 2014). The main disadvantage of using Scopus is that other relevant publications may not be included in the search (cf. Falagas et al., 2008) but this issue can be mitigated via the use of snowballing (cf. Li et al., 2020). The initial search rules produced 151 publications (refer to Fig. 1). Most studies (31.4% or frequency (f) = 91 documents) were from the Engineering discipline, followed by (in descending order): Chemical Engineering (15.2% or f = 44 documents); Medicine (14.5 % or f = 42 documents); and Social Sciences (9.3% or f = 27 documents). These search results indicate that studies on leading indicators are multidisciplinary and significantly pervasive in safety–critical

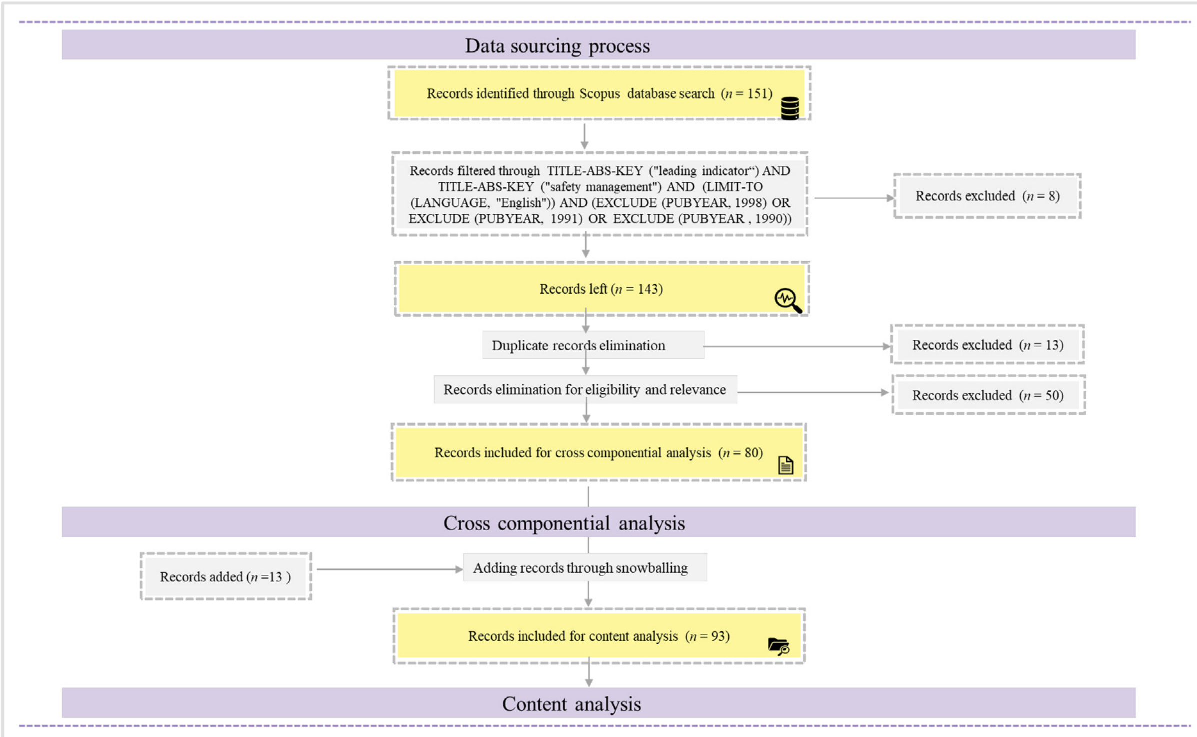

Fig. 1. Data selection steps for two-staged analyses.

industries such as construction, civil engineering, chemical and petrochemical industries, and healthcare sector. The earliest publication year of sourced studies commences from 1990 and the most prolific year of leading indicator studies is in 2020 with 19 documents.

To focus onto the most relevant publications, filters were subsequently applied with the search rules TITLE-ABS-KEY ("leading indicator") AND TITLE-ABS-KEY ("safety management") AND (LIMIT-TO (LANGUAGE, "English")) AND (EXCLUDE (PUBYEAR, 1998) OR EXCLUDE (PUBYEAR, 1991) OR EXCLUDE (PUBYEAR, 1990)), which refined the results to 143 publications. Subsequently, to maintain the recency and pertinence of sourced papers to the research topic, years of publication were limited to 2000–2022 (where 2022 includes only publication available at the time of sourcing). Bibliometric data sourced from Scopus is in CSV format and includes the details of 'authors,' 'year of publication,' 'DOI,' 'abstract,' 'authors' keywords,' and 'index keywords.' Through manual cleansing of duplicates (which excluded 13 records) 140 papers were selected for full-text sourcing. The final step of selection criteria was based on publications' length and eligibility by using the digital object identifier (DOI) detail published with each item, followed by manual screening of abstracts, to assess their relevance to the study's aim and objectives. As a result, 80 publications were selected for cross-componential analysis.

During stage two, the snowballing technique was adopted by examination of references found in this initial sample of 80 papers. Snowballing is especially useful for: extending the initial results of a systematic literature review; and ensuring a wide coverage of relevant publication materials is captured for subsequent analysis (cf. Greenhalgh & Peacock, 2005). Consequently, 13 more relevant publications were sourced from the initial 80 papers and a total of $f = 93$ documents were added for subsequent content analysis. The content analysis (as well as preceding cross-componential analysis) was conducted using computer-assisted qualitative data analysis software (CAQDAS) called – NVivo to deliver a richer interrogation of the prevailing academic discourse. Content analysis scrutinizes the meanings, contexts, and intentions contained in the analyzed document (Prasad, 2008) to draw replicable and valid inferences from the units of analysis by clustering closely related contents into categories. The emergent results from content analysis generate new insights, knowledge and representation of facts (Elo & Kyngäs, 2008). Therefore, complementing the second stage of analysis with relevant works (via the snowballing technique) was necessary to achieve a comprehensive scrutiny of the definition, types, and methodologies used for leading indicators' development.

The development of new understanding in content analysis is performed through inductive reasoning. A notable limitation associated with developing a new theory using inductive reasoning is that it requires deductive testing in practice to confirm validity (or otherwise) (cf. Wacker, 1998; Sidiropoulos, 2021). That said, theoretical development is the bedrock upon which new knowledge is propagated and subsequently tested and has received extensive applications in contemporary scientific literature (Wacker, 1998).

3. Measuring and maintaining safety: Safety performance indicators

Unlike lagging indicators, the definition, nature, identification process, and utility of leading indicators have failed to reach a consensus in theoretical and practical terms (Guo & Yiu, 2016; Haas & Yorio, 2016; Jazayeri & Dadi, 2017; Xu et al., 2021). Alruqi and Hallowell (2019) ascribe scant leading indicator studies to the lack of resources and the difficulty in objectively accessing the large volume of sensitive organizational data. Similarly, Mearns (2009) highlights that despite an abundance of data (*i.e.*, records of safety performance) being collected in organizations, limited knowledge of how to effectively use the data for safety improvement obstructs the application of leading indicators. However, Oswald (2020) states that the adoption of these concepts (leading and lagging indicators) from the economics discipline to safety management without due rigorous consideration is a major source of confusion amongst safety academics.

3.1. Relationship of leading and lagging indicators

To define leading indicators, many studies (cf. Alruqi & Hallowell, 2019; Hopkins, 2009; Podgórski, 2015; Sheehan et al., 2016) suggest contrasting the nature, function, and focus of leading indicators with lagging indicators. Some studies on these indicators describe the relationship of leading and lagging indicators as a continuum (Reiman & Pietikäinen, 2012); whereas others describe it as relative (Dyreborg, 2009), negative (Haas & Yorio, 2016), bidirectional (Kongsvik et al., 2010) or time dependent (Yorio et al., 2020). Other scholars (cf. Saqib & Siddiqi, 2008; Mearns, 2009; Øien et al., 2011; Murray, 2015; Swuste et al., 2016; Neamat, 2019) view the relationship of these indicators as undistinguishable, overlapping, and blurred and hence, both indicators are collectively referred to as process safety indicators (Swuste et al., 2016), safety performance indicators (dos Santos Grecco et al., 2014; Saqib & Siddiqi, 2008), or key performance indicators (Murray, 2015; Yorio et al., 2020). For example, Wurzelbacher and Jin (2011) attempt to develop a framework for evaluating occupational safety and health (OSH) program effectiveness using leading and trailing metrics. Similarly, Haas and Yorio (2016) develop 22 performance measurements that combine leading and lagging indicators, and categorize them as worker performance, organizational performance, and interventions indicators. Furthermore, other studies on the interrelationship between these indicators have developed models and frameworks that explicate the indicators' relationship based on severity and predictability of occurrence (Swuste et al., 2016, 2019). The Bowtie diagram represents a prominent visual metaphor that describes the sequential relationship of leading and lagging indicators in relation to accident occurrences (Swuste et al., 2016). The Bowtie's center is depicted as an accident or other unfavorable event, the left side demonstrates barriers targeted to prevent hazards (*i.e*., primary prevention), whereas the right side represents consequences and activities designed to minimize incident severity (*i.e.,* secondary and tertiary prevention; Wurzelbacher & Jin, 2011; Swuste et al., 2019). In this metaphor, leading indicators (on the left side of the Bowtie) reveal any gaps or faults of preventative measures and barriers adopted, whereas lagging indicators describe the consequences of that undesirable event or accident (Schmitz et al., 2021). Based on this explanation, Swuste et al. (2016) describe leading indicators as proxies for barriers, hazards, and management factors that inform the cases of process deviations or the stability of a safe system of working. In contrast, lagging indicators are proxies for the event at the center and consequences Swuste et al. (2016). Similarly, the Safety Pyramid (developed in process safety management studies) represents another schematic representation of two indicators' relationship and delineates four levels of event occurrences, each increasing in severity from the pyramid's bottom to top (Murray, 2015; Stauffer & Chastain-Knight, 2021; Swuste et al., 2016). The pyramid's lower level is tier 4 type leading indicators representing minor severity level events, known as challenges to safety management systems, which are followed by tier 3 leading indicators that are near miss occurrences (Murray, 2015; Stauffer & Chastain-Knight, 2021; Swuste et al., 2016). The top two levels are described as lagging indicators of which the last tier 1 level represents the events with the most severe consequences (Murray, 2015; Stauffer & Chastain-Knight, 2021; Swuste et al., 2016).

3.2. Elements of safety performance indicators

Both alluded models of safety performance indicators (*i.e*., Bowtie and Safety Pyramid) highlight the complementary and inseparable relationship of both leading and lagging indicators and their pivotal role in providing critical information on the status of safety within an organization (and/or satellite sites managed), as well as revealing the efficiency/inefficiency of adopted safety management systems (Øien et al., 2011). The virtually indistinguishable relationship between lagging and leading indicators is emphasized by several scholars (cf. Kongsvik et al., 2010; Haas & Yorio, 2016; Yorio et al., 2020) who note that lagging indicators can explain the efficiency of leading indicators. In this case, the relationship of indicators appears bidirectional or reverse causational and their function is interchangeable (Kongsvik et al., 2010; Haas & Yorio, 2016; Yorio et al., 2020).

However, the relationship between leading and lagging indicators becomes even more blurred when elements of indicators (such as near misses, safety climate, or frequency of toolbox meetings) are studied. A leading indicator element here, denotes specific quantitative or qualitative measurements/indicators with preventative or affirmative property that are developed and adopted by an individual company to monitor safety. According to Haas and Yorio (2016) and Oswald *et al*., (2020) some elements can be considered lagging or leading indicators depending on the focus and purpose of measurement (e.g., a near miss can serve as a leading indicator if it predicts a severe future event; Sheehan et al., 2016). Yet focusing on the event (near miss) as a minor severity level incident that has already occurred, will render the event as a lagging indicator (Murray, 2015). Table 1 provides examples of leading indicator elements (on the second column), aggregating them as groups (on the first column) by their description in pertinent literature.

Table 1 illustrates that other known proactive measurements of safety (e.g., safety climate, safety culture and near miss occurrences) appear as safety leading indicator elements (Alruqi & Hallowell, 2019), since they are all associated with measuring the status or the strength of safety (Erkal et al., 2021; Xu et al., 2021). Most leading indicators' elements represent practices of safety management systems (e.g., adopting zero injury technique, substance abuse program or safety training), which highlights the main function of leading indicators to measure the efficiency of policies, rules, and preventative steps of organizational safety management. However, leading indicators elements mentioned by every study in the 'safety management systems element' group are multifarious and distinctive from every other example, since a safety management system of each individual organization is unique and contextual (Xu et al., 2021).

3.3. Classifications of leading indicators

These elements of leading indicators (exemplified in Table 1) are broadly divided into two common dichotomous classifications *viz*.: (a) based on their stage of adoption, *active* and *passive* leading indicators (cf. Hinze et al., 2013; Jazayeri & Dadi, 2017); and (b) based on their function, *structural* and *operational* leading indicators (Falahati et al., 2020). According to Hinze et al. (2013), PLIs take a long time to measure, while ALIs can be measured within a shorter time period. In other words, PLIs are a manifestation of decisions, actions, or events that have taken place long before the operation or project has been initiated (*i.e*., the design stage); whereas ALIs are a manifestation of decisions, actions, or events that have taken place during the operation or project and, hence, can be timely corrected once observed Hinze et al. (2013). Examples of PLIs include: a steel-toed boots policy (Alruqi & Hallowell, 2019); the percentage of management personnel with 10-hour or

Table 1
Leading indicator descriptions in the literature.

Leading indicator described as…	Examples of leading indicator elements	Citations
Safety management system element	Alcohol/ drug testing; attitudes and safety climate; housekeeping; safety behavior of safety; fall protection; training and job safety talk; near misses; safety correction; safety inspection; and subcontractor safety.	Neamat, 2019
	Worker observation process; near miss reporting; project management team safety process involvement; job site audits; stop work authority; housekeeping program; and safety orientation and training.	Elsebaei et al., 2020
	Safety training; ergonomic opportunities identified and corrected; reduction of musculoskeletal disorder (MSD) risk factors; employee perception surveys; and safety audits.	Hughes & Ferrett, 2020
	Zero injury techniques; demonstrated management commitment; staffing for safety; pre-project and pre-task planning; safety education and training; employee involvement; safety recognition and rewards; incident investigations; substance abuse programs; and subcontractor management.	Hallowell et al., 2013
	Near misses; safety audits; safety culture; and safety climate measures.	Eaton et al., 2013
	Upper management involvement; training/orientation; pre-task safety meeting; safety inspections/ observations; hazard and accident analysis; owner involvement; safety record; worker involvement; safety resource; staffing for safety; written safety plan; personal protective equipment (PPE); substance abuse; and incentives.	Alruqi & Hallowell, 2019
	Safety climate;	Zohar, 2010; Schwatka et al., 2016
Safety hazard and risk perception surveys	Questionnaire-assessed safety hazards; and management practices.	Moore et al., 2022
	Survey of workers, regarding the human factor issues.	O'Connor et al., 2010
Safety culture	Accountability; consultation and communication; management commitment and leadership; audits and workplace OSH inspections; empowerment and employee involvement in decision making about OSH; positive feedback and recognition for OSH; prioritization of OSH; risk management and systems for OSH; and the provision of OSH training, information, tools and resources.	Sheehan et al., 2016
	Top-level commitment to safety; organizational learning; organizational flexibility; awareness; just culture; and emergency preparedness.	dos Santos Grecco et al., 2014
Safety status monitoring, recording and reporting practices	Information from a safety audit that can lead to systematic changes for safety, such as a change in equipment or procedure; A near miss report that explains a 'difficult to observe' unsafe action, such as fluid and momentary human error, that has readily been shared without fear of punishment; A safety walk report explaining a solved dynamic safety problem that unexpectedly arose on site; and A recorded safety observation that identifies and explains potential problems for upcoming high-risk activities, such as work at height.	Oswald, 2020
Organization's occupational health and safety (OHS) performance.	OHS leadership; OHS culture and climate; employee participation in OHS; OHS policies, procedures and practices; and OHS risk control.	Yanar et al., 2020
Assessment of adopted safety management system	Direct measures of safety management systems such as frequency or timeliness of audits.	Hopkins, 2009
Preventative measures	Activities, practices, and programs for preventing injuries and minimizing duration and severity of injuries when they do occur.	Moore et al., 2022

30-hour Occupational Safety and Health Administration (OSHA) certification (Jazayeri & Dadi, 2017); contract provisions that require subcontractor compliance with a site-specific safety policy or program (Hinze et al., 2013); and other safety management activities that are adopted prior to the project initiation stage. To a degree, PLIs are almost indistinguishable from *structural* leading indicators, which encapsulate all health and safety management efforts made by a company such as policies, objectives, and plans, procedures and guidelines (Cambon et al., 2006; Falahati et al., 2020). Similarly, there is an overlapping construct in the definition and examples of ALIs and *operational* leading indicators; where ALIs are described as a measurement of safety in real time and *operational* leading indicators are described as a measurement of the effectiveness of safety and health management systems in an operation stage (Falahati et al., 2020; Podgórski, 2015). Examples of ALIs include: quality of pre-job safety meetings (Alruqi & Hallowell, 2019); physical stress caused by overexertion (Costin et al., 2019); percentage of adherence to safety based on audits (Jazayeri & Dadi, 2017); and rate of involvement of upper management in safety walk-throughs (Hinze et al., 2013). These examples show that ALIs are monitored and measured both quantitatively and qualitatively. Quantification of ALIs is the most prevalent and conventional approach where safety management activities such as subcontractor safety audits, safety observations, and toolbox talks are measured in terms of frequency of occurrence (Swuste et al., 2016). However, many scholars (cf. Hopkins, 2009; Costin et al., 2019; Xu et al., 2021; Schmitz et al., 2021) argue that sole quantification of ALIs is insufficient and therefore, qualitative description and measurement of such indicators must be combined to establish a complete and in-depth picture of safety status. For example, a mere measurement of the frequency of toolbox talks fails to adequately explain the effectiveness, content, and quality of those toolbox talks, which can inadvertently promote the notorious 'box-ticking' approach in safety status measurement (Xu et al., 2021). Another drawback of only quantitatively measuring safety is that any positive or negative event(s) with low frequency and minor severity will remain statistically insignificant, in which case those records will not be recognized and the opportunity to learn from those occurrences will be lost (Floyd, 2021). Therefore, for holistic indication of safety performance and comprehensive monitoring of safety, quantification of safety activities must be accompanied with supplementary qualitative information (Floyd, 2021).

4. Findings

The ubiquity of lagging indicators implementation as a safety performance indicator by most organizations is ascribable to the ease of collecting, recording, and analyzing them (cf. Almost et al., 2019; Lingard et al., 2017). Numerous tools, theories and methods exist to analyze past events of reportable and recordable accident occurrences; epitomized by the fishbone diagram, five whys, root-cause analysis that attempt to determine cause(s) and underlying reasons of recorded accident cases, namely lagging indicators (Hughes & Ferrett, 2020). Whereas recent applications of machine learning and predictive/classification analytics (both stochastic or deterministic modeling variants) are more sophisticated methods that attempt to identify systemic vulnerabilities and determine accident predictors (Bortey et al., 2021; Erkal et al., 2021; Shrestha et al., 2020). However, studies on leading indicators reside within an incipient stage of development only (Mearns, 2009). The results of cross-componential analysis illustrated in Table 2 identify main components/features of both concepts (i.e., leading and lagging indicators). These include the focus, function, definition, underlying concept, risk assessment, what, and how metrics are measured as well as advantages and disadvantages.

Both leading and lagging indicators have their own merits in terms of the function they serve *viz.* in respective order: monitoring safety or unsafety (Reiman & Pietikäinen, 2012); measuring different level of precursors (e.g., safety behavior of workers and near misses) or consequences (e.g., near misses or dangerous occurrences) (Swuste et al., 2019); and responding by correcting in the moment or by learning after the occurrence and preventing them in the future (Hinze et al., 2013). Table 2 illustrates that most components used to contrast leading and lagging indicators differ for each indicator, except for five overlapping or common components (that are highlighted with light yellow shading in Table 2). These common components appear - once in *function and use* component (i.e., for external use of a company); once in *what they measure* (i.e., negative status of safety); once in *how they measure* (i.e., quantitatively); and twice in the *disadvantages* component, namely: (1) sole quantification-based safety performance indicators (i.e., leading and lagging indicators) fail to holistically indicate a safety performance; and (2) recording and analyzing only high severity and high frequency occurrences and ignoring seemingly statistically insignificant data obstructs the learning opportunity. The findings demonstrate that lagging and leading indicators emerge from two different safety concepts *viz.*, Safety-I and Safety-II, which (similar to the leading and lagging indicators) are frequently contrasted in safety science literature. However, like the Safety-II concept, the notion of a leading indicator is a relatively new concept in safety management that possesses some ambiguity around its functions, deviations in definition, and bear vagueness in implementation and application. Therefore, this drawback of leading indicators is explained (in Table 2) as being one of the main disadvantages that hinders the adoption of leading indicators.

Premised upon this finding, the content analysis stage focused on aggregating the themes of three main constructs of leading indicators that facilitate its explication *viz.*: (1) the definition; (2) clas-

Table 2
Cross-componential analysis of leading and lagging indicators.

Features	Leading indicators	Lagging indicators
Definition	Current situation that can affect future performance (Mearns, 2009).	Outcomes that result from our actions (Mearns, 2009).
	Precursors of failure or success (Swuste et al., 2016).	Occurrences of failures (Schmitz et al., 2021).
Examples	Safety culture, safety climate, near-misses, safety training, toolbox talks, safety training and orientation, safety inspections (Falahati et al., 2020).	Total recordable injury rate (TRIR), lost work day rate (LWDR), worker compensation rate (WCR), lost time cases (LTC) (Floyd, 2021; Jazayeri & Dadi, 2017).
Function and use	For monitoring and responding (Guo & Yiu, 2016).	For recording, reporting and learning from past mistakes (Alruqi & Hallowell, 2019).
	For internal use of a company (Reiman & Pietikäinen, 2012).	
	-	For external use of a company (Elsebaei et al., 2020).
Underlying concept	Safety-II and Resilience engineering (Patriarca et al., 2019; Pęciłło, 2020).	Safety-I (Hollnagel, 2014).
Risk assessment	Proactive and reactive (Sheehan et al., 2016).	Retrospective and introspective (Lingard et al., 2017).
Focus	Safety performance now and near future (Yorio et al., 2020).	Safety performance of the past (Alruqi & Hallowell, 2019).
	Safety status before accident occurrence (Haas & Yorio, 2016).	Safety status at the moment of accident (Neamat, 2019).
Measures (what)	Negative status of safety, i.e., absence of safety (Sheehan et al., 2016).	
	Negative and positive precursors: signs and signals of upcoming failure or success (Patriarca et al., 2019; Reiman & Pietikäinen, 2012; Xu et al., 2021).	Negative outcomes only: failures, errors, mistakes, accidents, near misses, dangerous occurrences (Lingard et al., 2017).
Measures (how)	Quantitatively (dos Santos Grecco et al., 2014).	
	Qualitatively (Reiman & Pietikäinen, 2012).	-
Advantages	Timely safety performance measure enables to prevent accident occurrences (Floyd, 2021).	Lesson learnt from the past enables data-driven and informed generation of preventative countermeasures (Oswald, 2020).
	Drive continuous improvement and error correction (Grabowski et al., 2007).	Great introspection practice for continuous learning organization (Oswald, 2020).
	Measuring success ("*things going right*") enables recognition and encouragement of workers' good safety practices (Hinze et al., 2013; Sheehan et al., 2016).	Sophisticated analysis methods have a potential to identify systemic vulnerabilities and to detect accident precursors (Hallowell et al., 2020).
Disadvantages	Ambiguity around leading indicator's definition, application and functions impedes its adoption by companies (Kenan & Kadri, 2014; Guo & Yiu, 2016).	Recording of lagging indicators becomes distorted from the actual events, when used as a benchmarking criterium (Costin et al., 2019; Floyd, 2021).
	Elements of leading indicators are unique and identified leading indicators are not readily generalizable to other organizations or projects (Xu et al., 2021).	Past mistakes and accidents are mostly non-generalizable for future construction projects (Elsebaei et al., 2020; Floyd, 2021).
	Sole quantification-based safety performance indicators (leading and lagging indicators) fail to holistically indicate a safety performance (Oswald, 2020).	
	Recording and analyzing only high severity and high frequency occurrences and ignoring seemingly statistically insignificant data obstructs the learning opportunity (Hopkins, 2009; Floyd, 2021).	
	The emergent nature of most leading indicators that are only discernible in the operation stage of projects makes the process of knowledge transfer (and adoption of developed leading indicators) difficult (Haas & Yorio, 2016).	Outcomes of analyzing (lagging indicators) based on basic analysis methods are invalid to identify systemic failures or to have predictability (Hughes & Ferrett, 2020). Whereas, sophisticated analysis methods (of lagging indicators) are not affordable and widely adopted and only statistically significant events can be analyzed in sophisticated analysis methods, hence there is a lack of empirical studies proving such methods' credibility (Erkal et al., 2021).

sification types; and (3) development methodologies. Therefore, Table 3 describes a compilation of leading indicators' definitions (arranged from early to recent years) and Table 4 expands upon the classification types of leading indicators identified through content analysis of extant literature.

The definitions of leading indicators included in Table 3 are arranged in chronological order from the earliest to the most recent to show their development in safety science. Moreover, a 'semantics' column was added to reveal how the definition (and understanding) of leading indicators has evolved over time. The definitions starting from 1999 to 2012 describe leading indicators as an outcome, *viz.,* indicator of events that has occurred (alongside the description as precursors, *viz.*, indicators predicting events that are going to occur). However, the outcome is defined as the main

Table 3
Etymology of leading indicator.

Definitions	Citation	Semantics
A safety indicator is a statistic or other unit of information that reflects directly or indirectly the extent to which an anticipated outcome is achieved or the quality of the processes leading to that outcome.	NOHSC, 1999 (cited in Guo & Yiu, 2016)	Outcomes; Precursors; Measurement of positive events; Assessment of safety management systems
Leading indicators provide information about developing or changing conditions and factors that tend to influence future human performance.	EPRI, 2000 (cited in Jazayeri & Dadi, 2017)	Precursors; Measurement of positive and negative events
Measurements linked to preventive or proactive actions.	Toellner, 2001 (cited in Xu et al., 2021)	Precursors;
A safety indicator is a measurable/operational variable that can be used to describe the condition of a broader phenomenon or aspect of reality.	Øien, 2001b (cited in Guo & Yiu, 2016)	Measurement of positive and negative events;
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.	Health, and Safety Executive (HSE), 2006	Measurement of negative events;
Leading indicators are conditions, events, or measures that precede an undesirable event and that have some value in predicting the arrival of the event, whether an accident, incident, near miss, or undesirable safety state.	Grabowski et al., 2007	Precursors; Measurement of negative events;
A safety performance indicator is a means for measuring the changes in safety level over time resulting from actions taken.	OECD, 2008	Outcomes; Measurement of positive and negative events;
An indicator that changes before the actual risk level of the organization has changed.	Kjellén, 2009	Precursors;
Leading indicators are proactive measures of performance before any unwanted outcomes have taken place.	Dyreborg, 2009	Precursors; Measurement of and negative events;
A safety indicator is a proxy measurement for items identified as important in the underlying model(s) of safety.	Wreathall, 2009	Assessment of safety management systems
An indicator should measure the state of the safety management system.	Hopkins, 2009	Assessment of safety management systems
Safety indicators are measures of the effectiveness of safety management tasks.	Cipolla et al., 2009 (cited in Guo & Yiu, 2016)	Assessment of safety management systems
Lead safety indicators indicate either the current state or the development of key organizational functions, processes and the technical infrastructure of the system.	Reiman & Pietikäinen, 2012	Precursors; Outcomes; Assessment of safety management systems
Positive performance indicators that address health and safety climate.	Agumba & Haupt, 2012	Outcomes; Measurement of positive events;
Leading indicators of safety performance consist of a set of selected measures that describe the level of effectiveness of the safety process.	Hinze et al., 2013	Assessment of safety management systems
Proactive and predictive measurements that enable safety condition monitoring, which reduces the need to wait for the system to fail to identify weaknesses and to take remedial action.	Eaton et al., 2013	Precursors; Assessment of safety;
Indicators that enable anticipation of performance evaluation are called leading indicators.	dos Santos Grecco et al., 2014	Precursors;
Leading indicators are safety-related practices or observations that can be measured during the construction phase, which can trigger positive responses.	Hallowell et al., 2013	Assessment of safety management systems; Measurement of positive events;
Characteristics that foment safety behavior, such as safety culture or safety climate.	Navarro et al., 2013	Assessment of safety and safety culture;
Something that provides information that helps the user respond to changing circumstances and take actions to achieve desired outcomes or avoid unwanted outcomes.	Step-Change in Safety, 2014 (cited in Guo & Yiu, 2016)	Precursors; Measurement of negative and positive events
A set of quantitative and/or qualitative measurements that can describe and monitor validly and reliably the safety conditions of a construction project.	Guo & Yiu, 2016	Assessment of safety
Precursors to harm that provide early warning signs of potential failure.	Shea et al., 2016 (cited in Xu et al., 2021)	Precursors; Measurement of negative events;
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.	Karakhan et al., 2018 (cited in Xu et al., 2021)	Precursors; Assessment of safety management systems;
Safety leading indicators are measures of the safety management system that correlate with injury rate.	Alruqi & Hallowell, 2019	Measurement negative events; Assessment of safety management systems;
Forewarns the analyst about potentially different actions to be undertaken in order to grasp an opportunity or to evade a threat.	Patriarca et al., 2019	Precursors; Measurement of negative and positive events;
The quantity of safety management activities performed to prevent injuries	Hallowell et al., 2020	Assessment of safety management system;
Leading indicators show the activities of an organization regarding the prediction and prevention of accidents before they occur.	Falahati et al., 2020	Precursors; Assessment of safety management systems;
Leading indicator are safety measurement which provide a future forecast of the safety performance based on the activities and practices implemented not incidents. So, it is proactive measure to what might happen in the future.	Elsebaei et al., 2020	Precursors; Assessment of safety management systems;
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.	Xu et al., 2021	Precursors; Assessment of safety management systems; Measurement of positive and negative events;

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Table 4
Typologies of leading indicators.

Types of leading indicators		Definition
Classification based on the length of time leading indicator takes to measure and respond to observed event	Passive	Passive indicators are those that cannot be altered in a short period of time (Jazayeri & Dadi, 2017). Measurements or information streams that provide an indication of the probable safety performance to be realized within a firm or on a project. They are predictive on a macro scale but have limited predictive value after a certain point in time or once a threshold is reached (Costin et al., 2019). An indication of the probable safety performance to be realized within a firm or on a project. The process being monitored by passive leading indicators cannot generally be altered in a short period of time. Passive leading indicators can be used to predict, on a larger or long-term basis, the likely safety performance to be realized by a company or on a particular project (Hinze et al., 2013). Indicators that take a long time to measure (Falahati et al., 2020). Indicators that are typically implemented before work begins and remain relatively static once a project has begun (Alruqi & Hallowell, 2019).
	Active	Indicators that can be readily changed during the construction phase - they measure quality of implementation (Alruqi & Hallowell, 2019). Measurements or information streams that provide an indication of the probable safety performance to be realized within a firm or on a project. They are dynamic and thus, more subject to change in a short period of time. ALIs may be characterized as the "pulse" of the construction project in terms of daily safety behaviors and practices (Costin et al., 2019). Indicators that can be measured within a shorter period (Falahati et al., 2020). Active leading indicators are those which are more subject to change in a short period of time (Hinze et al., 2013). Active indicators are those that can be subject to change in a short period (Jazayeri & Dadi, 2017).
Classification based on the target of measurement	Structural	Show the status of safety management systems, including policies, objectives and plans, procedures, and guidelines (Falahati et al., 2020). Indicators being applied for the evaluation of system compliance with a given specification. They measure whether individual components of the system are properly designed or evaluating the extent to which system procedures are implemented and being followed in the enterprise (Podgórski, 2015). The formal description of all the efforts that are made by the company into managing health and safety at the workplace (Cambon et al., 2006).
	Operational	Evaluate the effectiveness of the internal processes of safety and health management systems (Falahati et al., 2020). Indicators that provide information on the status of individual processes within the management system. Such indicators provide information on progress of change within the management system and assist in forecasting future status and planning (Podgórski, 2015). The level of integration and of influence of formal processes on the practices and the working environment of people (Cambon et al., 2006).
Classification based on the target of measurement	Safety management system indicators	Indicators that measure individual safety practices and activities, providing information about safety management system implementation and thus directing remedial actions (Guo and Yiu, 2016).
	Indicators of abstract safety constructs	Indicators that measure safety constructs such as management commitment, safety motivation or social support. Collecting information about abstract safety constructs often requires qualitative interviews and surveys (Guo and Yiu, 2016).
Classification based on function of measurement	Leading monitor indicators	Indicators of organizational potential to achieve safety. They do not directly predict the safety-related outcomes of the sociotechnical system since these are also affected by numerous other factors such as external circumstances, situational variables and chance (Reiman & Pietikäinen, 2012). Monitor indicators reflect the potential and ability of a given organization to operate safely (Podgórski, 2015).
	Leading drive indicators	Indicate development activities aiming at improving safety (Reiman and Pietikäinen, 2012). Drive indicators allow the measurement of the degree of execution of selected actions in priority areas of the management system, such as leadership, competence management, hazard control, change management, etc (Podgórski, 2015).
Classification based on severity of observed event	Tier 3 leading indicators	An actual event or discovery of a potentially unsafe situation, e.g., near miss. They are failure of process safety management systems that give an excellent road map to what part needs to be strengthened (Kenan & Kadri, 2014). Represents events involving challenges to safety systems, such as safe operating limit excursions, inspections of primary containment outside acceptable limits, etc (Murray, 2015). Events that are considered to be a challenge to a safety management system that exceed Safe Operating Limits (SOL) (Stauffer & Chastain-Knight, 2021).
	Tier 4 leading indicators	Indicators that monitor the health of important aspects of the process safety management system which give early indication of deterioration in the effectiveness of key safety system and enable remedial action to be undertaken to restore the effectiveness of these key barriers, before any loss of containment event takes place (Kenan & Kadri, 2014). Indicators that categorize operating discipline and management system performance (Murray, 2015).

Table 4 (*continued*)

Types of leading indicators		Definition
Classification based on the target of measurement	Predictive proactive indicators	Predictive proactive indicators supply information on the types of managerial actions that have been taken to reduce workplace risk (Haas & Yorio, 2016).
	Monitoring proactive indicators	Monitoring proactive indicators include health and safety related outcomes observed prior to the occurrence of a major incident such as small releases of hazardous substances or near misses, the results of safety inspections and behavioral observations, the results of safety audits, and safety attitudes (Haas & Yorio, 2016).

feature of lagging indicators according to the Bowtie diagram (Swuste et al., 2016). These early formative descriptions of leading indicators as 'outcomes' and/or 'precursors' represent some examples of leading indicators that are simultaneously lagging and leading (Lingard et al., 2017). However, post 2012 and until recent years, this description changes to precursors only, which signifies the increasing focus on the main function of leading indicators as antecedents. Table 3 is supplemented with Fig. 2, which combines bar chart and word cloud illustration of the words in the 'definition' and semantics' columns (of Table 3). The bar chart demonstrates the frequency of the terms used to define leading indicators in descending order, while the word cloud illustrates them (*i.e.*, frequency of words to describe leading indicators) by the their size (e.g., larger sized words have higher occurrence to describe leading indicators).

Apart from the keywords themselves (*viz.*, '*safety*,' '*leading*,' '*indicators*'), the terms such as '*precursors*' ($f = 17$), '*proactive*' ($f = 6$), '*outcomes*' ($f = 9$), '*negative*' ($f = 11$), '*positive*' ($f = 11$), '*measure/ment*' ($f = 28$) and '*assessment*' ($f = 16$) are the most frequent words used to describe leading indicators. Contrary to lagging indi-

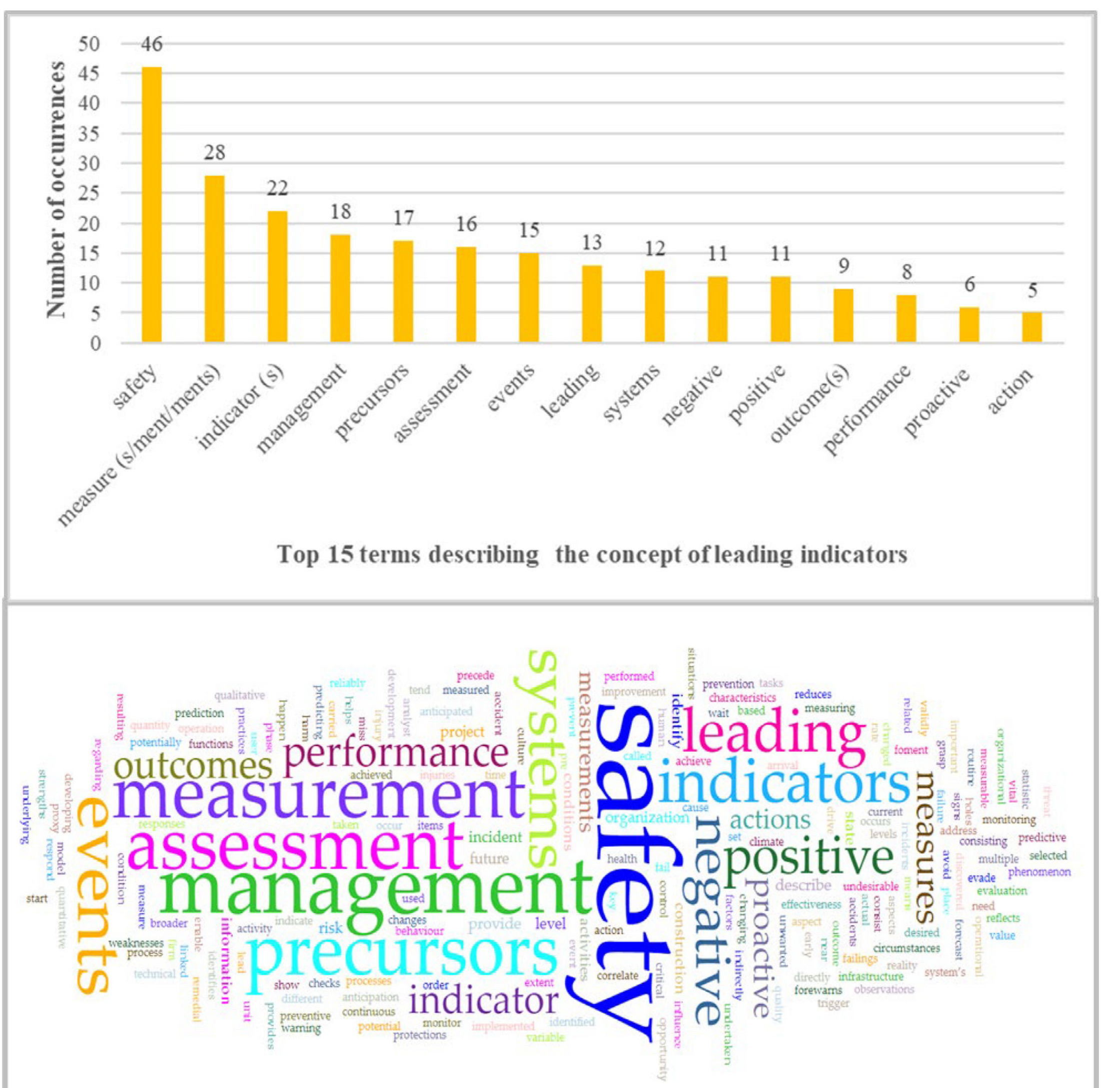

Fig. 2. Frequency of occurrence and word cloud depiction of terms defining leading indicators.

cators that measure negative events, leading indicators are defined to measure both negative and positive events - a feature that is pivotal for recognition of positive events and learning from success (Patriarca et al., 2019; Reiman & Pietikäinen, 2012). Therefore, the terms '*negative,*' '*positive,*' and '*events*' are frequently occurring words in the word cloud depiction. Regarding the target these indicators are measuring, there is a contrasting division between *safety management systems* on one side and *safety, safety culture* on the other side. This ambiguity around what is the target of leading indicators' measurement can be elucidated upon by the different types of leading indicators described in Table 4. This table presents six dichotomous clusters of classification (*i.e.*, with two subgroups within each cluster), four out of which are highlighted with light yellow shading. These four classification clusters contain the following leading indicators types: (1) PLIs and ALIs; (2) structural and operational leading indicators; (3) safety management system indicators and indicators of abstract safety constructs; and (4) predictive proactive indicators and monitoring proactive indicators. The first type of each of the four clusters focuses on measuring and monitoring safety management systems, whereas the second type of each cluster is concerned with measuring and monitoring safety and safety culture, respectively.

These dichotomous types of leading indicators (each type with different functions and focuses) create confusion around the nature, function, and application potentials of leading indicators, which also leads to the absence of their unanimous and operationally crisp definition. For example, variations in: definitions (whether they measure safety management systems or safety); time period to measure (whether they measure safety performances occurring in the long time or short time period); and function they fulfil (whether they are used only for measuring recording and learning or for monitoring and timely correcting), are respectively associated with PLIs and ALIs types. Therefore, it is crucially important to differentiate the two types of leading indicators. Namely, PLIs (similarly, structural leading indicators, safety management system indicators, and predictive proactive indicators) focus on monitoring and measuring safety in terms of adopted organizational safety management systems over an extended timeframe to correct and obtain feedback. Therefore, PLIs fulfil the function of measuring, recording, and learning, since obtaining feedback from adopted and implemented safety management systems policies, processes, plans, and guidelines requires long time period. On the other hand, ALIs (similarly, operational leading indicators, indicators of abstract safety constructs, and monitoring proactive indicators) are focused to monitor and measure an organization's safety and safety culture in the operation stage, which provides real time feedback of current safety status. ALIs serve the function of monitoring safety in real time and timely correcting issues arising in case an undesired event occurs. Leading indicators described within the literature predominantly bear the features (i.e., function and nature) of PLIs, but are rarely associated with the function and nature of ALIs.

The last construct of leading indicators is the methodologies used to develop them. Content analysis revealed prominent studies that develop and identify leading indicators using various methodologies (such as Delphi method; Erkal et al., 2021); Cross-sectional analysis (Manjourides & Dennerlein, 2019); and Analytical Network Process (ANP) (Ebrahimi et al., 2021)). Table 5 identifies that only 17 (*i.e.*, 18.28 %) out of 93 studies (*i.e.*, publications selected for this study) focus on developing leading indicators using various methodologies.

The source of materials used for developing and identifying leading indicators ranges from pertinent scientific literature to industry standards and survey responses. The most frequently used data source is '*past accident records*' *viz.*, lagging indicators. Eight of these 17 studies used organizations' past accident records to identify company-specific leading indicators. The next frequently used material source is '*pertinent literature*' ($f = 4$), followed by '*industry specific white papers and recommendations*' ($f = 3$) and '*survey responses*' ($f = 2$).

All developed leading indicators from each study (described in the third column of Table 5) were reviewed to identify which element of the sociotechnical systems and projects (such as human, machinery, site, or procedures) they represent. Most of the developed leading indicators ($f = 12$) refer to the '*human*' aspect of sociotechnical systems, followed by '*procedures*' ($f = 7$). The most common methodology used to develop, identify, or select leading indicators from a given source of materials is based on surveying opinions ($f = 4$) by congregating or ranking survey responses, through either the Delphi method or Focus groups method; followed by multi-criteria decision making (MCDA) methods (or multi-criteria decision analysis (MCDM) methods) ($f = 3$) such as the Analytic Hierarchy Process (AHP), Decision-Making Trial and Evaluation Laboratory (DEMATEL) or Analytical Network Process (ANP). This observation identifies that the methodologies for leading indicators' development predominantly rely on subjectivity and/or opinion or interpretation-based approach. However, such an approach must be combined with testing and revision in pilot or case studies to develop the most appropriate leading indicators for a specific organization and remain open to adjustments even after their adoption.

5. Discussion

The results of cross-componential analysis identify the main features of both leading and lagging indicators - both of which have inherent (and dissimilar) pros and cons, barriers, and misinterpretation of their purpose, function, and application (in Table 2). Lagging indicators constitute a mainstream measurement of safety, widely adopted by many safety–critical organizations in various industry. Yet, the function and purpose of using lagging indicators have been distorted from serving altruistic learning purposes to being recklessly promoted as one of the predominant success criteria of companies (Oswald, 2020). Where lagging indicators are recorded comprehensively for the purpose of learning and understanding the complex interaction of system elements and contextual factors in complex sociotechnical systems, they can uncover mistakes, early signs, and gaps in the safety management systems. Moreover, they can augment the development of precursors of undesirable events, namely leading indicators (Elsebaei et al., 2020).

5.1. New theory development

The process of developing leading indicators from past safety performance records is depicted in a new theoretical conceptual model presented in Fig. 3, which is premised upon the rich synthesis of literature previously analyzed. The model proceeds with differentiation between the application of PLIs (long double-sided arrow on the left side of the model) and ALIs (short double-sided arrow on the right side of the model). This is followed by the inputs for development (purple line) and application of (light yellow line) PLIs and ALIs down across the model. PLIs application is depicted as a long arrow ('Measurement of performances requiring long time period'), since PLIs measure the efficiency of organizations' safety management systems. This takes a longer time period to obtain feedback and to adjust safety management systems (where correction is required). For example, training courses implemented (which is part of organizations' safety management systems) requires a longer time period to reveal its efficiency, that is, the competency level of employees is revealed long after the comple-

Table 5
Methodologies used for leading indicators development and identification.

Methods used to develop leading indicators	Source being analyzed (LI are developed from)	Developed/ identified leading indicators	Citation	Element/ aspect of system
Analytic Hierarchy Process (AHP)	Pertinent literature and normative documents on OSH MS (ILO-OSH 2001, OHSAS 18001).	20 leading indicators (Key performance indicators)	Podgórski, 2015	Human; Procedures.
AHP and Bayesian network	OHSAS 18001: 2007 management system components; and ongoing construction project operations.	19 structural, 27 operational and 33 active leading indictors	Falahati et al., 2020	Human; Machinery; Sites.
Functional Resonance Analysis Method (FRAM)	Ongoing construction project (difference between WAP and WAD).	Not specified	Costantino et al., 2020	Not available.
Selection by research team of experts	Triangulation of case studies, project descriptions of safety award–winning projects, and expert brainstorming.	13 passive leading indicators	Hallowell et al., 2013	Human.
Review of the literature	Pertinent literature (18 articles).	15 leading indicators	Neamat, 2019	Human.
Content analysis and Natural language processing (NLP)	Accident investigation reports.	11 leading indicators (upstream precursors)	Shrestha et al., 2020	Human; Machinery; Sites.
Ranking survey answers	Hazard factors identified by Centre for Chemical Process Safety.	10 leading indicators	Baek et al., 2018	Human.
Hybrid method consisting of Delphi method and Focus groups	Data obtained from structured brainstorming of selected experts in focus group study.	41 leading indicators	Erkal et al., 2021	Human; Procedures; Sites.
Authors' conceptual model (based on two Rasmussen's safety models: the model of migration and the sociotechnical system view (STS))	Pertinent literature and Hypothetical project.	32 leading indicators	Guo & Yiu, 2016	Human.
Machine learning	Records of project performance and safety-related data.	Not specified	Jafari et al., 2019	Not available.
Machine learning	Seven years period data of project performance and safety-related records (i.e., monthly inspection records, accident cases, monthly project-related data).	Not specified	Poh et al., 2018	Not available.
Survey of Centre for Chemical Process Safety (CCPS) members	Responds from survey.	23 leading indicators	Kenan & Kadri, 2014	Human; Machinery; Procedures.
Cross sectional analysis	Recordable cases (RC) and days away restricted or transferred (DART).	6 passive leading indicators	Manjourides & Dennerlein, 2019	Procedures.
Ranking through fuzzy model based on experts opinion and Pareto principle	Health and Safety documents (i.e., industry white papers, standards, recommendation and guidance publications) and reports of major accident analysis.	44 leading indicators	Santos et al., 2019	Human; Machinery; Procedures; Sites
Systematic literature review	32 pertinent articles.	16 leading indicators	Xu et al., 2021	Human; Sites; Procedures.
Longitudinal Logistic Regression and Longitudinal Count Regression models	Safety records of 2006–2017 years from Mine Safety and Health Administration (MSHA) database.	3 leading indicators	Yorio et al., 2020	Procedures.
Human Factors Analysis and Classification System (HFACS) approach (to identify human factor) followed by Decision- Making Trial and Evaluation Laboratory (DEMATEL) method and the Analytical Network Process (ANP)	42 safety records of 2007–2018 years from Transportation Safety Board of Canada.	3 leading indicators	Ebrahimi et al., 2021	Human.

tion of training courses (in the operation stage). If the competency level is deemed to be inadequate, similarly a longer time period would be required to correct and adjust the training courses. However, ALIs application is illustrated as a shorter arrow ('Measurement of performances requiring short time period') to convey the shorter time period ALIs take to measure safety and safety culture.

Because the study concludes that the list of leading indicators to be adopted for every organization is unique and distinctive, lagging indicators are regarded as the most appropriate and evidence-based source of material for both leading indicators developments (*i.e.*, PLIs and ALIs). This introspective practice of deducing knowledge from past events (annotated with a white circled letter 'a') is a *terminus a quo* to understand and identify leading indicators that are most relevant to a specific company. Knowledge gained through analyzing lagging indicators allows generation of company-specific leading indicators that are predominantly of a negative nature, such as the measurement of undesirable outcomes (*i.e.*, accident occurrences that reveal gaps, failures, and mistakes in organizational safety management systems) that organizations are planning to avoid. Therefore, the insights and conclusion reached from analysis of lagging indicators must be combined with industry standard documents and latest guidance notes (annotated with a white circled letter 'b'), which enables generation of (positive) expected performance metrics. The mixture of knowledge about conditions to avoid that are observed from lagging indicators (annotated with red half-circular arrow i)

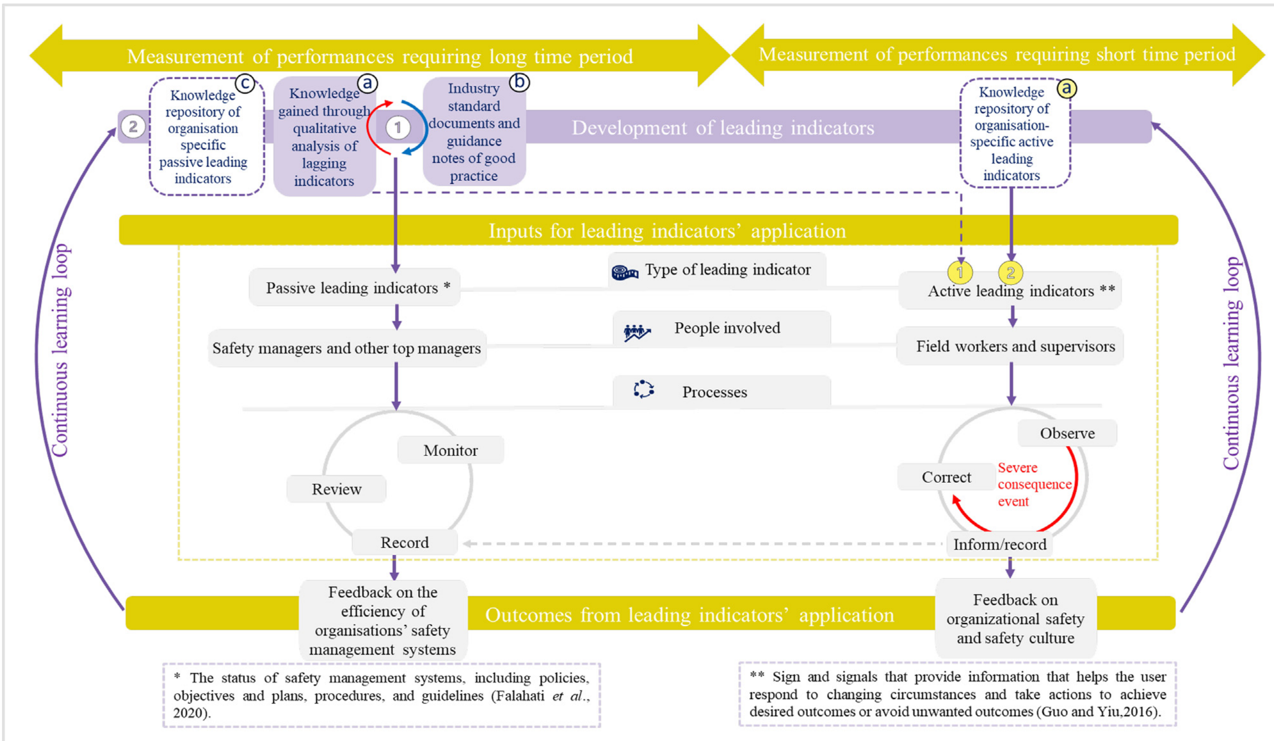

Fig. 3. Conceptual model of leading indicators development and application process for continuous learning organizations.

and normative or desired outcome metrics emerged from industry standard papers (annotated with a blue half-circular arrow), sets the foundation of initial PLIs' development (annotated with white circled number '1′ on the left side of the model).

Analyzing lagging indicators and learning about organizational safety potentials from industry guidance papers helps to identify a large majority of PLIs (e.g., competency or incompetency of workers, *viz.*, quality and efficiency of organization's training programs), which can be fed forward for application (left side of input element) as a first input. The second element of the input is people involved in the application of PLIs, followed by the third element, processes they need to adopt for application. Safety managers and other top managers (who are key decision-makers in company's safety management systems) are the people responsible for PLIs' application by using a cyclical process of monitor-record-review. As a result, application of PLIs generates the outcome (left side of outcome block in the model) of negative or positive measurement, that is, feedback on the organizations' safety management systems (and thus, also serves the functions of recording, assessing, reviewing and learning). The generated outcomes from PLIs' application render a new knowledge for developing and reviewing the existing PLIs (annotated with a white circled number '2′). Therefore, the second round of development or revision process of PLIs after the first-time application will involve three sources, *viz.:* (1) knowledge gained through analysis of lagging indicator (annotated with white circled letter 'a'); (2) industry standard documents and guidance noted of good practice (annotated with a white circled letter 'b'); and (3) knowledge repository of organization specific passive leading indicators (annotated with a white circled letter 'c'). Consequently, these steps of development and application of PLIs engenders an infinite loop of continuous learning by measuring and adjusting already adopted PLIs based on feedback obtained from a previous application(s).

Similarly, short time application (right side of the model) proceeds with identification of ALIs in the development stage and forwarding them for application as the first element of input. Subsequently, fieldworkers and supervisors (as the second element of input) adopt the cyclical process of observe-inform/record-correct (as the third element of input). This, in turn, creates the outcome of feedback (positive or negative) for safety and safety culture through ALIs functions of monitoring, responding, and learning. Similar to PLIs application, the outcome from ALIs application (*i.e.*, feedback on organizational safety and safety culture) generates novel insight for an organization's knowledge repository that contains organization-specific ALIs (annotated with a yellow circled letter 'a' on the model's right side). However, there are two main differences in the process of development and application of ALIs and PLIs. The first contrast to PLIs development is that ALIs development occurs in the process of application because it is an emergent leading indicator. Nonetheless, initial insights as to how to identify ALIs can be obtained from existing lagging indicators of that company (arrow heading to a yellow circled number '1′ on the right side of the model). Therefore, due to their emergent nature of ALIs, the model adopts the definition of ALIs as signs and signals that provide information to support users to respond to changing circumstances and take corrective actions to achieve desired outcomes or avoid unwanted outcomes (Guo & Yiu, 2016).

The second difference is in the process element of ALIs' application, where depending on the observed event, different steps might be taken. In case of a positive event being observed (*viz.* success), the event must be recorded in the safety management system for recognition (arrow heading from 'inform/record' step of ALIs' application side to 'record' step on the PLIs' application side). In such instance, ALIs serve the function of learning (from success), alongside the service of monitoring safety in real time. Conversely, a negative occurrence of different severity and emergency level might require immediate action of correction (red arrow on processes element of ALIs application), followed by observation of that correction and then the recording step. Alternatively, if the observer decides (to their best knowledge at that moment) that the negative occurrence has minor consequences and requires a team to correct it, then the observer must inform the workers who will be impacted by the action and then correct, observe, and record the incident/event.

This model of developing and implementing leading indicators attempts to change the common approach of trying to fit work-as-done (WAD) to work-as-planned (WAP), towards adapting the WAP based on the conditions and circumstances of work being performed. Since the condition and circumstances of sociotechnical systems (*i.e.*, construction projects) are dynamic and volatile, only guidance and feedback obtained through leading indicators can reveal the changing nature of the work environment and complex interaction of system elements (human, machinery and site). The model provides a signpost to what can be achieved through diligent collection of data by observing the complex and tightly coupled work environment; but without application and empirical studies, the model remains as a mere blueprint. Therefore, the model's development achieved through inductive reasoning (and premised upon pertinent literature) requires deductive application and validation using real-life case studies (as opposed to perceptual type studies implemented). Future empirical studies based on this model will intrinsically generate more knowledge about ALIs – *per se*, an area recognized to have a notable dearth in current literature.

Limitations of the study must also be noted, namely, the keyword search terms upon which the model is derived was limited to very specific terminologies used (*viz.* "leading indicators" and "safety management"). It could be argued that a broader search of literature (encompassing a wider range of keyword terms) could have introduced further perspectives into the theory build presented in this current research. Conversely, such an approach could also have diluted the research outputs (namely, new theory presented) reported upon. The choice of keywords is a notable limitation of the interpretivist philosophy because it is premised upon the individual researcher's subjective perspective and possible bias – a limitation widely acknowledged within literature (cf. Roberts & Edwards, 2022). This limitation must, however, be balanced with the advantage of generating new theory based upon existing published research that has already been validated (via a robust peer review process). Hence, the interpretivist approach is often more reliable and trustworthy than other philosophical stances (cf. Dudovskiy, 2018).

6. Conclusion

Construction accidents and injuries continue unabated across the globe despite the historic and considerable investment in research, training, technological, and legislative developments. To reverse the direction of this well-trod chartered path, a new modus operandi is needed to generate fresh insight and engender wider polemic debate. The work presented in this paper acts as a catalyst for that change and signposts much-needed new direction for future research.

6.1. Theoretical contribution of the study

Compilation and deduction of leading indicators' constructs (*i.e.*, definition, classification and development methods) from extant literature adds a valuable theoretical contribution to advancing the wider body of knowledge on leading indicators. The study concludes that inconsistency in leading indicators' definitions and functions are related to the difference between two types of leading indicators, namely passive leading indicators (PLIs) and active leading indicators (ALIs). PLIs measure and assess the elements of organizational safety management systems (e.g., the efficiency of training programs or contractor selection methods, impact of adopted preventative steps or designed work process). Whereas ALIs measure or unravel granular and dynamic elements of safety, such as preventable and correctable early signs of possible negative or positive events that arise from ongoing operations and decision makings. Therefore, focusing on ALIs as a proactive safety management serves as a gauge for ever-changing/fluctuating and unpredictable status of safety and risk in complex sociotechnical type workplaces. However, ALIs studies remain strikingly scant - only 4 out of 93 publications (included for this study) focus on this type of leading indicators. Given the capacity of ALIs to generate knowledge and immediate feedback from the action being performed in the operation stage (which allows close to real-time monitoring of safety or unsafety), more studies on their theoretical and practical applications are needed.

6.2. Practical contribution of the study

As a practical contribution, the conceptual model guides adopters of leading indicators how to differentiate the types of leading indicators (*viz.*, passive leading indicators and active leading indicators) and informs the process of developing, adopting, and implementing the two types of leading indicators. Consequently, the infinite loop of development and application of leading indicators, which encourages continuous learning of organizations (introduced in the model), will be invaluable for adopters to generate their own knowledge repository of leading indicators and to continuously learn and improve their safety and safety performance.

In terms of applying the conceptual model offered by this study, there are number of considerations that organizations must include to effectively adopt leading indicators as their safety performance measurement. Although an organization's lagging indicators and industry white papers are important sources (and constitute the starting point to develop leading indicators), a pivotal step prior to that is to comprehensively understand the main features of leading indicators by their definition, function, focus, and types. Without this knowledge, efficiency of developed leading indicators will remain questionable (regardless of the source of materials used to develop them) and hence, understanding the constructs of leading indicators is a first priority for adopting organizations.

The next priority for companies adopting leading indicators must be to improve recordings of lagging indicators. Since lagging indicators are a crucial source of knowledge for the development of organization-specific leading indicators, the efficiency and accuracy of these are determined by the accuracy and quality of lagging indicators' recordings. Furthermore, it must be highlighted that leading indicators are not an absolute measure of safety, but rather an indicative and guiding signal with which safety, safety culture, and safety performance of organizations can be monitored. Therefore, for a comprehensive observation, the development of leading indicators must encompass different elements of complex sociotechnical systems (*viz.* workers, machinery and sites) on different levels (organizational and procedural level), since accident(s) occurrence is the result of multiple sources of factors that are unpredictable and emergent.

Another caveat for efficient adoption of leading indicators is to measure them qualitatively as well as quantitatively in order to capture the breadth and depth of information. Instead of merely measuring frequency of positive or negative occurrences, the focus must be on observed elements/events themselves through continuous monitoring and anticipation by frontline workers.

Lastly, the knowledge about leading indicators' (particularly ALIs) constructs must be efficiently conveyed to frontline workers (through hands-on training and practices) because they are the stakeholders who are exposed to real challenges of changing work environment. Therefore, frontline workers play an important role in: observing the changing signs and signals; 'reading' those leading indicators in the work environment; and acting in a timely manner to correct unsafe observations or acknowledging and recording positive occurrences. The knowledge about leading indicators can be introduced on routine check sessions, by involving frontline workers in the process of detecting leading indicators. New theory development is the basis upon which progress is made. Hence, the importance of the present study in challenging existing knowledge and suggesting alternative approaches to enhance safety (to mitigate accidents) within society.

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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