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Review

Unravelling the Gordian knot of leading indicators

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ABSTRACT

With the aim of developing a new theoretical insight which will augment the promulgation of leading indicators' use, this present research studies pertinent literature. Associated study objectives are to: 1) generate insight into potential challenges, use and benefits of adopting leading indicators in safety management from pertinent literature; and 2) elucidate upon existing abstruseness between safety leading and lagging indicators. For an extensive and thorough literature analysis, two consecutive data analysis methods are adopted (*viz*., thematic and content analyses). Through thematic analysis, 13 clusters (each representing different uses of leading indicators) emerged, from which the 'health and safety' cluster was selected for a deeper analysis in content analysis. In addition, by reviewing the compendium of leading indicator examples collected from extant safety leading indicator literature, novel types of dichotomous leading indicators were identified, *viz*., *generic* and *specific* leading indicators. Subsequently, a synthesis of challenges and benefits of safety leading indicator adoption was generated through deductive content analysis. Furthermore, a new theoretical explanation into the relationship of safety leading and lagging indicators is proffered which also incorporates safety management dynamics representing different levels of safety maturity. This study constitutes a first attempt to: provide a structured synthesis of safety leading indicators' functions along with their challenges in development, implementation and adoption stages; shed a new light into the theoretical explication of safety lagging and leading indicators' relationship; and introduce safety management dynamics that establish different levels of safety maturity.

1. Introduction

There is increasing awareness amongst scholars, safety experts and practitioners about the importance and role of 'weak signals' to establish proactive safety management (Grabowski et al., 2007; Mousavi et al., 2018). These weak signals are more commonly known as leading indicators (LIs), although other synonymous terms (such as proactive indicators or heading indicators) exist to denote them (Drupsteen and Wybo, 2015). However, this inconsistency is not limited to how LIs are termed, but also their definition, function, characteristic, structure, specification, use, development method and development source are portrayed differently by scholars (Guo and Yiu, 2015; Sheehan et al., 2016; Xu et al., 2021). Moreover, these incongruities are compounded by the notion that the nature and function of LIs are deemed overlapping with their counterpart *viz*., lagging indicators (Sheehan et al., 2016; Patriarca et al., 2019). This ambiguity and the finer nuances existing between leading and lagging indicators has drawn attention from numerous safety experts and academics (Podgórski, 2015; Swuste et al., 2016; Santos et al., 2019). In addition to publications that contrast and extrapolate leading and lagging indicators, the Bowtie and Safety pyramid (also called Process Safety Indicator Pyramid) models also provide some explanation of the relationship that exists between these two indicators (Hudson, 2009; Samuel and Das, 2015; Zhen et al., 2022). For example, the Bowtie model describes LIs as information occurring prior to the event, which is at the centre of the bowtie shape and lagging indicators are denoted as the outcomes of the event (Mearns, 2009; Hudson, 2009; Schmitz et al., 2021; Bayramova et al., 2023). However, this conventional distinction between leading and lagging indicators does not universally apply to all examples of indicators (cf. Lingard et al., 2017; Oswald, 2020). For instance, there is a convergence in the

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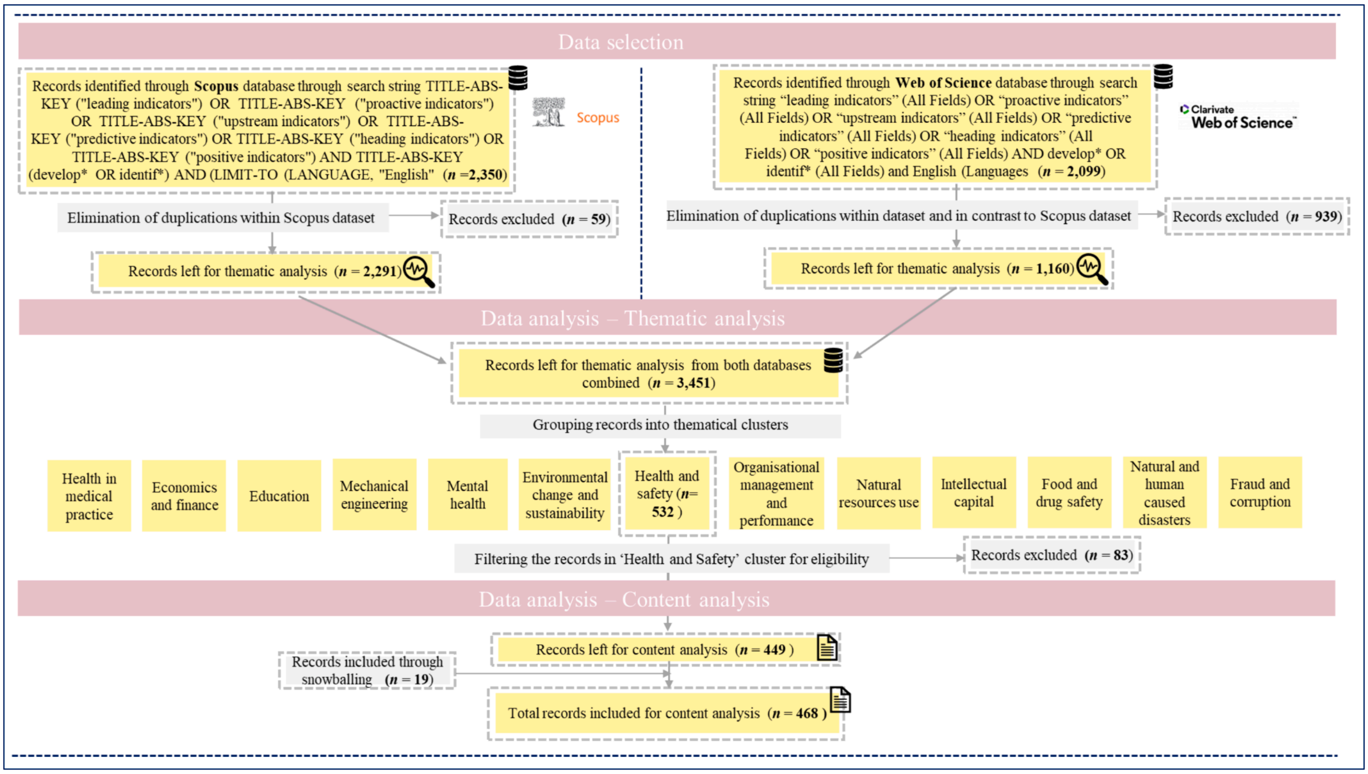

Fig. 1. Data selection and data analysis steps.

identification and use of an indicator such as near miss events, which in some cases can be referred to as a leading and others as a lagging indicator (Knijff et al., 2013; Haas and Yorio, 2016). For example, a near miss event such as slip or trip can be classified as a lagging indicator which occurred as a result of poor housekeeping at the worksite or it can serve as a LI informing about the potential occurrence of a much more severe accident (*ibid*).

This and many other nebulous details of LIs (such as development method, identification or selection of LIs) hinder their widespread adoption in safety management (Hudson, 2009; Guo and Yiu, 2015). Furthermore, the context in which LIs are being applied (i.e. safety management) engenders some inherent hurdles (Mengolini and Debarberis, 2008). Specifically, using LIs in its original provenance, i.e. in economics where a measured object is of quantitative and explicit nature is different from using LIs to measure an incorporeal object such as safety (Guo and Yiu, 2015; Oswald, 2020). Therefore, this current study reviews pertinent literature to provide more clarity about LIs, their adoption, their potential use in safety management and their challenges. Associated objectives are to: 1) identify potential challenges, use and benefits of adopting LIs in safety management; and 2) clarify any existing abstruseness between leading and lagging indicators. As a result of these findings, a new theoretical explanation of LI's potentials are introduced to enhance the extrapolation of proactive safety management and add much-needed clarity in the practice of becoming continuous learning organisations.

2. Methodology

To systematically review extant literature on 'LIs development and identification', the current study adopts an interpretivist philosophical stance (Denscombe, 2021; Golzad et al., 2023) and both inductive and deductive reasoning in sequence (Bayramova et al., 2021; Posillico et al., 2023) to generate a new theory by drawing insights embedded in the existing discourse (Fellows and Liu, 2022). Interpretivism enables a rich and in-depth study of the phenomenon being investigated through inference and interpretation; where knowledge and reality are deemed to be inter-subjective and are socially constructed through multiple meaning (Saunders et al., 2019; Clark et al., 2021; Collis and Hussey, 2021). Although not stated openly, an interpretivist epistemological view is an extensively adopted philosophical stance in the literature of safety management (cf. Borys, 2012; Alsamadani et al., 2013; Hallowell et al., 2013) which enables the generation and advancement of new knowledge and understanding based on diverse point of views.

The study adopts a sequential exploratory research design, where the process is performed in two consecutive steps. Step one adopts a thematic analysis for an extensive study of the literature through inductive reasoning, whereas step two involves analysing the data within the selected cluster through content analysis by utilising deductive reasoning for an in-depth analysis (Collis and Hussey, 2021). Consequently, the interpretivist philosophical stance predominates in both steps: in step one (i.e. thematic analysis), classification and grouping of publications and decisions taken on their relevance or otherwise to the research aim and objectives are performed through subjective interpretation of the data available in the literature; and in step two (i.e. content analysis), to identify any existing main challenges and benefits of LI via inference (Clark et al., 2021). As Elo and Kyngäs (2008) state, emergent outcomes from content analysis create new knowledge, insights and novel representation of facts, regardless of whether the analysis has been conducted inductively or deductively. The authors (*ibid*) also differentiate between *deductive content analysis* which involves coding the dataset according to preset categories from *inductive content analysis* that entails the process of open coding and creating categories as they emerge through the dataset and accordingly abstraction of categories. For this present study, selected *deductive content analysis* enabled the identification of common challenges and benefits of using LIs in safety management.

Bibliometric data accrued was obtained from Scopus and Web of Science (WoS) journal databases. Combining two databases is a common approach amongst scholars who adopt a systematic literature review because it allows inclusion of complementary publications that are

Table 1
Examples of leading indicators descriptions that denote their functions.

Description or definition of leading indicators that reflect their functions	Authors
The goal of leading indicators for safety is **to identify the potential for an accident before it occurs**.	Leveson, 2015.
The purpose of leading indicators is **to understand and manage the organizational circumstances thought to precede undesired occupational health and safety outcomes**.	Haas and Yorio, 2015.
The information gathered can not only **identify holes in your safety systems but can also be used as a positive safety metric to be shared with employees**.	Pettinger, 2013.
A measure or combination of measures that **provides insight into an issue or concept**.	Rhodes et al., 2009.
There are four main characteristics of leading indicators, namely: 1) *time frame*, the capacity of leading indicators **to precede the accident, incident or injury**; 2) *predictive value*, the ability of leading indicators **to predict the occurrence of negative event**; 3) *proactivity*, the capability of leading indicators **to proactively prevent and intervene with corrective action**; and 4) *measurability*, the facility of leading indicators **to evaluate safety performance**.	Akroush and El-Adaway, 2017.
The condition, the event or the measure that has some value **in predicting the occurrence of the undesirable event**.	Grabowski et al., 2007.
Something that **provides information about undertaken activities on the antecedents of safety performance**.	Mousavi et al., 2018.
Leading indicators are intended **to provide insight into the probable future state, allowing projects to improve the management and performance of complex programs before problems arise**.	Rhodes et al., 2009.
Leading indicators are **proactive measures of performance before any unwanted outcomes have taken place**.	Dyreborg, 2009.
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.
Leading indicators are those on which **the organisation can act to leverage achievement of the organisational goals monitored by the lagging indicators**.	Mengolini and Debarberis, 2008.
An indicator is leading if it **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.
Leading indicators **not only predict negatives (incidents, accidents and errors) but also success**.	Alexander et al., 2017.

relevant to the phenomenon being studied (cf. Barbosa et al., 2019; Xu et al., 2021; Ali et al., 2022). This systematic approach also helps to mitigate researcher induced bias when using an interpretivist philosophical stance (Posillico et al., 2022). Bibliometric data from Scopus journal database were retrieved through search string of (TITLE-ABS-KEY (“leading indicators”) OR TITLE-ABS-KEY (“proactive indicators”) OR TITLE-ABS-KEY (“upstream indicators”) OR TITLE-ABS-KEY (“predictive indicators”) OR TITLE-ABS-KEY (“heading indicators”) OR TITLE-ABS-KEY (“positive indicators”) AND TITLE-ABS-KEY (develop* OR identif*) AND (LIMIT-TO (LANGUAGE, “English”)). A total of 2,350 bibliometric details of publications were returned from Scopus journal database which contained ‘authors’, ‘title’ ‘year of publication’, ‘DOI’, ‘abstract’, ‘authors’ keywords’ and ‘index keywords’. As described in Fig. 1, all the bibliometric data were filtered for duplicates and 59 duplicate items were eliminated.

Similarly, bibliometric data from the WoS journal database were sourced via the same search string of (“leading indicators” (All Fields) OR “proactive indicators” (All Fields) OR “upstream indicators” (All Fields) OR “predictive indicators” (All Fields) OR “heading indicators” (All Fields) OR “positive indicators” (All Fields) AND develop* OR identif* (All Fields) and English (Languages) and returned 2,099 relevant publications. Items from the WoS were filtered for: duplicates within the dataset; and duplicates that already appeared in the Scopus database (consequently, 939 items were eliminated and 1,160 items remained). A cumulative total of 3,451 publications (2,291 items from Scopus journal database and 1,160 items from WoS) were included for thematic analysis. Exclusion of the records prior to thematic analysis step (i.e. $n = 59$ items from Scopus and $n = 939$ items from WoS; $n = 998$ items in total) were performed based on duplicate items only. Thematic analysis was conducted by: manual scanning of bibliometric data; colour-coding the bibliometric details of publications; and clustering them thematically in a Microsoft Excel spreadsheet. In the process of thematic analysis, 13 thematical clusters emerged from which the ‘*health and safety*’ cluster containing 532 publications was selected for full-text retrieval. This step of selection (i.e. including only ‘health and safety’ cluster for further analysis) was performed in accordance with set research aim and objectives of the study. Only 449 items were eligible with full text and hence, were included for further content analysis (whilst $n = 83$ items were excluded due to ineligibility). Furthermore, 19 items from issue 4 of the Safety Science journal (2009) were included as highly relevant, since these publications extensively discuss the relationship between leading and lagging indicators. Consequently, a total of 468 publications were analysed through content analysis using NVivo computer-assisted qualitative data analysis software (CAQDAS) which allows compiling emerging categories, themes and concepts throughout all items by coding into nodes. This content analysis step yielded a compendium of LIs examples, in addition to the synthesis of the challenges and benefits of LI use.

3. Measuring safety and predicting unsafety

LIs’ usage is widespread; from food and drug safety (cf. Lauková et al., 2020; Assiri et al., 2022), economics (cf. Vašíček et al., 2017) to environmental changes (cf. Carr et al., 2012) and education (cf. Thomson et al., 2020). The object or target being measured through LIs in these fields (whether for the purpose of avoiding or achieving a certain outcome) represent impalpable, nonphysical phenomena (i.e. imminent ‘black swan’ threats such as economic recession, disease outbreaks, natural disasters or risk of accident or unsafety) that are difficult to discern and measure directly, promptly or conclusively (Hudson, 2009). These phenomena occur in a closed system (i.e. systems like a black box such as human health) or in an open dynamic system (i.e. complex systems that has no definitive boundaries or state, such as construction projects) (Grenn et al., 2014; Read et al., 2021). These objects are being measured through LIs for various reasons *viz.*: 1) the length of time between the action or influence taken and their consequences is long and difficult to correlate (Mengolini and Debarberis, 2008); 2) the object being measured occurs by the impact of multigranular, multilevel and multifarious elements (Leveson, 2015); 3) manifestation (or otherwise) of those measured objects are not easily controlled/influenced or tracked (Arnold, 2015); and 4) the object being measured requires continuous monitoring, since the measurement (or the state of the object) is dynamic over time (Haas and Yorio, 2016). Measurement of safety falls under all these four categories, since safety is dynamic over time (Leveson, 2015), not easily discernible or sampleable (Hudson, 2009), the impact of steps taken to improve safety takes longer time to measure (Ale, 2009). Moreover, safety occurs or fails to occur due to multifaceted and nuanced interplay of multifarious elements (Mousavi et al., 2018). Hudson (2009) highlights some of the intrinsic impediments to measuring safety, namely: lack of a theoretically coherent framework of how and why accidents happen; and the inherent difficulty associated with the timescale of outcomes, where workers find it incomprehensible that their actions or inactions have an impact on the safety outcome. Furthermore, Mengolini and Debarberis (2008) cite the paradox associated with safety which states that the success or return from efforts put to maintain safety is not visible or measurable, since the

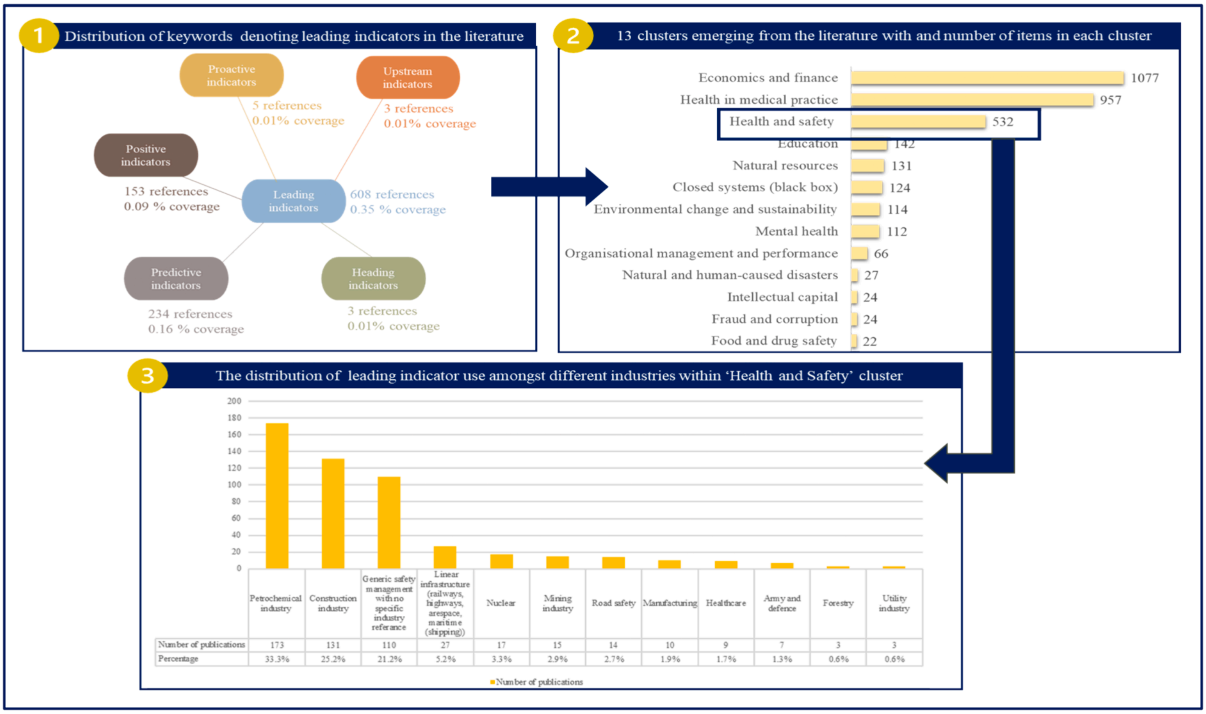

Fig. 2. Coverage of keywords in the literature (1); 13 clusters emerging from the literature with their quantities (2); and the use of leading indicators in safety management distributed amongst different industries (3).

outcome from enhancing safety is indiscernible. The authors (*ibid*) highlight that due to this reason, organisations tend to opt for a more solid measurement of safety, i.e. lagging indicators (which reflect the outcome or past performance of safety). Such an approach (i.e. using only lagging indicators) denotes: the measurement of safety or success by association (Grabowski et al., 2007; Oswald, 2020); monitoring and tracking unsafety (Khan et al., 2010; Raben et al., 2018); and being guided by outcomes only (Almost et al., 2019; Xu et al., 2023). However, safety is not a binary state of its presence and absence; rather there is a 'grey area' or period between those two, where the condition might not be safe but an accident has not yet manifested (Guo and Yiu, 2015). This 'grey area' is also referred to as '*drifting to danger or disaster*' (Zwetsloot et al., 2014) '*slow deterioration of the process*' (Mengolini and Debarberis, 2008) or '*false comfort zone*' (Kleindorfer et al., 2012). Rasmussen's model of migration is a prominent example describing this blurred boundary between safety and unsafety, where systems may become prone to degenerate over time and members involved may feel a false sense of safety and become less heedful (Kleindorfer et al., 2012; Read et al., 2021). Hence, the role/function of LIs becomes an invaluable solution for organisations focusing upon improving their proactivity in safety management and becoming continuous learning organisations by: 1) informing about deviations and changes in safety in that trans-boundary area; and 2) serving as a weak signal of imminent vulnerabilities and shortcomings in safety practices in a timely manner.

3.1. Functions of leading indicators

Apart from definition, characteristics or typology of LIs, their functions are a key construct or important feature to expound such concept, especially for their adoption stage (Rhodes et al., 2009; Sheehan et al., 2016; Bayramova et al., 2023). Yet, functions of LIs described in the literature are multifarious. Alexander et al. (2017) focus on LIs' function to measure and predict positives (i.e. success in maintaining safety, resilient capacity and continuous learning) rather than solely concentrating on negatives (i.e. incidents, accidents and errors). Quigley et al. (2012) emphasise the two characteristics of LIs that provide a measurable indicator: first, as a feedback about the process compliance to a specified performance standard; second, as a predictor of future process problems. Laitinen et al. (2013) similarly highlight the feedback function of LIs, calling for development of real-time *outcome LIs* instead of *activity LIs* such as number of safety audits conducted, number of workers trained or number of risk assessments completed. Whereas Guo and Yiu (2015) accentuate two, informative and decision aiding functions of LIs' *viz.* their ability to: 1) provide information about the state of safety; and 2) help decision makers take remedial actions. The authors (*ibid*) state that these two functions are an important feature of LIs for promotion of double-loop learning which involves reflecting upon any existing safety model and enabling the construction of a new model and explanation through continuous validation. Functions of LIs are also reflected upon in the studies focusing on their definitions and characteristics. Table 1 exemplifies some of the definitions and descriptions of LIs which implicitly reflect their functions.

Bolded areas of the text in the first column of Table 1 highlight some of the functions of LIs. Most commonly, LIs are described to have a predictive, interventional and corrective functions. Xu et al. (2021) perform similar exploration of definitions, characteristics and functions of LIs but in reverse i.e. the study develops a working definition of LIs by studying some of the characteristics and functions of LIs. Many scholars (Zheng et al., 2019; Xu et al., 2021; Salmon et al., 2022; Haji et al., 2022) agree that LIs are unique to every company based on their: safety management systems; safety culture maturity level; and allocated resources for safety management (to develop LIs) and hence, cannot be generalised. Therefore, to adopt LIs as a gauge of safety, two points become fundamental requirements for successful LIs implementation and adoption, namely to: 1) understand the meaning and purpose of LIs rather than merely adopting previously generated LIs from other companies; and 2) consider capabilities and weaknesses of the organisations (i.e. safety maturity level of organisations) that are planning to adopt LIs.

Table 2
Challenges and considerations associated with stages of development, implementation and adoption (use)of leading indicators.

Stages	Challenges and precautions	Considerations and potential solutions
Development of leading indicators	Lacking consensus on the definition, purpose and type of LIs and the indicated phenomena (i.e. safety), and absence of clear guidance or tool on how to develop LIs (Guo and Yiu, 2015; Akroush and El-adaway, 2018; Haji et al., 2022).	Successful utilisation of LIs requires three solutions viz.: 1) a clear conceptual framework for deriving LIs and their associated set of purposes; 2) a selection process that determines which LIs are to be applied and how; 3) a specification of how LIs fit into management and decision-making processes (Guo and Yiu, 2015).
	Avoiding fragmented or single level view on LIs and their effect on safety performance (Xu et al., 2021).	LIs should be developed to describe and monitor specific safety conditions through a systematic development process where safety conditions are viewed as a dynamic phenomenon created, improved, and maintained by safety practices (Guo and Yiu, 2015).
	Removing or significantly reducing biases in the process of developing, selecting, using and measuring LIs (Leveson, 2015).	While heuristic biases cannot be eliminated, a structured method for identifying, detecting, and managing LIs can reduce the impact of our biases (Leveson, 2015).
	Tending to use only statistically sensible data by safety managers hinders recognition, identification or effective use of LIs (Hopkins, 2009; Haji et al., 2022).	While a quantitative indicator can be useful for benchmarking, a qualitative indicator provides deeper explanation of the how or why and opens opportunity for improvement by providing insightful context (Mengolini and Debarberis, 2008; Oswald, 2020).
	There is no specific set of LIs to monitor safety and safety culture (Mengolini and Debarberis, 2008).	LIs should be developed for: product/element level, system level and system of systems level because every level requires a different set of LIs (Rhodes et al., 2009).
	Avoiding adoption and use of LIs by directly sourcing from other projects, organisations or industries without adjustments (Xu et al., 2021).	Since safety management within each organisation is unique and contextual, organisation or project specific LIs must be considered (Xu et al., 2021).
	The difficulty in developing any theoretically well-motivated indicators that can be 'objectively' linked and shown to predict actual major process incidents prevents the generation of effective and believable LIs (Hudson, 2009).	Initially, conditions impacting safety changes must be studied. After which LIs should be developed based on the assumptions generated (i.e. how safety is changing) (Leveson, 2015).
Implementation of leading indicators	Difficulty to convey to users in worksites the constructs of LIs (Costin *et al.*, 2019).	To develop established, learnt and shared understanding of: what is normal, expected and desired (versus what is not normal, unexpected and undesirable); what to observe, monitor, expect and fear when experiencing LIs in worksites (Costin *et al.*, 2019).
	Due to similarity to classical metrics in the base measures collected, it may be difficult to secure a buy-in from an organisation's management and practitioners to use LIs as they may be superficially dismissed as "something we are already doing." (Rhodes et al., 2009; Akroush and El-adaway, 2018).	Project leadership teams should: 1) self-determine (with input from their safety professionals and workers) the LIs needed to drive higher levels of performance; and 2) be willing to hold themselves (and their respective teams) accountable for sustained performance improvement (Toellner, 2014).
	Effective ways to present the information in a concise and graphical form are required to address the specific information needs of the organisation or project to augment effective decisions (Rhodes et al., 2009; Toellner, 2014).	Data must be presented in an unambiguous fashion (Toellner, 2014).
	A dearth of information about LIs' validation hinders their extrapolation (Rhodes et al., 2009).	In the early phases of LI use, the individual organisation still should further validate the conditions under which a LI can be most useful in their organisation by observing its usefulness in various programmes over time (Rhodes et al., 2009).
	The fact that interpretation of LIs is a blend of statistical analysis and subjective assessment based on experience (Rhodes et al., 2009).	Guidance to tailor LIs to the project environment and usage experience must be carefully developed with highly knowledgeable staff or subject matter experts (Rhodes et al., 2009).
	It may be difficult to secure leadership support for using high level engineering talent for a "task" (for interpreting the collected data, i.e. LIs) that was previously performed by junior analysts (Rhodes et al., 2009).	The effective use of LIs requires: a systems engineering programme in order to gather and analyse the indicators; dedicatation of experienced personnel's time to the interpretation of the resulting information. Utilising indicators for real-time management of programmes requires decision making using this information at all levels (Rhodes et al., 2009).
	Deciding whether to use LIs as standalone, combined or aggregated sets could become challenging (Rhodes et al., 2009).	Selecting appropriate LIs in the context of organisational factors is a rich area for future research. Future studies must focus on: understanding the relationships between the LIs; whether it is possible or necessary to find appropriate ways to aggregate LIs; and when aggregation should not be undertaken (Rhodes et al., 2009).
	Adequate training must be developed for these indicators to obtain a wide level of infusion across industry. This includes two	Decision-makers should receive a short course focused on describing LIs, the utility of the indicators, and the resources needed to

(*continued on next page*)

Table 2 (*continued*)

Stages	Challenges and precautions	Considerations and potential solutions
	levels of training, one for the decision-makers and one for the measurement practitioners (Rhodes et al., 2009).	implement them. Practitioners training courses should focus on selecting the optimum indicators, how to analyse and interpret for leading insight rather than lagging insight, and detail discussion and exercise for the indicator (Rhodes et al., 2009).
Adoption (use) of leading indicators	A critical aspect of adopting LIs is their potential manipulation when corporate safety culture is not firmly established. The focus on "*what can be measured*" rather than "*what should be measured*" might have a misleading impact on understanding and management of systems' states (Hudson, 2009; Patriarca et al., 2019).	To adopt a dynamic and agile methodology which allows to continuously identify and refine the most appropriate LIs (Patriarca et al., 2019).
	Difficulty in determining an accurate forecast of accidents due to the complexity and abundance of variables in safety systems constitute an obstacle in LIs use (Mengolini Debarberis, 2008; Guo and Yiu, 2015; Akroush and El-adaway, 2017).	During the implementation process, LIs should be continually improved and adjusted by comparing the results with the intended effects (Akroush and El-adaway, 2017).
	Data collection takes time and the lack of a centralised repository to build a core history overshadows potential benefits of using LIs (Rhodes et al., 2009; Guo and Yiu, 2015).	Collecting LIs and other contextual data in a centralised database enables establishment of safety analytics where organisations can identify holes in their safety systems and provide a source of positive safety metrics for employees (Pettinger, 2013).

4. Analysis and findings

LIs have many other synonymous expressions such as proactive indicator, heading indicator, positive indicator, upstream indicator and predictive indicator (Hinze et al., 2013; Haas and Yorio, 2015; Robson et al., 2017; Xu et al., 2021). Fig. 2 describes (section 1 in the figure) occurrences of synonymous expressions for LIs with their coverage (in percentage) in the literature and frequency (*f*) of references in the publications that were selected in this study. Both the coverage and number of references indicated in the figure was determined by examining the abstracts of selected publications in text search query using NVivo. A '*predictive indicator*' is the most frequently used way of describing LIs (with 0.16 % coverage and $f = 234$ references), followed by '*positive indicator*' (with 0.09 % coverage and $f = 153$ references). This is also related to the difference in the use and application of LIs in various fields. For example, reference to LIs as a '*proactive indicator*' is most common in safety management use, whereas reference as '*predictive indicators*' is prevalent in healthcare in medical practice. However, such specific reference and use of LIs are not exclusive to the clusters described and reference to LIs in the safety management context can be equally described as leading, proactive or upstream indicators.

In addition, all 13 emergent clusters that were identified through thematic analysis are illustrated in section 2 of Fig. 2 and represent those different applications or areas of LIs use. The most prominent use of LIs is in economics and finance ($f = 1{,}077$ articles); followed by its application in monitoring health in medical practice ($f = 957$ articles); and then in safety management ($f = 532$ articles). As numerous scholars state (cf. Haas and Yorio, 2015; Walker and Strathie, 2016; Patriarca et al., 2019; Oswald, 2020) the concept of LIs derives from the field of economics and was later adopted to use in safety management. Falahati et al. (2020) cite that the use of LIs in safety management was pioneered by the nuclear industry and followed by chemical process and petroleum industry. For example, guidance notes (about how to adopt and use LIs) published in the nuclear and chemical industry by institutions such as the Organisation for Economic Co-operation and Development (OECD), International Atomic Energy Agency (IAEA) and World Association of Nuclear Operators (WANO) showcase early adoption of LIs (Mengolini and Debarberis, 2008). Patriarca et al. (2019) mention that the induction of LIs in safety management practices expanded post the Baker report on the British Petroleum (BP) Texas City explosion event (cf. Baker et al., 2007). Akroush and El-adaway (2017) allude to the use of LIs in the safety management of construction projects by referring to the work of: Hinze and Hallowell (2013) which identifies 50 active LIs; the Construction Industry Institute (CII, 2012) research which registers 100 passive LIs; and Rajendran and Gambatese (2009) which finds around 300 different LIs.

Therefore, to identify the distribution of LI use/research amongst the safety critical industries with high-risk activities, the '*health and safety*' cluster (from those 13 clusters included in section 2 of Fig. 2) was selected for further analysis. By reviewing the bibliometric details of all 532 items that focus on LIs in health and safety, 13 different subclusters were generated based on the industry or sector each item is representing. 12 of them represent industry-specific studies and one subcluster describes generic use of LIs (no specific industry reference). Section 3 of Fig. 2 illustrates that petrochemical ($f = 173$ items) and construction ($f = 131$ items) industries are respectively on top of the list. Whereas 110 items from the total of 532 publications concentrate on LIs' use in health and safety generically, rather than focusing on one industry use. For example, these studies are directed towards: validation of LI examples; application of LIs in complex systems; or classification of LIs. Next on the list is the group of linear infrastructure ($f = 27$ items) which contains LIs use in health and safety of railways, highways, aerospace and maritime, followed by nuclear industry with 17 publications.

4.1. Examples of leading indicators in pertinent literature

An extensive review was performed to identify then tabulate (in Microsoft Excel) a critical mass of LI examples during the content analysis step; LI examples containing 2,423 items were consequently generated. The table created consists of 4 columns, *viz.*: 1) article citation (i.e. authors' last name and year of publication); 2) number of LI examples identified in each article; 3) LI examples; and 4) description/elaboration of each LI example (as exemplified in Appendices). The description column contains different content *viz.*: some of the LIs are described and measured through an equation (cf. Peñaloza et al., 2021; Quaigrain and Issa, 2021); and others provide descriptive instructions of how to use and measure that LI example (e.g. '*continuous improvement*' LI is described as '*simplifying incident reporting by generating incident reporting flowchart from 10 + page document*'). Most indicate to elements of safety, such as *safety culture* (cf. Santos et al., 2019; Abubakar et al., 2021), *safety management* (cf. Hallowell et al., 2020; Ali et al., 2022) or *safety leadership* (cf. Reiman and Pietikäinen, 2012; Guo and Yiu, 2015). Structurally, LI examples themselves are in the form of: a word or phrase (such as, *competence*, *communication* or *senior management commitment*) (Almost et al., 2019); a statement that is concerned about presence or absence of certain condition, activity, situation or task, e.g.: '*supervisors undergo safety leadership training*', '*there is a substance abuse program set in place and advertised to workers*', or '*workers' observations are recorded and*

Table 3
Summary of leading indicators' functions with their corresponding type and source and method to achieve each function.

Function Number	Examples of leading indicator function	Type of leading indicators that are appropriate for the function	Method and source of information used to achieve the function
F1.	To indicate to generic points (or safety elements) in safety management that were not considered (i.e. to identify unknown unknowns).	Generic leading indicators	Generic LIs can be identified through review of relevant normative documents and research publications at an early phase of LI adoption.
			Generic LIs can be identified through a review of dataset contained within centralised database of LIs at a later phase of LI adoption.
F2.	To identify unknown practices or factors for achieving safety or preventing unfavourable occurrences.	Specific leading indicators	Organisations can develop specific LIs through a review of relevant normative documents and publications with best practices at the early phase of LI adoption.
			Organisations can identify specific LIs through a review of the dataset contained within a centralised database of LIs at the later phase of LI adoption.
F3.	To continuously monitor safety.	Active leading indicators	At an early phase of LIs adoption, active LIs can be collected through frequently arranged safety observations, safety inspections and safety monitoring at the operations stage
			At the later phase of LIs adoption, active LIs are continuously collected in real time at the operations stage by training staff to recognise them.
F4.	To prevent occurrences of unfavourable events/outcomes.	Active leading indicators + Passive leading indicators	At an early phase of LIs adoption, by training staff (who are conducting safety observations, safety inspections and safety monitoring at the operation stage) to how to: 1) apply timely corrective measures through recognising active LIs and 2) eliminate unfavourable and timely uncorrectable events, conditions or activities through recognising passive LIs.
			At a later phase of LIs adoption, through training staff who are continuously involved in operation stage (to continuously monitor) to actively recognise emerging active LIs and accordingly apply corrective measures (then later report the event in order to gather in centralised database of LIs).
			At a later phase of LIs adoption, through proactive assessment (e.g. testing emergency preparedness or assessing efficiency or effectiveness of safety efforts) and simulation (i.e. running 'worse case' scenarios) at the design stage by using passive LIs.
F5.	To mitigate the impact of unfavourable occurrences.	Active leading indicators + Passive leading indicators	Through the adoption of active and passive LIs as a form of feedback mechanism (i.e. weak signals informing about the current or timely status of safety) and corrective tool/guidance (by reacting accordingly and in a timely manner to the weak signals (negative or positive) received).
F6.	To measure impact and efficiency of safety performance, safety efforts or safety policy (i.e. efficiency of safety management systems).	Passive leading indicators + Active leading indicators	Through assessment (e.g. testing emergency preparedness or assessing efficiency or effectiveness of safety efforts) and simulation (i.e. running 'worse case' scenarios) at the design stage using passive LIs and continuously monitoring at the operations stage using active LIs.
F7.	To predict future safety performance.	Qualitative passive leading indicators + Quantitative passive leading indicators	Through qualitative and quantitative assessment and analysis of safety efforts implemented by the organisation. Through quantitative and qualitative assessment of safety performance and safety efforts during safety audits, safety observations, safety inspections and safety monitoring.
F8.	To predict near future or in time safety performance.	Qualitative active leading indicators + Quantitative active leading indicators	Through continuous monitoring of emerging events by assessing them quantitively and qualitatively. Through qualitative and quantitative assessment and analysis of current status/condition, ongoing events and emerging factors.
F9.	To assess current/ ongoing safety performance.	Negative active leading indicator + Positive active leading indicators +	By contrasting negative and positive active LIs collected through continuous safety observation, safety inspection and safety monitoring at the operations stage. By contrasting negative and positive passive LIs collected through continuous safety observation, safety inspection and safety monitoring at the operations stage.

(continued on next page)

Table 3 (*continued*)

		Negative passive leading indicator + Positive passive leading indicators	By contrasting negative and positive active LIs recorded in the database of LIs. By contrasting negative and positive passive LIs in the database of LIs.
F10.	To assess earlier put safety efforts.	Negative passive leading indicators + Positive passive leading indicators	By contrasting negative passive LIs (which inform about the shortcomings in safety efforts implemented) and positive passive LIs (which inform about the strength in safety efforts implemented) based on the data collected through continuous safety observation, safety inspection and safety monitoring at the operations stage.
			By contrasting negative passive LIs (which inform about the shortcomings in safety efforts implemented) and positive passive LIs (which inform about the strength in safety efforts implemented) based on the data in the database of LIs.
F11.	To serve as feedback of previous and ongoing safety efforts.	Negative passive leading indicators + Positive passive leading indicators	By studying negative passive LIs and positive passive LIs based on the data collected through continuous safety observation, safety inspection and safety monitoring at operation stage.
			By studying negative passive LIs and positive passive LIs based on the data in the database of LIs.
F12.	To identify areas for improvement (for companies to proactively learn or to adopt safety learning approach).	Negative leading indicators	By studying negative LIs based on the data collected through continuous safety observation, safety inspection and safety monitoring at the operations stage.
			By studying negative LIs based on the data in the database of LIs.
F13.	To identify opportunities for learning and to acknowledge the positive impact of early and continuous safety efforts (for companies to proactively learn or to adopt safety learning approach).	Positive leading indicators	By studying positive LIs based on the data collected through continuous safety observation, safety inspection and safety monitoring at the operations stage.
			By studying positive LIs based on the data in the database of LIs.
F14.	To indicate the activities/tasks that need to be performed to maintain safety.	Specific leading indicators	By developing specific LIs through the review of normative documents, organisations current safety activities and publications with best practices at early phase of LI adoption.
			By developing and continuously revising specific LIs through the review of data contained within database of LIs.
F15.	To assess the quality of safety efforts in safety management systems.	Qualitative active leading indicators + Qualitative passive leading indicators	By studying qualitative data collected and obtained from administrative records of organisation (relevant to their safety activities, safety policies and documents of their research development on safety) and by monitoring emerging changes and trends from industry, other organisations and government.
F16.	To benchmark the state of safety and identify new trends.	Quantitative active leading indicators + Quantitative active leading indicators	By studying quantitative and quantified qualitative data from administrative records of organisation (relevant to their safety activities, safety policies and documents of their research development on safety) and by monitoring emerging changes and trends from industry, other organisations and government.

evaluated' (Akroush and El-adaway, 2017).

Through revision of these LI examples, two different types of LIs emerged *viz.* generic LIs and specific LIs. Generic LIs are abstract and do not specify any activity or task to be followed or counted. Examples of generic LIs are '*safety auditing*' (Xu et al., 2021), '*workload*' (Sun et al., 2019), '*cramped spaces*' (Jemai et al., 2021) or '*employee involvement*' (Almost et al., 2019). They serve the function of indicating to an aspect of safety that need to be considered but do not provide a specific step/task/activity to act upon. Another main characteristic of generic LIs is that they represent LIs which are not easily quantified or perception-based qualitative type elements such as '*audit compliance*' (Erikson, 2009), '*safety behaviour*' (Jemai et al., 2021) '*adequate barriers are set against the identified hazards*' (Reiman and Pietikäinen, 2012) or '*inadequate assessment of contractor training and competency*' (Tamim et al., 2020).

Whereas specific LIs represent a specified condition or situation that must be achieved (or avoided) or activity that must be performed and their frequency. Examples of specific LIs are '*written safety policy signed by senior managers in place*' (Guo and Yiu, 2015), '*number of accident investigations that received attention*' (Almost et al., 2019) or '*entry of worker-on-foot in equipment blind spot*' (Golovina et al., 2016). As the name suggests, specific LIs are more detailed and descriptive in terms of the conditions or activities that are being measured, and they can be quantified in contrast to generic LIs. This novel dichotomous classification of LIs elucidate about less-known functions of LIs, *viz.* to signal to the aspects of safety that should be included in safety management (refers to generic LI function) and to specify a required condition, situation or activity (refers to specific LI function) to achieve a certain goal (e.g. avoidance of unfavourable events or maintenance of safety status).

4.2. Challenges of leading indicators' development, implementation and adoption

Previous studies on LIs use in safety management literature researched: LIs' definition (cf. Guo and Yiu, 2015; Xu et al., 2021); contrasted LIs with lagging indicators (cf. Sheehan et al., 2016;

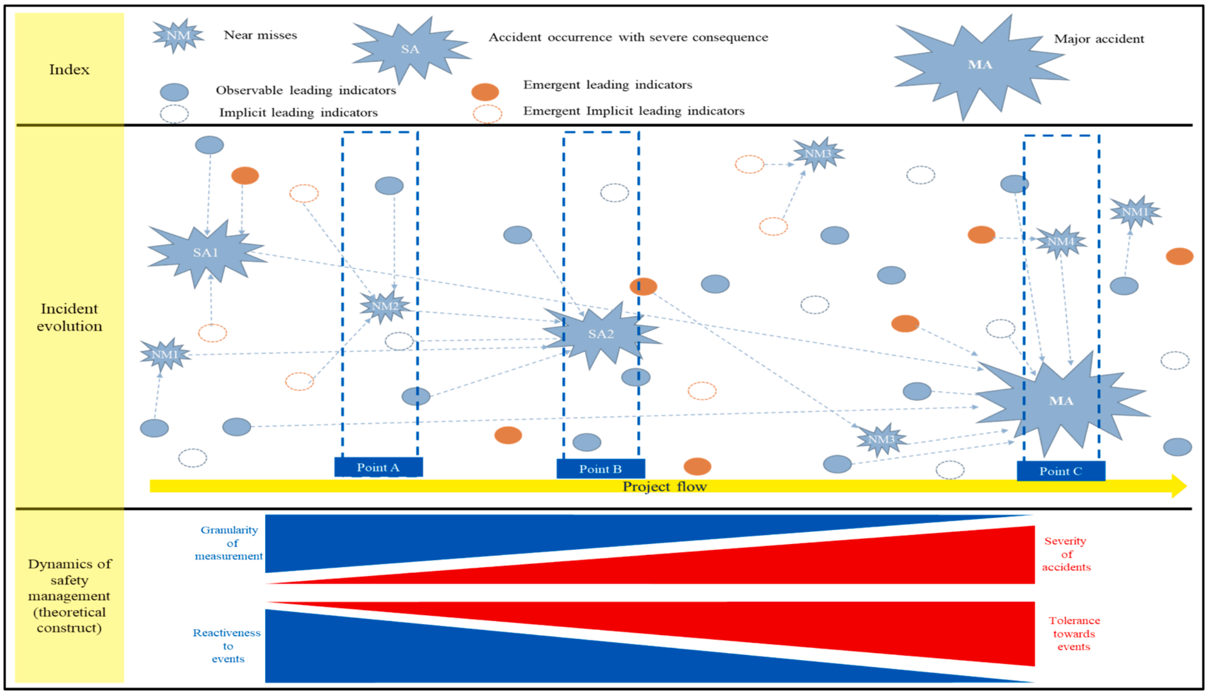

Fig. 3. Pictorial representation of lagging and leading indicators — 'Dynamic theory of incident evolution'.

Quaigrain and Issa, 2021); and studied the taxonomy of LIs (Alruqi and Hallowell, 2019; Bayramova et al., 2023). These studies attempted to address the ambiguities and inconsistencies existing around LIs' development, selection, implementation and use, since these obscurities hinder the extrapolation of LIs and proactive safety management. Table 2 illustrates some of the examples of challenges associated with LI use in health and safety. These challenges are categorised into three groups representing three stages, *viz*. development, implementation and adoption (or use) of LIs.

Challenges at the *development stage* are commonly related to a lack of theoretical understanding of LIs and absence of systematic guidance for developing LIs. The *implementation stage* entails difficulties in conveying the constructs of LIs to users (i.e. direct users of LI, analysts of LIs and top managers) and in achieving their buy-in. These *implementation stage* challenges necessitate both theoretical clarity (i.e. to understand LIs constructs) and empirical testing and evidence, alongside the training requirements. Challenges in the *adoption (or use) stage* of LIs cumulatively reflect leadership commitment and organisational safety culture maturity level. Top managers' support in terms of resources required for a full leverage of LI benefits and their commitment to progress towards proactive safety management are pivotal at this stage (Akroush and El-adaway, 2018). Similarly, superior safety culture and a continuous learning mindset shared amongst their staff lays a solid foundation for successful LI adoption (Grecco et al., 2014; Deepak and Mahesh, 2019).

5. Discussion and theory development

Although scant, there are some examples of successful LIs adoptions by different organisations in safety critical industries which partake high risk activities (cf. Toellner, 2014; Marks et al., 2013). These studies are propitious to glean not only challenges and considerations of LIs adoption but also potential benefits of using LIs can be derived from such empirical works. To fully apprehend potentials of LIs, an understanding about LIs' functions in line with their types is *sine qua non*. However, there is a glaring knowledge gap in the literature of LIs in terms of a systematic study that specifically focuses on the function of LIs; albeit some studies fleetingly refer to their function as their characteristics (cf. Guo and Yiu, 2015; Akroush and El-adaway, 2017; Almost et al., 2019; Santos et al., 2019).

The functions that negative and positive LIs serve are discussed by Reiman and Pietikäinen (2012), where they are respectively referred to as the '*dirty dozen*' and '*positive bunch*'. The authors (*ibid*) emphasise that for each identified or used negative LI, a positive LI must be adopted, not only to ensure the absence of an unfavourable event and to confirm the presence of positive and favourable outcome, but also to assess whether organisations are meeting their important safety prerequisites. This function of LIs enables focusing and enhancing organisational potential for safety and supports continuous organisational learning. Examples of LIs' functions are compiled in Table 3 (second column), each of which is incorporated with a specific type of LI used for a respective function (third column). The fourth column accordingly describes where each LI can be sourced from or how they can be developed and how those respective functions can be achieved.

Additionally, the table provides guidance as to what stage of LIs adoption each function can become relevant and feasible. There are two stages differentiated, *viz.* early stage (highlighted in grey shading in Table 3) and later stage (highlighted in gold shading in Table 3). Early stage here denotes a first ever introduction of LIs in safety management of a company, whereas the later stage implies the stage where an organisation is continuously using LIs and has collected historical data of LI use.

The process of selecting a specific LI function (from Table 3) will depend on an organisation's: purpose or plan in terms of their safety management improvement and priorities; existing safety performance history and data; and safety maturity level (which represents their safety capacity, commitment and capability). For example, if the organisation is at the outset of introducing LI use into their safety management, they would greatly benefit from the first function (F1 in Table 3) of LIs.

Namely, to use the function of "*to indicate to points in safety that were not considered (to identify unknown unknowns)*", the company would explore generic LIs through a review of relevant normative documents and scientific publications. Whereas at a later stage of LIs adoption, the company can benefit to identify their unknown unknowns through using generic LIs that are identified from a centralised database of LIs (i.e. the repository that was generated via their continuous use, collection and analysis of LIs). However, some of the functions described in Table 3 are exclusive to only the later LIs adoption stage. For example, functions F5, F6, F7, F8, F15 and F16 in the table are only applicable to the later stage of LIs adoption, where functions can be achieved in the presence of an LIs data repository which enables establishment of safety analytics. This in turn generates safety intelligence specific to the company where they can: proactively evaluate and improve their safety process; learn from their past and current safety performance; and continuously assess and review their LIs and safety models.

5.1. Evolution of events: Leading or lagging indicators – A new theoretical perspective

Ambiguity around which indicator is leading or lagging draws attention of many scholars (cf. Knijff et al., 2013; Sheehan et al., 2016). For example, Hopkins (2009) reviews the distinction of lagging and LIs by referring to: 1) an investigative report by the Baker panel (Baker et al., 2007) which focuses on the BP Texas city explosion; and a guidance report by the UK Health and Safety Executive (Health and Safety Executive, 2006) about developing process safety indicators. Hopkins (2009) persuasively discusses the difficulties and inconsistency around the description and examples of leading and lagging indicators in those reports. As a result, this publication drew considerable attention amongst scholars and became a theoretical debate which culminated in (amongst other things) a special issue in the Safety Science journal dedicated to this topic (Patriarca et al., 2019; Santos et al., 2019). In this special issue contributing authors express their agreement and disagreement alike with the points Hopkins (2009) is making, but also contribute their own perspectives about the complexity of measuring safety as well as characteristics, function and contribution of leading and lagging indicators (Santos et al., 2019). Following the review of this theoretical debate, the relationship existing between leading and lagging indicators can be described in the form of pictorial representation as illustrated in Fig. 3. In the index section of Fig. 3, explosion shapes, small, medium and large, respectively describe near miss (e.g. slip, trip), severe consequence occurrence (e.g. caught-in between, fall from height or loss of life type accidents) and major catastrophic accident occurrences (e.g. accidents with major impact to number of lives and severe environmental damage and facility destructions). Whereas oval shapes in the figure represent LIs that are observable, implicit and emergent observable and emergent implicit (or not easily observable and discernible).

All the elements depicted at the incident evolution section in Fig. 3 can be described as a signal (or feedback or 'communication means' of complex systems) coming from the system that are occurring in the lifecycle of any project or complex system depicted as a yellow right-pointing 'project flow' arrow in the figure. Assigning elements as leading or lagging indicators depends on two factors *viz*.: 1) on which point of the timeline the event occurs (e.g. after or before one of the events) and 2) which event is the priority and where the focus is being concentrated, so to avoid the occurrence of that event (Hudson, 2009; Murray, 2015). As stated in the Bowtie Diagram, occurrences of event can be classified as leading if they represent efficiency of control measures which occurs prior to an accident and is represented as a lagging indicator if they appear after the incident and describe the consequence of an accident (Samuel and Das, 2015; Abdelmalek and Soares, 2021; Schmitz et al., 2021). Similarly, a plethora of researchers explain the promiscuity existing between lagging and LIs by referring to: their use and application context (Hinze and Hallowell, 2013; Oswald, 2020); the way they are measured (e.g. when leading indicators can statistically both lead and lag) (Hinze and Hallowell, 2013; Lingard et al., 2017); their function (e.g. when lagging indicators predict another outcome) (Sheehan et al., 2016; Yorio et al., 2020). Therefore, it is a matter of which event occurrence a company wants to avoid and after which accident occurrence the company begins to react with corrective measures. In other words, which events are deemed 'tolerable' within company's safety culture and safety management practice. For example, if a company's ambition is to avoid a major accident occurrence (depicted as an explosion shape with 'MA' in Fig. 3) then all the occurrences depicted in the figure, (namely, observable or explicit leading indicators, implicit leading indicators, emergent leading indicators and emergent implicit leading indicators) including near misses (depicted as an explosion shape with 'NM' in Fig. 3) and accidents with severe consequences (depicted an as explosion shape with 'SA' in Fig. 3) will be accounted as LIs. Hence, the focus of that company will be to apply corrective measures towards prevention of major accident occurrences. In this first scenario depicted as point C in Fig. 3, events that are generally considered to be a lagging indicator (i.e. near misses and accidents with severe consequences) serve as LIs by prompting or signalling to the occurrence of major accidents. Such an approach illustrates an example of safety management that is far from proactivity where: safety is managed through less granular measurements; corrective measures are initiated reactively after the occurrence of severe accidents; and a company's tolerability to accidents are higher and early signals (i.e. near misses and any type of LIs) which could prevent occurrences of severe accidents are dismissed or ignored. These descriptions are illustrated at the bottom of Fig. 3 as a spectrum of: granularity of measurement; severity of accidents; tolerance towards events; and reactiveness to events. All these four scales are theoretical constructs that represent the dynamics of safety management.

However, on the second scenario (point B in Fig. 3), if company's ambition is to avoid the occurrences of severe accidents (SA in the figure), then all the 'minor' occurrences prior to that serious accidents will serve as LIs including all types of LIs and near miss occurrence. In such circumstances, a company's effort towards safety management becomes more granular and proactive, because it starts to react to near misses (that are occurrences with a minor consequence) and apply corrective measures.

For a third scenario (point A in Fig. 3), if the company's safety maturity level is on higher level and the company aims to tackle near miss occurrences, then the company's safety effort and control countermeasures will be driven by LIs (most likely by active LIs that are emergent in the live project). These three scenarios also represent three different safety maturity levels of companies; where what a company measures can serve as LIs of their safety maturity level. That is, the more granular the safety measurement and initiator of corrective action become, the more proactive and preventative their safety efforts and the higher their safety maturity level becomes (Glendon, 2009). This also denotes that the earlier a company reacts to a weak signal, the less tolerant the company becomes to negative events. Indeed, as more acceptable and non-reactive a company becomes to occurrences of less severe negative events, the more susceptible they become to the occurrences of more severe events' occurrences.

5.2. Contributions, limitations and future work

All these stated theoretical contributions purvey a new perspective, sought-after clarity and opportunities for researchers to develop a blueprint model for knowledge management systems that will finetune existing understanding about accident occurrences. Likewise, the study's outcomes serve as a guidance and elucidation for safety practitioners and experts as well as early adopters of LIs in safety critical industries and for continuous learning organisations with higher safety maturity level. However, these outcomes bear some limitations and considerations. For instance, events illustrated in Fig. 3 should not be assumed as a cogent link. Rather they are illustrated arbitrarily to describe the relationship between leading and lagging indicators and to reflect the emphasis existing in pertinent literature around the use of LIs (i.e. weak but early signals and feedback from complex systems) and benefits of applying corrective measures at early stage to maintain safety (rather than waiting for severe or major accident occurrences). For example, factors leading to occurrence of different severe accidents (SA1 and SA2 in Fig. 3) are dissimilar. LIs for SA1 severe accident occurrence are combination of emergent LI, observable LI and emergent implicit LI. Whereas LIs of SA2 occurrence are due to observable LIs, implicit LI as well as near miss event occurrences. Furthermore, whilst such inductive development of new theory constitutes a notable contribution to knowledge, the products of such work (namely the theoretical construct presented in Fig. 3) must now be tested deductively in practice to monitor, measure and assess the performance and validity of the model theory proposed and to verify the negative correlations illustrated between safety management dynamics. In addition, benefits or functions of LIs (in Table 3) alluded to in this study are not an exhaustive list, since they were obtained from previous studies which are subject to current study's choice of keywords. That is, a broader search of literature (encompassing a wider range of keyword terms) could have introduced further perspectives and increase the number of functions included. Moreover, the benefits stated emanating from LIs functions requires empirical testing through user and adopter validation. Such applied and evidence-based studies will also provide more insights about the challenges of adopting LIs.

6. Conclusion

The current study offers new theoretical contributions in the form of: exploration of LI development, implementation and adoption challenges; inquiry into the LIs' potential benefits that are embedded in their functions; and conceptualisation of the relationship between leading and lagging indicators. Notable differences in the attributes of lagging and LIs were observed. Lagging indicators: are associated with unfavourable outcomes and adverse consequences; have the power to halt the system; and are more discernible than LIs. Whereas LIs are: weaker and not easily detectable unless sought after; dynamic and time dependent, hence require continuous monitoring; and indistinct and blended into the status quo (the time period when there is no accidents). Nevertheless, collectively both leading and lagging indicators are feedback or response emanating from the interrelationship of elements in complex sociotechnical systems. Accordingly, it is incumbent upon organisations' choice on which signal (weaker, stronger or combination of both) they are willing and able to base their safety management. However, due to the malleability of both leading and lagging indicators and regardless of the metric chosen to adopt, their accuracy will be threatened with poor safety culture in an organisation and this will lead to management of metrics rather than management of safety. Therefore, one of the main hurdles, organisations must address from the outset is their preparedness, priorities and safety culture maturity level.

However, for efficient LIs adoption and sustainable proactive safety management approach, LIs must be adopted with systems thinking approach where LIs are developed and used within a sociotechnical systems (STS) rather than merely focusing on human behaviour or identifying LIs for machinery or plant. In addition, such an approach must be applied through the use of active LIs (alongside other LI types) which will: enable constant monitoring of emergent features of STS; and facilitate early detection of changes in safety status. Furthermore, elements that LIs are indicating should be structured in a nested or multi-tiered way. For example, if a company adopts safety culture as LIs of safety, then LIs for measuring safety culture must be adopted. Similarly, if the company adopts safety inspection or safety observation to monitor safety culture of the company, then LIs to measure and monitor the efficiency of those methods must be developed and recorded. Therefore, the process of adopting the proactive safety management approach must have certain measurements or LIs to continuously monitor the efficiency of the approach. Finally, the design and construct of countermeasures and barriers generated through continuous LI use will be limited to the knowledge that organisations have and their past experience only. Therefore, to improve the quality and extent of data collected through LIs, organisations are recommended to: create a centralised safety analytics platform; and incorporate knowledge and insights about LIs and safety challenges from practices of other relevant organisations and industries. Such undertaking, in turn, will provide a thorough and more comprehensive safety intelligence and will enable organisations to learn from their own shortcomings as well as from mistakes occurring in other organisations' projects (by uncovering unknown unknowns). However, such voluminous data requires a systematic and automated process which relies on human–machine synergy to: analyse the data on a continuous basis; and select pertinent LIs from a database for a proactive safety management. In such a centralised database or platform of safety intelligence, both lagging and leading indicators are crucial elements or signals emanating from complex systems from which more insights can be deduced whether timely or after-the-fact. Therefore, new theory built in this current study becomes critical to ensuring the next step change leap in safety science, whereas the polemic debate presented seeks to challenge conventional thinking and intends to instigate a new line of scientific enquiry.

CRediT authorship contribution statement

Aya Bayramova: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **David J. Edwards:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition. **Chris Roberts:** Writing – review & editing, Supervision, Project administration. **Iain Rillie:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

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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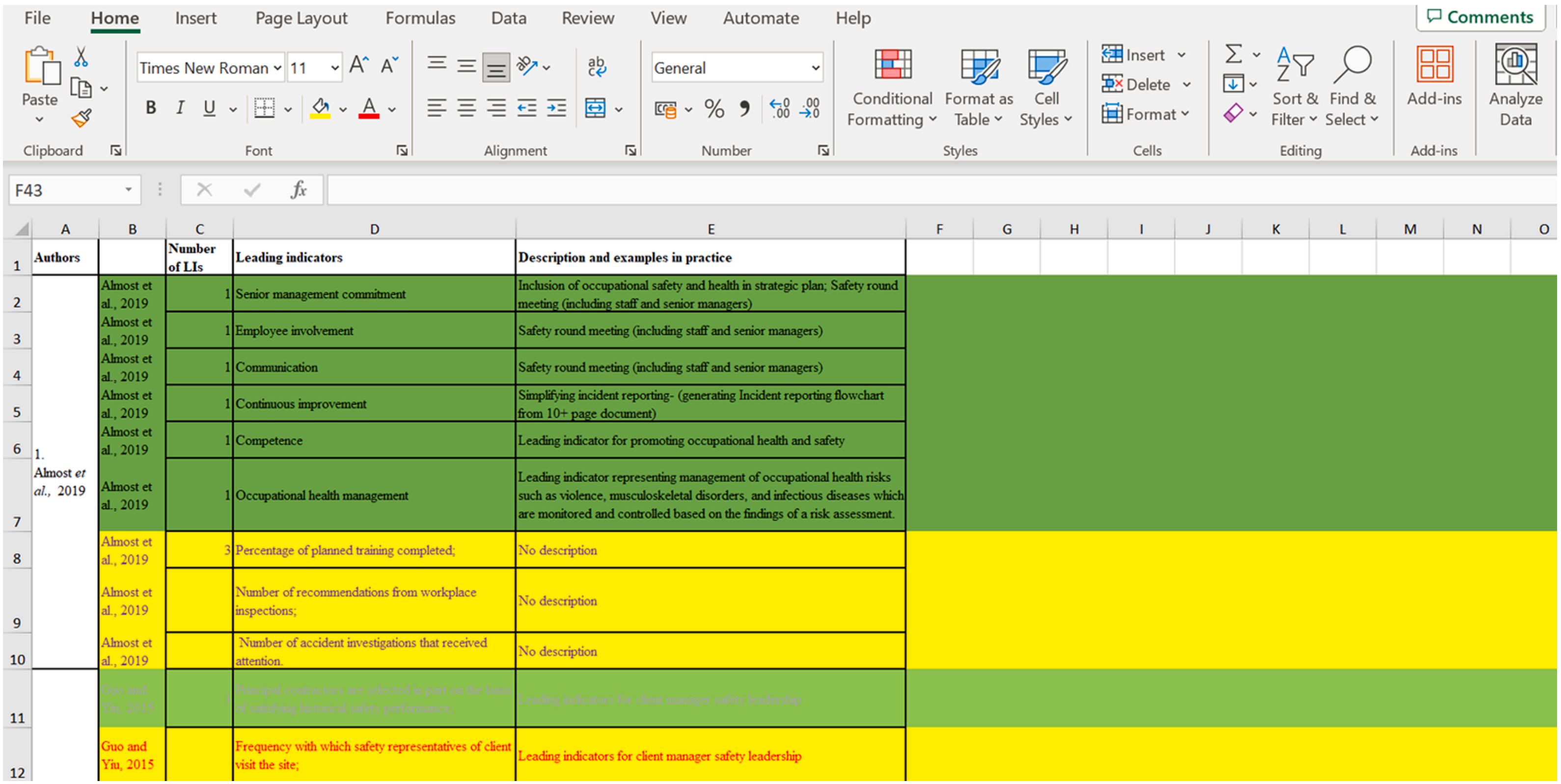
Appendix 1. Screen dump of database table consisting of safety leading indicator examples identified in previous literature



	A	B	C	D	E
1	**Authors**		**Number of LIs**	**Leading indicators**	**Description and examples in practice**
2	1. Almost *et al.*, 2019	Almost et al., 2019	1	Senior management commitment	Inclusion of occupational safety and health in strategic plan; Safety round meeting (including staff and senior managers)
3		Almost et al., 2019	1	Employee involvement	Safety round meeting (including staff and senior managers)
4		Almost et al., 2019	1	Communication	Safety round meeting (including staff and senior managers)
5		Almost et al., 2019	1	Continuous improvement	Simplifying incident reporting- (generating Incident reporting flowchart from 10+ page document)
6		Almost et al., 2019	1	Competence	Leading indicator for promoting occupational health and safety
7		Almost et al., 2019	1	Occupational health management	Leading indicator representing management of occupational health risks such as violence, musculoskeletal disorders, and infectious diseases which are monitored and controlled based on the findings of a risk assessment.
8		Almost et al., 2019	3	Percentage of planned training completed;	No description
9		Almost et al., 2019		Number of recommendations from workplace inspections;	No description
10		Almost et al., 2019		Number of accident investigations that received attention.	No description
11		Guo and Yiu, 2015	3	Principal contractors are selected in part on the basis of satisfying historical safety performance;	Leading indicators for client manager safety leadership
12		Guo and Yiu, 2015		Frequency with which safety representatives of client visit the site;	Leading indicators for client manager safety leadership

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