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Process safety indicators, a review of literature

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ABSTRACT

Indicators for process safety can provide insight into safety levels of a process or of a company, but it is clear that the 'silver bullet' has not yet been identified. In secondary literature a difference is made between leading and lagging safety indicators. Primary literature questions this distinction, as well as the quantification of safety indicators. Safety Indicators for management and organisation have an ambiguous relationship with latent errors and conditions, being mentioned over and over in retrospective safety analyses of major accidents. Indicators for occupational safety do not necessarily have a relationship with process safety. In addition, it can be expected that regulators of major hazard companies will ask to identify and implement both lagging and leading indicators, and anchor these indicators in a safety management system. Therefore, the subject 'safety indicators' will remain in the spotlight, at least in the time to come.

1. Introduction

In a competitive market environment, companies need to perform optimally if they want to survive in the long term and to be amongst the top of the sector. In the 1990s the term 'Performance Management' was introduced in management literature. Performance can be translated in this context as managing performance with the ultimate goal to perform better. First one thinks of financial and economic matters in terms of productivity, quality and environment. However, safety is also an important area for performance indicators. In practice, performance management becomes evident in the selection of representative indicators. These indicators reflect the status of the working environment and production processes realistically, and are used to obtain an optimal situation. A specific type of indicator for the safety domain is presented in this article, that is, the process safety indicator.

Literature on this topic sometimes refers to boilers of steam engines and trains. In the 19th century boilers exploded regularly, until it was understood that pressure, temperature, and strength-thickness of boiler walls were important technical indicators for these explosions (Fig. 1).

The frequency of these explosions dropped dramatically after the introduction of safety valves. In the second half of the 19th century, with the Siemens Martin and the Bessemer process, steel boilers could be produced and the strength of the boiler wall was under control (Rolt, 1955; Hijmans, 1963).

One hundred years later two publications on safety indicators for occupational safety appeared in America, one by Thomas Rockwell (1959) and one by William Tarrants (1963). Rockwell was looking for a measure of safety performance, and formulated requirements for indicators, which should be reliable, quantifiable and easy to understand. The indicator should also be stable, reproducible, sensitive to changes, and cost-effective. According to the author, accidents, with or without lost time did not meet these requirements. In line with a common safety metaphor of that time, Heinrich's domino's, unsafe acts were taken as starting point for indicators (Table 1) (Heinrich, 1941; see also Gulijk et al., 2015).

Four years later, William Tarrants doctorated at the University of New York on causes of accidents. Accidents and near-accidents were defined as unplanned events interfering with a job and not necessarily resulting in damage or adverse effects. This definition of accidents differed from Rockwell's focus on unsafe acts, and followed the insights after World War II of external factors as causes of occupational accidents, like for instance Winsemius (1951) (for an overview see Swuste et al., 2014). According to Tarrants, accidents

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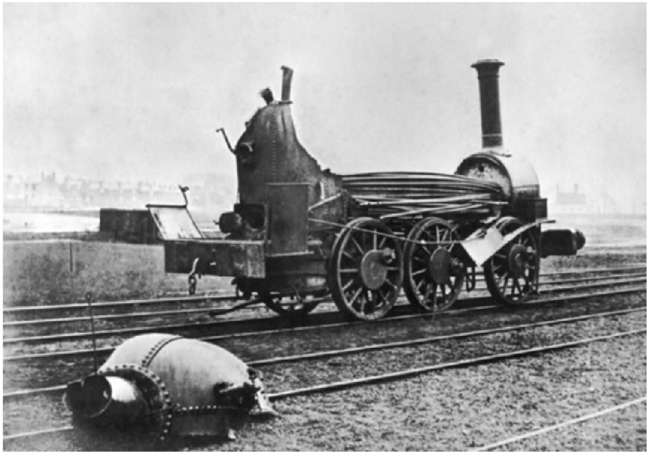

Fig. 1. Exploded train steam boilers.

Table 1
Unsafe acts as safety indicators (Rockwell, 1959).

1.	Working with loose tools underfoot
2.	Working without goggles when required
3.	Working under suspended loads
4.	Failure to use guards as provided
5.	Working in unsafe postures
6.	Wearing improper or loose clothing
7.	Use of shock tools with mushroomed heads
8.	Improvising unsafe ladders and platforms
9.	Running
10.	Misuse of air hose

were always preceded by errors or unsafe conditions, or a combination of errors and unsafe conditions (Tarrants, 1963, 1970). He proposed to include incidents and accidents as a basis for indicators.

Various authors indicated that well into the 1990s, and even till now, one particular indicator had been the key safety indicator in process industry, the LTIF, the Lost Time Incident Frequency (Visser, 1995; Hale, 2009; Harms-Ringdahl, 2009; Pasman and Rogers, 2014; Leveson, 2015; Pasman, 2015; Knijff et al., 2013). LTIF represents the number of days of absence to work due to an accident, per million hours worked. At that time, improvements in safety performances were equal to improvements in LTIF values. For example by Shell, between 1957 and 1994 the indicator dropped from about 20 to less than 2. The same focus on LTIF was present in many other companies in the process industry. Therefore many companies in the late 1990s promoted a zero accidents approach. This appeared to be a miscalculation. Obviously, process disturbances accelerating major accident scenarios might also induce scenarios of occupational accidents, meaning that occupational safety and process safety can be intertwined. But, because of the accepted difference between the origin and pathways of major accidents and occupational accidents, LTIF figures cannot be regarded as indicators of process safety.

In the 1990s major accidents in high-risk industries reoccurred (Kletz, 1993). Examples were: exploding tanks during welding, radioactive emissions, tripping reactors, overfilling storage tanks, failing pipelines, metal fractures by extreme temperature variations, etc. (Pigeon, and O'Leary, 2000; Hopkins, 2000; Körvers, 2004; Sonnemans and Körvers, 2006; Körvers and Sonnemans, 2008; Guillaume, 2011 Kidam and Hurme, 2013). Apparently companies were, and still are, unable to recognize so-called 'weak signals' or process deviations with potentially major effects. From the second half of the 1970s these weak signals and deviations were divided in three groups, being technical/process engineering, organisational and human factors, including the quality of leadership (see Swuste et al., 2015). A comparison of major accidents worldwide between 1970 and 1980 and the first decade of this century showed no difference between these two periods. Apparently recognition of weak signals at all levels of the organisation as well as by (sub) contractors work is still a problem, and managing disaster scenarios seems an extremely difficult topic (Table 2).

Apart from not recognizing these 'weak signals' as precursors to major accidents, other explanations are possible, like limited analysis capabilities of process safety techniques, safety management systems that do not have sufficient control over potentially hazardous processes, or limitations of existing safety metaphors, models and theories. However, these metaphors, models and theories are still too conceptual in nature to predict accidents and to deduce relevant safety indicators (Knegtering and Pasman, 2009; Le Coze, 2013). Also, the increased numbers play a role. There are ever more nuclear plants operating, ever more process installations, air traffic increased substantially, etc. Furthermore, the vulnerability of these systems is enhanced by an increased complexity and dominant market forces. This latter influence leads to outsourcing, increased production efficiency and modular or fragmented organisational structures (Le Coze, 2014). Against this background, this article answers the following two questions:

> Can process safety indicators provide insight and knowledge in levels of safety of processes or business, both current and future? And if so, which indicators are qualified?

2. Materials and methods

In 2009 Andrew Hopkins and Andrew Hale issued a Safety Science special issue on process safety indicators (Hopkins and Hale, 2009), with nineteen different contributions from researchers, consultants and safety experts working in large companies. This issue was the start of this literature review, both in scientific and in professional literature. Scientific literature publishes results of original studies, and includes a formalized, anonymous referee system. Professional literature can be original work, or can report, summarize, comment on scientific literature, making it accessible to a wider audience than the scientific community and interested parties. Usually a referee system similar to scientific journals, is lacking. The scientific journals in this overview, presenting papers on this topic from North American, European, Central Asian, and Australian authors, were restricted to Ergonomics, Journal of Hazardous Materials, Journal of Industrial Engineering, Journal of Loss Prevention in the Process Industries, Journal of Management, Journal of Safety Research, Process Safety and Environmental Protection, Reliability Engineering and System Safety, Safety Science, and the Dutch Journal of Occupational Sciences.

Professional literature was mainly restricted to reports of national organisations, like the American Baker report (2007), reports of the Centre for Chemical Process Safety (CCPS, 2010, 2011, 2014), British reports of the Control of Major Accident Hazards (COMAH, 2012), of the Health and Safety Executive (HSE, 2006) and of the UK Oil and Gas Industry, "step change in safety" (2006). Professional literature from international organisations comes from the International Organisation of Oil and Gas Producers (OGP, 2011) the Organisation for Economic Cooperation and Development (OECD, 2008a, b), the European Process Safety Centre (EPSC, 2012), and the European Chemical Industry Council (Cefic, 2011). Professional literature includes books on management, as Olivier and Hove (2010), Heuverswyn and Reniers (2012), and Pasman (2015). For

Table 2
Major accidents, a déjà vu (Le Coze, 2013).

High-risk industries	Period	
	1970s–1980s	2000–2010
Nuclear	Chernobyl, 1986	Fukushima, 2011
Offshore drilling	Piper Alpha, 1988	Deepwater Horizon, 2010
Fuel storage	Port Edouard Heriot, 1987	Buncefield, 2005
Aerospace	Challenger. 1986	Columbia, 2003
Aviation	Tenerife, 1977	Rio Paris, 2009
Chemical – petrochemical	Flixborough, 1976, Bhopal, 1984	Toulouse, 2001, Texas City, 2005
Railway	Clapham Junction, 1987	Ladbroke grove, 1999
Maritime I	Zeebrugge, 1987	Costa Concordia, 2012
Maritime II	Exxon Valdez, 1987	Erika, 2003
Air Traffic Management	Zagreb, 1976	Umberlingen, 2002

each type of information source following topics are covered in separate sections:

- Safety expert metaphors, models and theories as a basis for process safety indicators;
- Leading and lagging indicators;
- Indicators of management and organisation;

3. Process safety indicators in the scientific literature

3.1. Safety metaphors, models and theories as a basis for process safety indicators

The history of safety metaphors, models and theories are described in publications of Swuste and co-authors (2010, 2014, 2015) and Gulijk et al. (2015). This literature distinguishes between sequential, epidemiological and system-dynamic metaphors, models and theories. The domino metaphor Heinrich describes an occupational accident process as a linear sequence of events caused by human or technical errors. The technical errors related to exposure to mechanical, electrical or chemical hazards, like order and cleanliness, missing enclosures of rotating parts of machine, with irregular floors and unguarded holes and heights (Heinrich, 1941). Examples of human errors, according to Heinrich are far-out the most the dominant cause of accidents and shown in the aforementioned Table 1.

Next to immediate causes, epidemiological models and theories are emphasizing latent failures and conditions originating from the organisation and management of production. Turner (1976, 1978) was the first to highlight the concept of ‘incubation period of major accidents’, a period weak signals of serious accidents are undetected. The bowtie metaphor (Nielsen, 1971; Johnson, 1973; Wijk, 1977), the Tripod theory (Groeneweg, 1992; Wagenaar et al., 1994) and Swiss cheese metaphor (Reason, 1997) are also examples of this group, all used for the analysis of occupational and major accident. These metaphors and theories are still sequential in origin and focus on errors of so-called 'front line operators'. However, these errors are almost unavoidable in the context of the organisation in which they occur. The models are also called complex sequential, because several scenarios may lead to accidents.

System dynamic models and theories emerged in the 1980s. Like epidemiological models these models and theories are based on cybernetics, and provide explanations for major accidents. The 'normal accident' theory of Perrow (1984) is an example. Not errors of front line operators will determine risks of major accidents, but characteristics of production systems. Two determinants are leading; the degree of coupling of a production process and the complexity of interactions. The coupling reflects the presence or absence of buffers between system elements, and variability of the sequence of process steps. Interaction refers to physical or chemical transformations of processes and the presence or absence of so-called common-mode functions, where one system element will steer two or more following system elements. When coupling is tight, and interactions are complex serious accidents are inevitable and characterized as ‘normal accidents'. Late 1980s the concept of 'high reliability organisation (HRO)' appeared. HRO's are organisations, which in terms of Perrow have complex interactions and tightly coupled processes. Air traffic control and flight manoeuvres on aircraft carriers are examples of HRO's where hardly any normal accident occurs. The core concept of a HRO is the reliability of processes and system characteristics, and of people who have to operate these processes (Rochlin, 1986; Weick, 1987; Roberts, 1988). HRO's are extremely effective ‘learning organisations’. In the same period Wildavsky postulates the notion of resilience. Within organisational theory the concept of resilience has been known already for some time. Competition and the economic climate will create various setbacks and organisations have to respond effectively to these threats (Wildavsky, 1988).

Almost a generation later the HRO concept was introduced in Europe as ‘resilience engineering’ (Hollnagel et al., 2006). A final example of the system-dynamic group is the 'drift to danger' model of Rasmussen (1997), wherein the dynamic information flow between stakeholders can bring a system beyond its safety envelop. In the sections below a few examples of the metaphors, models and theories mentioned above will be discussed.

3.2. Leading and following indicators

A lot has been written on process safety indicators. However, there is little published empirical research on this topic. Often in the literature a distinction is made between so-called leading and lagging, providing insight into the level of safety of a system (Allford, 2009). However, safety is a dynamic condition of a system and is only measurable indirectly by proxies.

The bowtie metaphor illustrates the relationships between scenarios barriers and management factors. In the centre is a state where energy (hazard) has become uncontrollable, the central event, leading to consequences (Fig. 2).

The model has a hidden time factor. Management factors taking care of the acquisition, maintenance and, more generally, the quality of barriers, may undermine insidiously the effectiveness of these barriers over a long time period of time. If a hazard, energy, becomes uncontrollable and reaches the central event, scenarios reaching consequences usually will unroll very quickly. Scenarios left to the central event may take days, week, months, or even longer, while the ones at the right side develop in seconds, or even shorter. The distinction between leading and lagging indicators in

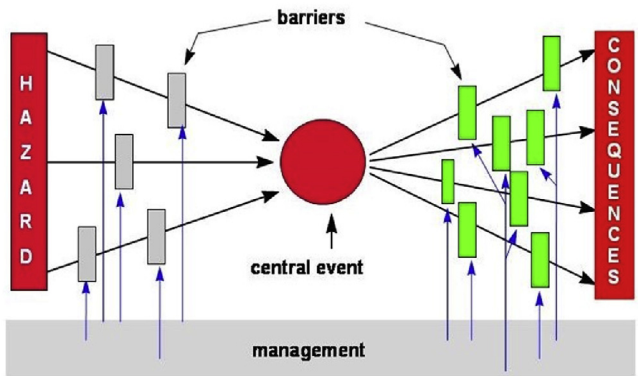

Fig. 2. Bowtie metaphor.

this model is relatively easy. Leading indicators provide information on the left hand side of the central event and the lagging indicators on the right hand side. Thus leading indicators basically are proxies for hazards, for barriers, for scenarios and management factors. Lagging indicators are proxies of the central event, of 'loss of control' and of consequences (Grabowski et al., 2007; Øien et al., 2011a). According to this approach, leading indicators provide information on distortions of processes and thus on the stability of a system. Effects of interventions, which can be applied on both sides of the bowtie, will be reflected in these lagging indicators.

Indicators are seen as tools for safety monitoring of a system. In addition, leading indicators are associated with active and lagging indicators with a reactive safety monitoring (Hopkins, 2009). Hale (2009) has a different view: both leading and lagging indicators should provide information about the quality and effectiveness of barriers. From the list of definitions (Table 3), however, the distinction between the lead and lag is less obvious than one would expect.

The confusion goes even further when relationships are discussed between these two types of indicators (Harms-Ringdahl, 2009). If there is any difference, one would expect a logical connection between the two. This has not been demonstrated yet (Mearns, 2009). Such a relationship is expected from the bowtie metaphor. After all, a scenario left of the central event, continues its way to the right. A number of authors do not distinguish between leading and lagging anymore, because of this ambiguity a more general terminology is used, like key indicator, safety performance indicator, or key performance indicators (Guldenmund and Booster, 2005; Saqib and Siddiqi, 2008; Eriksen, 2009; Mearns, 2009; Grote, 2009; Øien et al., 2011a). Even with barriers, there is some confusion. This is evident from the various terms in use, like defence, protection layer, safety critical element, safety function. It is not clear whether these terms are synonyms or that different authors assign different meanings to the terms (Sklet, 2006). Proposals were suggested to create some order in this confusion. For example, research from the Technical University of Eindhoven in the Netherlands suggests a division in four different types (Körvers, 2004; Körvers and Sonnemans, 2008; Sonnemans et al., 2010):

1) safety-critical deviations from normal procedure – leaks, accidents;
2) monitoring - inspections aimed at human actions, observations, monitoring the effectiveness of safety barriers;
3) safety audits, organizational risk factors, training, safety inspection of equipment;
4) culture index – attitude survey, questionnaire.

Another classification from Pasman and Rogers (2014) makes an explicit reference to 'loss of containment (LOC)'. Concerning the process industry, LOC is elementary. This results in lagging indicators. Leaks are observable, and countable. LOC as lagging indicator emerged first; leading indicators are less easy to define and are of a later date:

1) mechanical integrity - inspections, audits; quality and unresolved action points;
2) settled action points - from process hazard analysis (PHA), from investigation to near misses;

Table 3
Definitions of process safety indicators from scientific literature.

References	Definitions
Rockwell, 1959; Tarrants, 1963	No definition of process safety indicators, only occupational safety
Martorell et al., 1999	The definition should contain; name, range, information required. The indicator is mathematical, and linked to the information necessary for the evaluation of the indicator
Leeuwen, 2006	Safety Performance Indicators are measurable units indicating processes/activities performances to manage these processes and activities
Sonnemans and Körvers, 2006, 2010; Körvers and Sonnemans, 2008	Repeated disturbances, both technical, as organisational, as on human performance
Hopkins, 2007	Indicators show how process safety risks are managed
Grabowski et al., 2007; Duijm et al., 2008	Building blocks of accidents, conditions, events, preceding unwanted events, and are to some extent capable to predict these events
Eriksen, 2009	Indicate the level of management of individual barriers to achieve goals
Dryeborg, 2009	A measure of root causes and safety performance of a production process
Hale, 2009	A measure of a safety level of a system, and if necessary responsible persons taking actions
Harms-Ringdahl, 2009	A measure providing feedback for improvements, if safety is sufficiently accomplished. An observable measure giving insight is a difficult to measure concept as safety
Kjellén, 2009	Predicts future changes in risk levels
Le Coze, 2009	A measure for disturbances, failures in a process system, and for interaction between those involved in safety management
Wreathall, 2009	A proxy for items from underlying safety models.
Knegtering and Pasman, 2009; Zwetsloot, 2009	Lagging indicators, precursors of LOC incidents, leading indicators measure the quality of the management system
Vinnem, 2010	Based upon the prevention of incidents, near-incidents, barrier performances
Øien et al., 2011a	A measure for the status of risk reducing factors
Reiman and Pietikainen, 2012	Provides an indication of the present state, or the development of organisations key functions, of processes, and the technical infrastructure of a system
Hassan and Khan, 2012	Risk based indicators measure the integrity of resources, operational, mechanical, human
Khawaji, 2012	Detection of failures in hazard analysis, design, non-adequate controls, and cause by extreme conditions

3) training, competence - quality training, test results, number of trained employees.

These formats differ, but have in common that both indicators are related to technology, as well as management and organisational activities. The latter part will be covered in the next section.

Gradually it becomes clear that process safety indicators is a complicated topic (Hassan and Khan, 2012). Failing management factors and thereby failing barriers are scenario-dependent (Zemering and Swuste, 2005; Bellamy, 2009; Dryeborg, 2009; Kjellén, 2009; Le Coze, 2009) and scenarios, appearing in the bowtie metaphor as straight lines, can in reality develop rather capriciously. Serious accidents are never the result of one assignable error or malfunction, but of a pattern of events which have their roots in the technology, the organisational and management domain. It is questionable whether such a pattern can be caught by one or a limited number of indicators (Körver and Sonnemans, 2008; Grote, 2009; Knegtering and Pasman, 2009).

Latent failures and conditions from epidemiological models are failures and conditions which are present but which reveal themselves only when they are addressed during an accident scenario (Fig. 3) (Reason, 1990a,b; Wagenaar et al., 1994).

Fig. 3 is a model for major accidents in the oil industry and it looks like a simplified version of the bowtie metaphor, which includes psychological factors, like the 'psychological precursors' and the' unsafe acts'. This model has subsequently led to the well-known Swiss cheese metaphor (Fig. 4).

Latent conditions and errors are detailed in the Tripod theory as the so-called basis risk factors (Groeneweg, 1992). These basic risk factors related both to technology (design, materials), as to management (maintenance policy, procedures, communication, training, conflict management goals, protective equipment), as to the organisation (organisational structure, environmental conditions, order and cleanliness). Logically indicators should provide information about the system elements from Fig. 3, the holes in cheese slices of Fig. 4, and on the quality of the basic risk factors. However, both figures also show how complicated it is to distinguish between leading and following indicators. This is only reinforced by system-dynamic accident models. The normal accident theory may lead to indicators of system characteristics, the degree of coupling and complexity. These predict the occurrence of major accidents and thereby leading.

Rasmussen's model (1997), also an example of a system dynamics model, is based on an extensive stakeholder analysis and resulted in his accident analysis method Accimap. This model shows the relative influence of different groups, information, interaction and conflicts between these groups. Rasmussen emphasizes this information and the dynamics of decision making which will affect process safety and that can bring the system into a state where it can get out of his so-called safety envelope (Fig. 5).

This safety envelope is a state in which a system is operating safely. A production process, the ellipse in the centre of Fig. 5, has a normal variation caused by, for example, physical parameters as temperature and by variations in the quality of raw materials and intermediate products. Rasmussen compared these variations with the Brownian movement of gas molecules. The Brownian motion

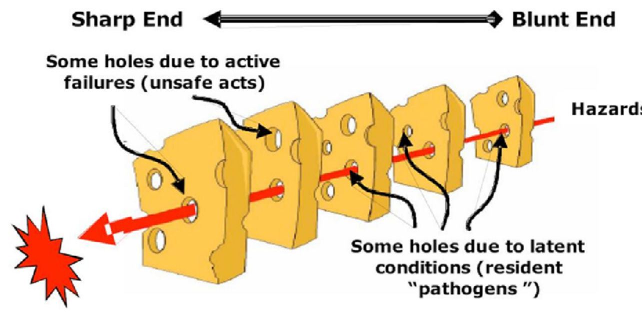

Fig. 4. Swiss cheese metaphor (Reason, 1997; Qureshi, 2007).

remains within the boundaries of the safety envelope. Two gradients can bring a production process to the limits of the safety envelope and makes the system unstable; the gradient towards least effort and pressure from management to produce as cost-efficiently as possible. These boundaries, the arcs left and right in the figure are, according to Rasmussen, not universal but company-specific and can be starting points for process safety indicators, providing information about the extent to which boundaries are reached. However, the pace and the dynamics of technological change and market-driven changes to a faster, cheaper and more efficient production, are much greater than the rate of changes of management structures and legislation. This pushes the drift to danger. Therefore investigation and analysis of serious accidents cannot be separated from research to decision making, which integrates the knowledge and the context of this decision. This approach provides risk management with an understanding of the dynamics of the safety of processes and the need for stakeholders to determine boundaries and to gain insight through feedback control, when a state of drift to danger will occur (Svedung and Rasmussen, 2002).

Serious accidents are a result of external disturbances and dysfunctional interactions among system components. Thereby safety is defined as a control problem. As with drift to danger, serious accidents will develop from hazards, as safety limits of the system components, when control structures will not function properly and process models do not match the actual state of the system. The discussion of metaphors, models and theories shows that the formulation of relevant indicators is not an easy one. Table 4 provides an overview of process safety indicators, being mentioned in scientific articles discussed.

3.3. Indicators for management and organization

Results of audits and feedback from employees are important information sources for managers to identify signs and indications of accidents (Grabowski et al., 2007; Duijm et al., 2008). Whether these two sources provide enough background for indicators is a question. Similar to process safety, also management and organisational indicators are generally formulated in the scientific literature (Table 5).

Some indicators are linked to interventions, as can be expected from management indicators. However, when indicators are

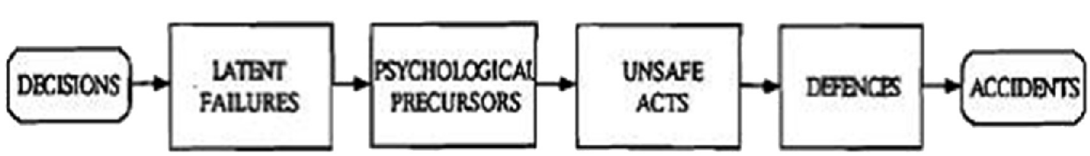

Fig. 3. General scheme of an accident scenario (Wagenaar et al., 1994).

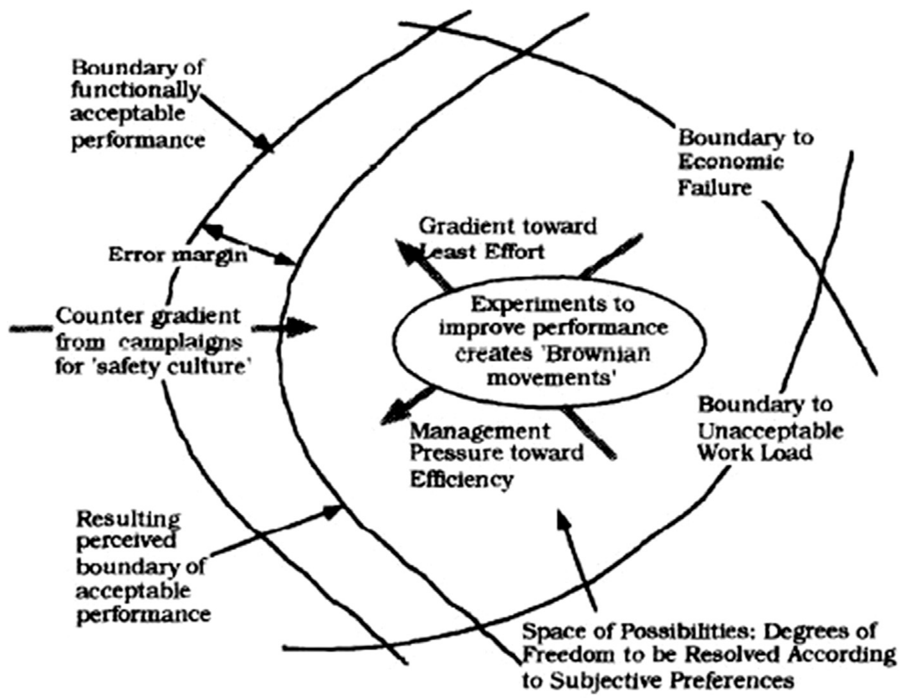

Fig. 5. Operational boundaries of a safety envelop, 'drift to danger' (Rasmussen, 1997).

Table 4
Process safety indicators from scientific literature.

Indicators	References
Process safety	
Alarms, failures, numbers per time period	Martorell '99, Hopkins '09, Bandari '13
Exposure to dangerous substances/activities	Martorell '99, Sklet '06, Kampen '13
Process deviations, number	Sonnemans '06, Körvers '08, Hale '09, Kongvik '10, Øien '11 ab, Reiman '12, Bandari '13
State of safety, unwanted	Grabowski '07, Bandari '13
Incidents, number	Körvers '08, Kampen '13
Leakages, number, amount	Vinnem et al., '06, Körvers '08, Harms '09
Barriers quality	Bellamy '09, Dryeborg '09, Hale '09, Reiman '12, Bandari '13
Fires, explosions, number, costs	Vinnem et al., '06, '10, Bandari '13
Loss of containment, amount, number	Webb '09, Bandari '13
Process design, failures, maintenance, quality control, failures	Harms '09
Tests, failures	Hopkins '09
Safety system, frequency of activation	Kampen '13, Bandari '13
Inherent safe installations, number	Kampen '13

quantified there seems hardly any relationship with management quality and thus with safety.

Interestingly, indicators seem to be mainly based on experience from companies or on common sense. Hardly any empirical research was found in the literature, apart from a casuistic study of the Technical University Eindhoven (Körvers, 2004; Sonnemans et al., 2010), and a survey of TNO among members of the Dutch Society of Safety Science - NVVK investigating the member's experience with safety indicators (Kampen et al., 2013). The study of Körvers and colleagues was conducted at three high-hazard industries in the coating sector, the plastic granules sector and the production of pharmaceutical ingredients. In their study, repeated breakdowns and defects in production were coupled with a top 20 of dominant scenarios with safety consequences. Latent factors were examined for these repeated breakdowns, as well as the quality of relevant barriers. The study to these indicators proved to be successful and the research yielded some interesting observations. Process failures were frequently preceded by equipment failure or by other disturbances. Signals were not recognized as a possible early stage of a process accident scenario, if the immediate consequence was not serious enough. On the other hand, information on non-functional barriers could be known within the company, but was not used from a safety perspective due to a lack of time and lack of effective communication between different departments. Thirdly, it appeared that safety departments of the companies surveyed were hardly involved in the daily production and therefore were not sufficiently aware of the common process hazards and risks. Finally, companies were not aware of the impact of decisions of the top and middle management on barrier quality.

The NVVK survey was conducted among 172 members of the Dutch Society, mainly working in larger process industries. Companies were using in total 15–37 different indicators, which almost entirely were related to occupational safety. Companies with good scores on occupational safety used more complex indicators for the state of their primary process. But at the same time results were hardly used to improve the organisation. Also no relation was found

Table 5
Management and organisational indicators in scientific literature.

Indicators	References
Management and organisation	
Behaviour, unsafe situations, positive feedback	Rockwell 1959, Reiman and Pietikainen, 2012
Safety management, activities	Martorell et al., 1999, Reiman and Pietikainen, 2012, Bhandari and Azevedo, 2013
Safety culture, climate, index	Körvers and Sonnemans, 2008, Dryeborg 2009, Harms-Ringdahl, 2009, Reiman and Pietikainen, 2012
Audits, number performed, settled action points	Basso et al., 2004, Körvers and Sonnemans, 2008, Kampen et al., 2013, Reiman and Pietikainen, 2012
Inspections, settled action points	Körvers and Sonnemans, 2008 Hopkins 2009, Webb 2009, Reiman and Pietikainen, 2012
Safety observations, number	Körvers and Sonnemans, 2008, Hale 2009, Kampen et al., 2013, Reiman and Pietikainen, 2012
Safety procedures, accessibility	Körvers and Sonnemans, 2008, Kongsvik et al., 2010, Bhandari and Azevedo, 2013
Safety training, program, frequency	Basso et al., 2004, Körvers and Sonnemans, 2008, Webb 2009, Kongsvik et al., 2010, Reiman and Pietikainen, 2012, Kampen et al., 2013, Pasman and Rogers, 2014
Toolbox meetings, frequency, presence	Hale 2009
Safety commissions, settled action points	Harms-Ringdahl, 2009
Work procedures, correctly followed, transfer of shifts	Basso et al., 2004, Kongsvik et al., 2010, Bhandari and Azevedo, 2013
Safety stops during enhanced risks	Kongsvik et al., 2010, Bhandari and Azevedo, 2013
Human performance meetings, number	Øien et al., 2011b, Reiman and Pietikainen, 2012
Work permits, transfer, correct performance	Øien et al., 2011b, Webb 2009
Contractor-subcontractor, selection, training	Reiman and Pietikainen, 2012
Decisions, safety arguments	Reiman and Pietikainen, 2012
Competence profiles, training	Reiman and Pietikainen, 2012
Manning, shift size	Reiman and Pietikainen, 2012
Contingency plan, training	Reiman and Pietikainen, 2012
Risk assessment during process changes (MoC)	Reiman and Pietikainen, 2012
Safety analyses, number, trends	Reiman and Pietikainen, 2012, Pasman and Rogers, 2014
Safety documentation	Reiman and Pietikainen, 2012
Safety initiatives personnel	Reiman and Pietikainen, 2012

between indicators and self-reported ‘loss of containment’ at these companies. The most commonly used indicators were the lost-time accidents, unsettled issues of safety reports, safety training of workers and near-accidents with potentially serious consequences.

3.4. Occupational safety and process safety

Many people will intuitively see a difference between occupational safety, with a great variety of types of hazards and process safety, with a focus on ‘loss of containment’. The size of the possible consequences plays a role. According to Kjellén (2009), for indicators this difference might be much smaller, seen from a 'hazard-barrier-target' – energy model perspective. However, further research should shed a light on possible overlap between these two types of safety indicators. Companies have a need for simple, understandable and communicable indicators and lost workday as an indicator meets this demand (Table 6).

Despite the fact that the lost workday indicator is sensitive to serious forms of underreporting the lost time accidents were often incorrectly used as indicator for process safety, as shown by the many reports of investigations into major accidents (Tarrants, 1970 Kjellén, 2009; Knegtering and Pasman, 2009; Øien et al., 2011b).

4. Process safety indicators from the professional literature

4.1. Safety metaphors, models and theories as a basis for process safety indicators

The importance of process safety indicators for the process industry is evident in the list of its definitions (Table 7). These definitions fit well with those found in scientific literature (Table 3).

Still there are differences. A focus on improving and benchmarking is prominent, while scientific literature speaks about barriers and safety levels. In the professional literature, three metaphors are frequently referred to; Heinrich's pyramid metaphor (ANSI/API RP754 2010; CCPS, 2010; OGP, 2011), Reason's Swiss cheese metaphor (ANSI/API RP754 2010; CCPS, 2010; HSE, 2006; OGP, 2011; UK Oil and Gas Industry, 2006; Hopkins, 2007), and the bowtie metaphor (CCPS, 2010; OGP, 2011).

Step change in safety, a publication of the British consortium of companies from the oil and gas (UK Oil and Gas Industry, 2006), has modified Shell's Hearts and Minds metaphor (Parker et al., 2006), and relates specific leading indicators to three levels of their ‘safety maturity model’ (Fig. 6).

An initiative of Dutch companies working with large-scale hazardous materials is Veiligheid Voorop (Safety First) (VNO-NCW, 2011). In its documentation the development of process safety indicators is explicitly mentioned, thereby following the coming guidelines of Seveso III. Apart from a scientific focus on process safety indicators, also public authorities (regulators), companies and business organizations support these publications, but stress the importance of experience gained and immediate practical application of results.

4.2. Leading and lagging indicators

Prominent organizations on process safety published reports on this topic (HSE, 2006; OECD, 2008a, b; ANSI/API, 2010; OGP, 2011;

Table 6
Indicators for occupational safety in the scientific literature.

Indicators	References
Occupational safety	
Near accidents, number	Tarrants 1963
Accidents with/without lost days, number	Martorell et al., 1999, Grabowski et al., 2007, Webb 2009, Kampen et al., 2013
Order and cleanliness	Kampen et al., 2013

Table 7
Definitions of process safety indicators in the professional literature.

Definitions	References
Leading and lagging system guards are a double assurance the risk control system is operating as intended, or giving warnings of problems in development	HSE, 2006
Give results of a risk control system (lagging) or (mal)functioning of critical elements of risk control system (leading).	HSE, 2006
Provide information on outcomes of actions (lagging) or the current situation, affecting future performances (leading).	UK Oil and Gas Industry, 2006
Allow organisations to verify if risk control measures taken are still active	OECD, 2008a, b
Performance indicators quantify objectives set and measure performances, enabling to manage, improve, and being accountable.	Olivier and Hove, 2010
A standard for measuring the efficiency and performance of process safety	CCPS, 2010
An indicator gives information, effective in improving safety	ANSI/API, 2010
Indicators are standards of performance and effectiveness of the process safety management system, and associated elements and activities are tracked.	CCPS, 2010
Serious safety incidents (lagging) or performance of parts of the safety management system (leading).	CCPS, 2011
Measurement, analysis of incidents in the area of process safety and facilitate benchmarking	Cefic, 2011
Information indicating a company controls its main risks, equipment integrity and the level of safety of the (production)process.	OGP, 2011
Indicators are the measured variables, linked to safety critical measures	EPSC, 2012
Provides information on the safety situation	Bellamy and Sol, 2012
A key factor for the success of process safety	Bhandari and Azevedo, 2013
An indicator is representative to achieve the possibility/capacity of a result suggested	Heuverswyn and Reniers, 2012

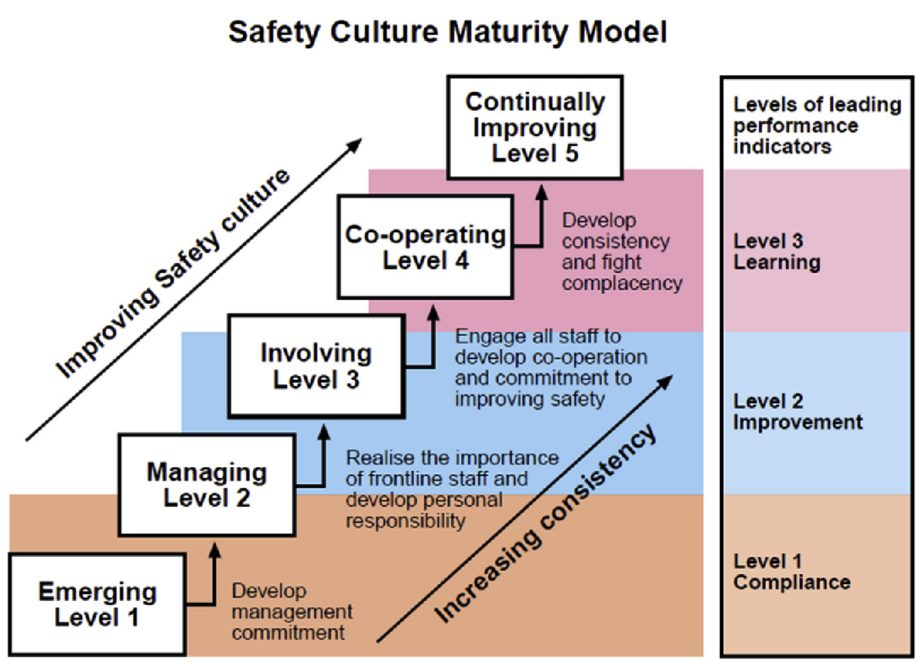

Fig. 6. HSE safety culture maturity model.

CCPS, 2011; Cefic, 2011; UK Oil and Gas, 2012), and many conferences were organised around this theme by the European Chemical Industry Council and the European Process Safety Centre (Cefic-EPSC, 2012). The BP Texas City refinery disaster served as a catalyst for these reports and conferences. The research team of this major accident (Baker Report, 2007) showed clear deficiencies in process safety management, a conclusion which was equally applicable to other refineries and chemical companies. National and international safety committees and organisations supported this comment, like the British Health and Safety Executive (HSE), the US Chemical Safety and Hazard Investigation Board (CSB). The American Petroleum Industry (API), the Centre for Chemical Process Safety (CCPS) and the International Association of Oil and Gas Producers (OGP) subsequently developed guidelines for key performance indicators (KPIs) to reduce and eliminate process risks (Table 8).

HSE provides guidelines for management and safety experts, based on the practice of the British chemical industry for developing, selecting and implementing process indicators for major process risks, including a road map. Important is the timely discovery of weaknesses (leading) in the risk management system, and not so much failure monitoring (lagging). The process safety management system should first identify major accident scenarios, then barriers are selected for each scenario, the so-called risk control systems (RCS). Finally each critical RCS is linked to lagging, and leading indicators, providing dual assurance. At the end of 2015, high-hazard-high-risk companies should measure their process safety performance, using leading and lagging indicators.

Table 8
Process safety indicators in professional literature.

Indicators	References
Process safety	
Alarms, failures, number per time period	OGP 2011, OGP 2008
Exposure dangerous materials/activities	UK Oil and Gas Industry, 2006
State of safety, unwanted	OECD, 2008a, b
Incidents, number	CCPS 2011
Leakage, number, amount	CCPS 2011, ANSI_API 2010, Cefic 2011
Fires, explosions, number, costs	OGP 2011, HSE 2006, CCPS 2011, ANSI_API 2010, Cefic 2011
Loss of containment, amount, number	OGP 2011, HSE 2006, CCPS 2011, ANSI_API 2010, Cefic 2011
Process design, failures	UK Oil and Gas Industry, 2006, OGP 2011, OGP 2008, HSE 2006, OECD,
Maintenance, quality control, failures	2008a, b, OGP 2011, OGP 2008, OECD, 2008a, b,
Tests, failures	OGP 2011, HSE 2006
Safety system, frequency of activation	OGP 2011, ANSI_API 2010
Installations inherent safe, number	OECD 2008a, b
Process disturbances outside design envelop, number	EPSC 2012, ANSI_API 2010
Safety system, frequency of failure	HSE 2006, ANSI_API 2010
Storage dangerous materials, amounts	OECD 2008a, b

Table 9
Management and organisation indicators in professional literature.

Indicators	References
Management and organisation	
Behaviour, unsafe situations, positive feedback	OECD '08
Safety management activities	UK Oil & Gas Industry, '06, OECD '08
safety culture, climate, index	OECD '08
Audits, number performed, settled action points	UK Oil & Gas Industry, '06, OECD '08, CCPS '11, ANSI_API '10
Inspections, number performed	HSE '06, UK Oil & Gas Industry, '06, CCPS '11, ANSI_API '10
Inspections, settled action points	EPSC '12, OGP '11, CCPS '11, ANSI_API '10
Safety observations, number	UK Oil & Gas Industry, '06, OECD '08
Safety procedures, accessibility	OECD '08
Safety training, program, frequency	OGP '11, OECD '08, CCPS '11
Toolbox meetings, frequency, presence	OGP '11
Work procedures, correctly followed, transfer of shifts	OGP '11, HSE 2006, CCPS '11
Human performance meetings, number	OECD '08
Work permits, transfer, correct performance	UK Oil & Gas Industry, '06, OGP '11, OGP '08, OECD '08, CCPS '11, ANSI_API '10
(Sub)contractors, choice, training	OGP '11, OECD '08
Competence profiles, training	UK Oil & Gas Industry, '06, OGP '11, OGP '08, HSE '06, OECD '08, CCPS '11, ANSI_API '10
Manning, shift size	OECD '08
Contingency plan, training	OECD '08, ANSI_API '10
Risk assessment during process changes (MoC)	OGP '11, OGP'08, HSE'06, OECD'08, CCPS '11, ANSI_API '10 EPSC '12, CCPS '11
Temporarily shutting down safety systems	
Inspection program installation	EPSC '12, OGP '11
Safety analyses, number, trends	UK Oil & Gas Industry, '06
Safety meetings personnel & management	UK Oil & Gas Industry, '06, OGP '11
Safety documentation	OECD '08, SCiS '12
Safety studies, number	UK Oil & Gas Industry, '06, OGP '11, OECD '08, ANSI_API '10
Operational procedures, correctness/availability	OGP '11, OGP '08, HSE '06, CCPS '11, ANSI_API '10
Emergency procedures, correctness/availability	HSE '06, OECD '08, CCPS '11, ANSI_API '10
Law offences, deviation of standard	UK Oil & Gas '06, OGP '11, HSE '06, OECD '08
Communication during normal operation and emergencies	HSE '06, OECD '08
External communication and cooperation	OECD '08
Hazard identification and risk analysis	OECD '08
Product safety	OECD '08
Reports/studies of (near) accidents	OECD '08
Safety culture, number/frequency of evaluations	CCPS '11
Safety policy published and communicated	UK Oil & Gas Industry, '06
Suggestions for safety improvements, number	UK Oil & Gas Industry, '06

This is the strategic goal of the British COMAH (Control of Major Accident Hazards) Competent Authority, which is similar to the Dutch BRZO Competent Authority.

The Organisation for Economic Cooperation and Development (OECD) published the 2008 Guide on Developing Safety Performance Indicators in 2 versions: one for industry and one for public authorities and civic associations. These documents, developed by a group of experts from the public and private sectors, are based on 'best practices' of measuring safety performance. A distinction is made between:

o Result indicators, which are reactive, lagging, and either specify a desired result is achieved but not why, and
o Activities indicators, proactive, leading, identifying a specific safety performance relative to a benchmark (tolerance level) and can indicate why an outcome is reached

It is stated that safety performance indicators could indicate if critical elements of safety controls are functioning adequately before catastrophic failure occurs. Both outcome indicators and activity indicators can be linked to the various elements of the safety management systems in companies, or to various groups concerned (public authorities, aid-giving organizations such as police, fire, etc. and citizen groups).

The American ANSI/API Recommended Practice 754 is particularly aimed at refineries and chemical industry, providing precise definitions and an indicator classification for benchmark purposes. A distinction is made between 4 different types of process safety events (PSEs) which, in order of decreasing severity, are referred to as tier-1 to tier-4, and are linked to different kind of events, and corresponding indicators (Fig. 7).

Tier-2 is defined as a near-miss event, as an indication of a barrier weakness, which can be seen as leading. Statistics show a much higher frequency of Tier-4 events, than tier-1, therefor the different process safety indicators are shown schematically as a pyramid.

The Centre for Chemical Process Safety, gives further details on ANSI/API RP754, including examples of leading indicators and associated quantifiable parameters. Identified risks, accident scenarios and related barriers are the starting point for indicators. The process safety management system is starting point for leading and lagging indicators of the 'risk based process safety overview' (CCPS, 2014). Again, quantifiable parameters are suggested, coming from a slogan broadly accepted in industry 'you cannot manage what you do not measure'.

The International Association of Oil & Gas Producers OGP issued OGP report no. 456, Recommended Practice on Key Performance Indicators, following a previous OGP report no. 415 on Asset Integrity, and refers to both HSE guidelines and the ANSI/API RP754. OGP links leading indicator to preventive barriers and lagging indicator to de-escalating barriers. For so-called critical barriers a combination of a leading and a lagging indicator is suggested to test the strength of the barrier. A subsequent indicator could detect barriers defects, as advised by the HSE. However, the distinction between leading and lagging, is, according to the report, not always clear.

Leading indicators in Step Change in Safety of the British Oil and Gas Industry are the result of a comprehensive analysis of current practices in their oil and gas industry. While lagging indicators provide information on the outcome of actions, leading indicators detect a present situation which could have an effect on future results. Depending on the status of safety culture in an organization, three types of leading indicators are identified: 1) compliance, 2) improving the performance, 3) learning organization. The choice of the indicator should fit the organization. Examples of leading indicators for all three levels are given. Step Change in Safety also instils conditions for adequate, effective and usable safety indicators: they need to be accessible and linked to the safety management system in charge, they need to be objective and measurable and lead to control actions. Indicators are only effective when they are part of a continuous learning process of a company. Results from indicators should not stand alone.

Finally, Cefic, the European Chemical Industry Council, issued his Guidance on Process Safety Performance Indicators, for benchmarking purposes, and pays no attention to leading indicators.

Next to the distinction between leading and lagging, other indicator classifications are mentioned in the professional literature. One is based upon the so-called 'performance pyramid', including a hierarchy with result-indicators for the outcome of the safety management system as the highest level. At an intermediate level, system-indicators measure the efforts the system, and operational-indicators are defined at the grassroots level which measure concrete achievements in the organization (Olivier Van and Hove, 2010). Also Heuverswyn and Reniers (2012) are using a trichotomy of indicators. Management-indicators show whether conditions are present to achieve desired goals. Process-indicators show whether assumed objectives are feasible, and whether the effort as planned was performed correctly. Finally, result-indicators are proxies for performance, what has been achieved given a preset goal.

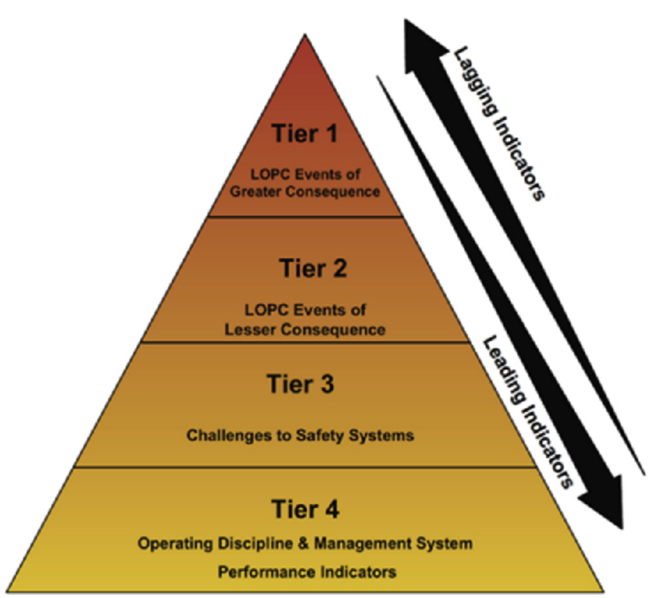

Fig. 7. Process safety indicator pyramid (ANSI/API, 2010).

4.3. Indicators for management and organization

Table 9 represents organisational and managerial indicators found in the professional literature. As with the same item in scientific literature (Table 5), and with process indicators from both sources in Tables 4 and 8, the resemblance is striking.

4.4. Occupational safety and process safety indicators

In literature a clear distinction is made between occupational and process safety. Their origin is different; their scenarios, barriers, and consequences. But recent research shed another light on this matter, showing that minor, more frequent, accidents can provide information about the major or catastrophic accidents. This relationship, however, is limited to the same risk category (Bellamy, 2015), suggesting that both types of accidents partly follow the same scenario pathway.

5. Discussion and conclusion

Installations in production processes can, for various reasons reach the border of their so-called (safety) design envelop. Based upon their craftsmanship, experienced operators will take action preventing a further development of major accident scenarios. Process safety indicators may act as an additional instrument, showing these changes in risk levels and their relation with the effectiveness of the safety management system in place. But it seems too futuristic yet, to use indicators as a predictive signal for forthcoming major accidents. This reflects the attention on the topic, only the last eight or nine years process safety indicators are a topic in the scientific and professional press. Eight-nine years is not a very long time period and not surprisingly the topic of process safety indicators is still under discussion. It is also reflected in its definitions. The tables show a variety of definitions, both within the scientific and within the professional literature.

The safety metaphors, models, and theories discussed should be a basis for the search indicators. These metaphors, models, and theories have been developed at different periods in time for different reasons and in different industries, explaining their different conclusions and insights. Both the bowtie, and the Swiss cheese metaphor point in the direction of barriers and of management, or latent factors. In the drift to danger model one of these latent factors refers to the impact of decisions and conflicts that may arise between safety, and other company goals. Decision making is broadly defined and includes both decisions on the scope and efficiency of the production, on maintenance and turnarounds, as on the quality of outsourcing and the impact of laws and regulations.

The list of definitions shows quite some similarity between the definitions in the scientific and professional literature. Definitions of research groups remain closer to the safety metaphors and models by explicitly referring to (repeated) process disturbances, barrier quality, root causes and precursors of loss of containment. The definitions from the professional literature are closer to regulation requirements, to practical applicability, and to effectiveness of process safety management. Regularly an explicit distinction is made between leading and lagging safety indicators. The American ANSI/API thereby introduced their four level pyramid. Distinction between the different levels is not very clear and the pyramid seems to be dictated more by legal than by theoretical arguments.

The scientific literature questions a difference between leading and lagging. The more general term of safety indicator is recommended. A final difference between the academic literature and the more practically oriented professional literature is the function of safety indicators. In the professional literature indicators primarily seem to have a descriptive function. They are used to monitor progression over time within a company or to compare results between companies, the so-called benchmark (Grote, 2009; Sedgwick and Stewart, 2010). Differences between indicators for management and organisation in the two literature sources are less marked.

Safety metaphors, models, and theories can guide the formulation of process safety indicators. This review shows a complicated metaphor/model/theory-indicator relationship. But literature seems to agree on a scenario/barriers–indicator relation. A search for process safety indicators may start with a selection of major accident scenarios, say the top-15 or top-20 of the most dominant scenarios selected both by process engineers, plant managers and operators. This selection will be input for a HAZOP type of session, to detect barriers present per scenario, including management supporting systems and management actions related to these systems.

To meet the need for quantification, dominant in industry, numbers of activities, incidents, interventions etc. are counted. Problems with quantification, both for process as for management/organisation indicators have been mentioned several times. Numbers do not contain any information on quality (Hale, 2009; Hudson, 2009; Øien et al., 2011b). More experience with safety indicators is needed (Guastello, 1993; Chaplin and Hale, 1998). A similar argument counts for organisational causes of accidents. With hindsight latent factors, or conditions are clear, but prospectively the relationship with hazards and risks seem relatively vague (Kongsvik et al., 2010; Øien et al., 2011a; Bellamy and Sol, 2012; Pasman, 2015).

To conclude, process safety indicators seem to provide insight into the safety of a process or a company. Confirmation, based upon empirical research is necessary. However, it is clear that the 'silver bullet' has not been found yet (Webb, 2009). Safety indicators associated with barriers quality, scenarios and on effects of decision-making appear to be the most obvious ones. Logically, this will make safety indicators, process- and company-specific. The challenge is to define indicators that provide insight into the quality of barriers and development of scenarios. Future international regulations, like Seveso legislation updates, possibly will allow process safety indicators to remain in the spotlight (Knijff et al., 2013).

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