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Review

Safety management systems: A broad overview of the literature

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ABSTRACT

This paper describes safety management systems (SMSs) on five core aspects: definition, evolution, models, purpose and common elements of SMSs. A safety management system implements safety management activities, so an overview of definitions of safety and safety management sheds light on the content of an SMS. SMSs emerged from the risk concept and safety defences. The development of SMSs was boosted by research into 'safety', 'management' and 'system' theories, (safety) risk analysis techniques, safety audit tools, and related standards. Consequently, the study of SMSs became a multidisciplinary topic and through modelling SMSs, a generic framework can be established aiding the effectiveness of SMSs.

There are two main groups of models informing SMSs: (1) accident related models, and (2) organisational models. The relationship between these two models is outlined in this paper. Moreover, we discuss that SMSs studies and models are developed for two main purposes: control and compliance. To control means by implementing safety systems or subsystems, an SMS is able to control risks and to improve continuously, as well as comply with the appropriate standard management systems. As the key to implementing a functional SMS is to carry out common managerial processes, we map the elements of various SMSs to a generic SMS to explore the extent to which they correspond. Like a diamond needs to be cut with facets to show its brilliance, this paper intends to determine and clarify the 'facets' of an SMS, and to distinguish all issues clear-cut for the modelling of an SMS.

1. Introduction: overview approach and objective

A safety management system (SMS) is either a system that is used to manage and control safety or it is a management system specifically aimed at safety. Taking three perspectives, i.e. safety, management and system, an SMS is the intersection of these. How an SMS evolves over time depends to some extent on the individual progress of each of these three aspects. Safety primarily focuses on its opposite, i.e. accidents, loss or injuries, which are often described using models and metaphors (see Swuste et al., 2010, 2011). The terms management and system both have broad meanings: management involves planning, organising, leading and controlling functions (Robbins and Judge, 2012); the elementary principle of a system is input–process–output (Hale et al., 1997; Hammer, 1971; Waring, 1996).

The following steps were taken for this overview (Fig. 1):

1. Select keywords and databases; initial keywords used were 'safety', 'management' and 'system';
2. Filter the outcome using the resulting titles;
3. Extract papers;
4. First bibliometric analysis of texts (e.g. abstract);
5. Refine overview sources.

Although the term SMS is widely used, its definition, scope, modelling and purpose still need to be clearly defined. To gain insight into the origins and development of SMSs, this paper will focus on the following five questions.

1. What is an SMS? (Definition)
2. How does an SMS evolve? (History)
3. How are SMSs modelled? (Model)
4. What are SMSs used for? (Purpose)
5. What are the constituting elements of SMSs? (Elements)

2. Definition of an SMS

2.1. Definition of safety

Safety is a broad and abstract concept, which is best described in terms of a particular state or situation (Table 1). This state is freedom

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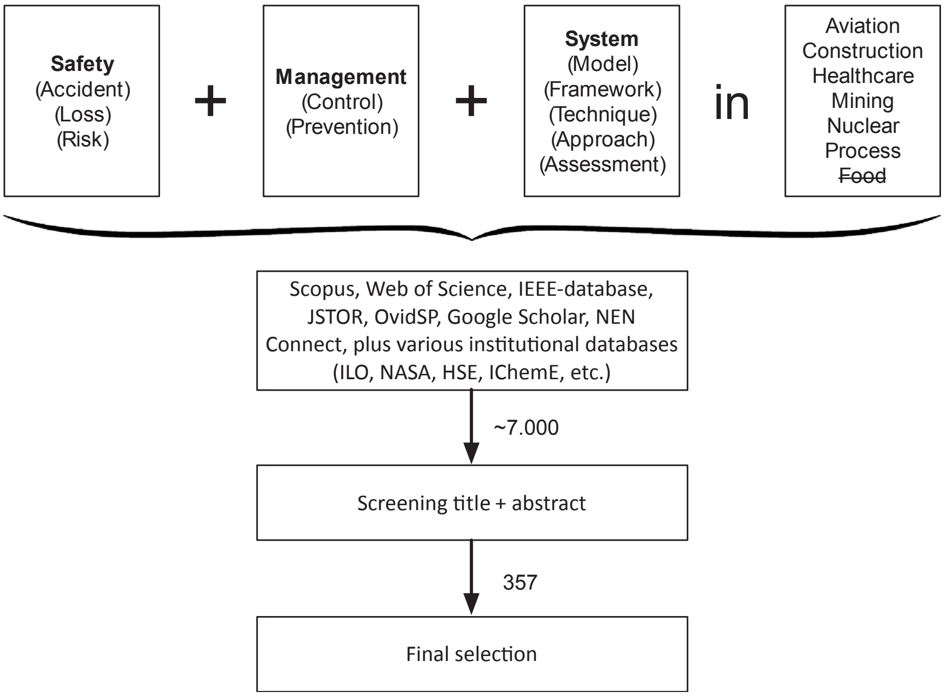


Fig. 1. Procedure for selection of papers for overview.

Table 1
Safety management system definitions.

Authors	Industry	Definition
Kysor, 1973		A Safety Management System (SMS) can be defined as a planned, documented safety program that incorporates certain basic management concepts and activating elements into a well-organized safety system. The safety activity areas and supporting elements that comprise this system act and interact on one another to help achieve the desired safety level or risk level. A total safety management system consists of objects: parameters such as input, process, output, and feedback control; attributes: properties of parameters such as the external manifestation of the way in which an object is known, observed, or introduced in a process; relationships: bonds that link objects and attributes in the system process
Carrier, 1993	Offshore	ADCQ's Safety Management System (SMS): a system designed to cover a broad band of safety activities and provide positive management control
Waring, 1996	General	Functionalist/engineering world view: a set of documented procedures or people using such a set of procedures Interpretive world view: a human activity system including control monitoring communication, operational and other elements as well as complex human factors
IAEA, 1999	Nuclear	The safety management system comprises those arrangements made by the organisation for the management of safety in order to promote a strong safety culture and achieve good safety performance
Mitchison and Papadakis, 1999	Legislation (directive)	A Safety Management System (SMS) is defined in the Directive (Seveso II) as including 'the organisational structure, responsibilities, practices, procedures, processes and resources for determining and implementing the major-accident prevention policy', in other words the system for implementing safety management
Edwards, 1999; Hsu et al., 2010	Aviation	A safety management system is no more than a systematic and explicit approach to managing safety – just as a quality management system is a systematic and explicit approach to improving the quality of a product to meet the customer's requirement
DOE	Energy	Safety Management Systems provide a formal, organized process whereby people plan, perform, assess, and improve the safe conduct of work. The Safety Management System is institutionalized through Department of Energy (DOE) directives and contracts to establish the Department-wide safety management objective, guiding principles, and functions
Ivan et al., 2003	Transport	A highway Safety Management System (SMS) is a systematic process designed to assist decision makers in selecting effective strategies to improve the efficiency and safety of the transportation system
ERA, 2007	Railway	Safety management system means the organisation and arrangements established by an infrastructure manager or a railway undertaking to ensure the safe management of its operations
ICAO, 2007	Aviation	A safety management system (SMS) is an organized approach to managing safety, including the necessary organisational structures, accountabilities, policies and procedures
Stolzer, 2008	Aviation	A dynamic risk management system based on quality management system (QMS) principles in a structure scaled appropriately to the operational risk, applied in a safety culture environment
Waddington et al., 2009	Aviation & Nuclear	Safety Management System (SMS) approach aimed at harmonizing, rationalizing and integrating management processes, safety culture and operational risk assessment
Thomas, 2011	Transport	Modern SMS could be defined as an arbitrary collection of activities that were deemed necessary actions to discharge responsibilities under the new age of the delegated responsibility of self-regulation

from 'something' that could have negative consequences, such as harm to humans or animals, economic loss, or any other form of damage or loss. In other words, safety is the condition whereby unexpected events, such as accidents and incidents, are being avoided. In specific contexts, safety can be defined in more practical terms. For example, in a hospital, the safety of patients means keeping patients in a stable condition by avoiding the risk of adverse events (Shojania et al., 2001).

This paper is concerned with industrial safety; hence, the unexpected events and risks arise within the context of industrial activities. However, a zero-risk situation, or absolute and unconditional safety, does not exist. Although some companies nowadays attain a zero accident or injury record for a certain period of time, it does not imply they are risk-free. Because 'risk is a measure of the probability and consequence of uncertain future events; it is the chance of an undesirable outcome' (Yoe, 2011, p. 1), while safety is, according to IEC 61508, 'freedom from unacceptable risk' (NEN, 2005, p. 13). We can therefore conclude that the safety of an industry is judged by its acceptable risk.

Whatever the context, the overall scope of *safety* can be divided into human, environmental and equipment safety (Dezfuli et al., 2011a, 2011b). The scope of safety, however, often depends on the context or on particular research views. For example, according to IEC 61508, defining the scope of safety is a step towards the building of automation and control systems (Novak et al., 2007), which is a definition focussed primarily on technology. In other words, the scope of safety refers to the particular objects that safety management focuses on.

2.2. Definition of safety management

Following the first workmen compensation act of 1908, which stated that 'in effect, that regardless of fault, management would pay for injuries occurring on the job' (Petersen, 1978, p. 11), safety gradually became a management issue. *Safety management* is the concept of 'the MANAGEMENT [capitals in original] of safety and uses the same concepts, principles and techniques as used in other areas of management' (DNV, 2012, p. 2). When comparing *safety* with *safety management*, the former refers to a state or condition, the latter is a process or a series of certain activities. Furthermore, *safety* is the freedom from unacceptable consequences, *safety management* is the process to realise certain safety functions. In this current context, the aim of (safety) management is safety, protecting human beings, the environment, equipment and property from unacceptable risk.

Managing safety is a comprehensive effort and needs an organisation to determine safety requirements (Strutt et al., 2006), design a safety management structure and process, and decide which activities need to be implemented in order to achieve pre-defined safety requirements. Harms-Ringdahl (2004) states that management actually tends to create a safety management system by combining the management process and activities into one system. But how can safety management activities be designed in a systematic and scientific way? This should be done by applying certain *techniques* (Leveson, 2011; Petersen, 2003), *approaches* (Dhillon, 2010; Petersen, 2001; Wu et al., 2010), and *models* (Gower-Jones and van der Graf, 1998; Hale et al., 1997).

2.3. Definition of safety management system

Since 1973, the safety management system has gradually developed into a main topic for safety science (Kysor, 1973). An SMS is commonly defined as the management procedures, elements and activities that aim to improve the safety performance of and within an organisation. 'Modern SMSs could be defined as an arbitrary collection of activities that were deemed necessary actions to discharge responsibilities under the new age of the delegated responsibility of self-regulation' (Thomas, 2011, p. 3). *Safety management* means 'a systematic control of worker performance, machine performance, and the physical environment' (Heinrich et al., 1980, p. 4). To structure this systematic control, the *safety management system* bundles all safety management activities in an orderly manner. An SMS is a very practical concept, widely used in different industries (Table 1).

According to the definitions in Table 1, apart from *safety*, *management* and *system*, several other key words characterise an SMS, such as *activity*, *approach*, *control*, *operation*, *process* and *procedure*. Although these definitions are provided in various contexts, they represent the broad meaning of an SMS and its common understanding from users. In this paper, we will explore with which aspects and words SMS have been described in the literature.

Apart from the broad definitions coming from different industries, the concept of an SMS sometimes gives rise to confusion when compared with other similar terms. Some of these concepts are discussed below.

2.3.1. The concept of risk management system

As safety management focuses on managing risk, the structure of a risk management system sometimes represents a rough SMS, but actually is only a part of a complete SMS. Following Greenwood and Spadt (2004) a risk management system consists of a policy, a risk data system, and a risk system for assessing and evaluating risks. Risk not only pertains to safety but also to economics, i.e. financial risk. However, the principles are similar for any kind of risk management system (ISO, 2009). It means objects for risk management could be well beyond the scope of safety risk. At the same time, a safety management system is also more than a risk management system. There are many examples of SMSs in which a (safety) risk management system is an important component, despite the fact that some regard a safety management system a phase of risk management (Demichela et al., 2004). Safety risk management is a critical component in the SMSs proposed by the International Civil Aviation Organization (ICAO) and the Federal Aviation Administration (FAA). Hale's SMS also contains a *risk control system* as one of its two constituent components (2005). Although there are many other SMS frameworks of that do not have a risk management system as an actual component, they do identify, evaluate and control hazards, which also represent a way to manage risk.

2.3.2. The concept of control system

Control systems approximate the function of an SMS. Management Control Systems (MCSs) as defined by Anthony (1980) are the processes by which managers ensure that resources are obtained and used effectively and efficiently in the accomplishment of an organisation's objectives. This concept comes from systems engineering, which states that by applying control, an input can be translated into an output. Similar to a risk management system, a risk control system involves risk identification and assessment (You, 2003). 'A loss control system for an insurance classification plan has a policy holder database, a predictive apparatus and a derived actual loss ratio generator' (Zizzamia, 1999, p. 1). Working in insurance, Bird developed a loss control system and a loss control management concept. Loss control management 'provides ideas, tools and inspiration to help keep personal injuries, with the resulting human suffering and severe economic losses, to a minimum' (Bird, 1974; Bird and Loftus, 1976, p. iii). Several recent models also contain control loops, like Leveson's STAMP control loop for operating processes (2004) and the SADT technique Hale used for his SMS framework (1997). A risk control system is sometimes used for a specific engineering or management system at the worksite, where control is needed to achieve a certain reliability or safety level. Control is an important part of an organisational management system, focussing on hazards, risks and safety activities.

3. History of safety management systems

3.1. Development of safety management over time

As described above, the main purpose of safety management and its supporting system is to control risks and, by doing this, to prevent accidents. The history of SMSs therefore partly coincides with the history of accident prevention or, more generally, the history of safety science itself. As this history has been described extensively elsewhere (Swuste et al., 2010, 2011), we suffice here with a brief overview. Overall, we see two main impetuses for the commencement of safety management systems: work carried out at insurance companies and accident prevention efforts by industry.

3.1.1. The insurance perspective: analyse loss patterns and develop risk management

Accidents caught the attention of insurance companies as they can be costly. Insurance is a means of protection from financial loss, so researchers became interested in the analysis of loss patterns. Heinrich (1931) analysed a vast amount of industrial accident records from insurance companies and based his accident models and theories on these: the iceberg model, an accident sequence model (domino theory) and the 300-29-1 ratio injury model. After reconsidering many loss patterns, especially the causes of loss, in later versions of his book notions of organisational management and risk management are introduced (1980). Similarly, Bird (1974, 1976) also analysed insurance companies' accidents reports, and revised Heinrich's injury model ratio based on these analyses, which were then used as input for his version of loss control management. However, the connection between accidents and loss control was not yet fully matured at the beginning of the development of SMSs.

The concept of risk is a critical output of insurance studies that just demonstrates this connection. Modern risk management started in the mid-1950s, as large companies began to develop self-insurance against risks. 'Self-insurance covers the financial consequences of an adverse event or losses from an accident' (Dionne, 2013, p. 149). As mentioned previously, risk management is a constituent part of safety management systems. Derived from the financial field, it offers methods to identify, assess, and mitigate risks, and subsequently to reduce loss. Industrial safety management has benefited to a large extent from the methods and techniques used in risk analysis.

3.1.2. The industry perspective: prevent accidents and develop safety defences

From a company's perspective, safety means that no accidents happen in factories, plants, or projects. Accident prevention is the primary task for safety management because accidents cause not only financial loss but also reputation damage. A safety goal (e.g. zero-accidents) is much more clear-cut than any risk acceptance levels in organisational management; zero accidents simply means no accident. In order to achieve such a straightforward goal, safety defences are used to prevent accidents, which includes safety equipment, devices and many behavioural activities. Even though the concept of defences (also called barriers) has been elaborated further in several theories and models (such as the Hazard-Barrier-Target model and Reason's Swiss Cheese model) they are indeed the practical safety management devices, developed and delivered in companies before formal SMSs emerged.

Safety equipment or devices are the hardware defences that prevent or protect against any harm. Setting up 'the installation of safety devices as complete a system of mechanical safeguards as possible' could indeed prevent accidents. These basic safety appliances, checked by a safety committee in London from 1917 on, led to a reduction of accidents (Vernon, 1919, p. 51). The introduction of *system safety* techniques in the 1950s improved their reliability and effectiveness further. System safety is primarily concerned with engineering reliability using quantitative methods. It helps decrease failures of components and systems of machines and installations; it also reinforces safety hardware systems.

In parallel, safety behavioural activities were developed for the prevention of accidents. In the early 1900s, with the introduction of legislation for workers, companies began to pay more attention to safety management activities such as the introduction of an accident recording system, individual safety measures, i.e. personal protection equipment, and safety measures on the shop floor. For example, in 1912 DuPont started to maintain a full record of accidents and introduced basic safety training. Another example of individual safety activities is the FAA-programme for carrying out accident prevention responsibilities. It briefly describes the activities of a maintenance system, fire warning, air traffic control, flight checking and training, accident investigation and hazard identification as separate activities. All these activities are the safety defences in the aspect of *management* above.

3.1.3. The commencement of SMSs: merging the risk concept with safety defences

A first glimpse of safety management systems appears when risk management is applied to loss control and safety defences are developed to prevent accidents. As a matter of fact, the frequency of use of the term risk has increased significantly since the 1960s, which roughly coincides with the use of the term *safety management system* (data obtained from Google's Ngram viewer). Statistically and logically, (safety) risk plays an important part in safety management systems. As safety defences become more advanced and complicated along with the improvement of technologies, management systems are required to implement, maintain and update these. In general, risk analysis and safety defences provide management with both strategical and practical information.

3.2. The period 1970–1990

3.2.1. Accident theories as driver for the development of an SMS

Following Heinrich's accident causation sequence (1959), various accident causation and prevention theories – e.g. Haddon's (1973) energy transfer theory – were updated (Smillie and Ayoub, 1976). The general idea of cause-effect and consequence began to take shape (Nielsen, 1974). Bird's 'Management Guide to Loss Control' discusses the cause and effect sequence model (1974). In order to control hazards and prevent accidents, the concept of barriers was introduced. The term 'barrier' is one of Haddon's ten strategies of safety countermeasures (Haddon, 1973). MORT (Management Oversight and Risk Tree) was developed for U.S. nuclear risk management as a safety assurance system (Johnson, 1973, 1980). Originally based on an energy transfer model, MORT extends this concept with (preventive and defensive) physical barriers that can be put in place to stop the transfer of energy.

In the same period, after Kysor (1973) had introduced the concept of an SMS, Adams (1976, 1977) proposed that accident prevention has the same function as a safety management system. He outlined a system, which is based on 'the philosophy that accidents in the workplace have their root cause in the management structure; the objectives of the organisation; how management is organised and how operations are planned and carried out' (Adams, 1977, p. 279) Later, Weaver (1980) compared and evaluated various safety management and accident prevention systems. He pointed out that cases of the early sequence model are beyond management control. As these cases are at the root of different accident causes, a series of ideas about safety management were proposed. The steps of the accident prevention model and a flowchart of the safety management process directed the causation and prevention theory towards a framework of SMS (Denton, 1980; Saari, 1984).

3.2.2. System safety, the socio-technical concept and the system theory in support of SMS

During the 1970–1990s, system safety techniques increasingly became a subject of safety management studies and contributed to initial efforts to establish SMSs (Collins and Dickson, 1989; Grose, 1971; Hammer, 1971; Holt, 1971; Lee et al., 1985; Pope, 1971; Weathers, 1982). System safety tools and techniques can be used to analyse, identify and display potential hazards. For instance, the International Atomic Energy Commission's General Design Criteria for Nuclear Power Plants Construction Permits (Seth, 1971), NASA's R&D operating system (Connors and Maurer, 1975), and the design phase of the Intermediate Capacity Transit System (ICTS) (Rumsey, 1980) are all applied system safety approaches despite their different safety purposes.

The socio-technical concept arose in conjunction with the first of several field projects undertaken by the Tavistock Institute in the British coal mining industry (1949). Between 1950 and 1970, the use of this concept also increased in other industries, such as the projects of 'The Shell Philosophy' and 'Coal Mining' (Trist, 1981). Socio-technical systems were then for the first time mentioned in relation to safety management as a methodology for organisational design (Robinson, 1982).

The system theory provides an SMS not only with an approach but also with mechanisms and structure. The 'Man-machine-environment-system' (MMES) was proposed in 1981 and combined with *cybernetics* used in safety actions systems, which include system analysis and preference synthesis (Kuhlmann, 1986). Kuhlmann claimed that cybernetics could clarify the elements of a system and the relationships between those elements and the environment. As a result of applying a system framework and its accompanying techniques to safety management, the development of SMSs became more practical and applicable.

3.2.3. Specialised organisations and legislation

In the 1970s and 1980s, three developments made safety management systems a topic of more general interest, namely (1) the increased demand for regulation in European countries; (2) official reports following major disasters and; (3) the introduction of international standards for quality management systems as a basis for SMSs (Hale et al., 1997). Kuhlmann (1986) also developed a scheme for standardised hazard protection, using three levels of enforcement namely, instrument safety law, administrative regulations and technical standards. Both Hale et al. and Kuhlmann emphasised that specialised legislation plays a pivotal role in safety management. To authorise these laws, regulations and standards, safety-related organisations and dedicated departments in government and industry were established.

To publish specific laws and regulations to improve safety management, specialised organisations are needed. At the beginning of the 1970s, a number of specialised safety organisations were set up, such as the Occupational Safety and Health Administration (OSHA) in 1970 the US, the Health and Safety Executive (HSE) in 1974 in the UK, and the World Safety Organisation (WSO) in 1975. These organisations not only published laws, regulations, and collected accidents and incidents information, but also raised awareness for safety management. These organisations provide a platform for safety professionals and update their information continuously.

The increasing awareness for safety and the occurrence of serious accidents lead to more laws, rules and regulations. In the chemical industry, after the Italian Seveso disaster in 1976, the Seveso directive (Directive 82/501/EEC) was published; the Indian Bhopal disaster (1984) resulted in the Seveso-II (Directive 96/82/EC), which was updated after the French Toulouse accident (2001). In the nuclear field, following the Three Mile Island accident (1979) and the Chernobyl disaster (1986), 'a joint protocol forming a bridge between the two existing international nuclear liability regimes was established' (NEA, 2006, p. 3). In oil and gas, after the Piper Alpha disaster (1988), the regulations for offshore safety management were improved (Singh et al., 2010). To sum up, major accidents thrust the development of safety legislation forward.

A standard is defined as 'something used as a measure, norm, or model in comparative evaluation' according to the Oxford dictionary. There are international general standards, or industrial standards, issued by organisations such as ISO (general), ILO (general), HSE (general), ICAO (civil aviation), IAEA (nuclear), IChemE (chemical), IOGP (oil and gas), SPE (petroleum) and NASA (aeronautics and space travel). During this period (1970–1990) international standards for SMS were beginning to emerge. For example, in 1981, ILO published the Occupational Safety and Health Convention and Recommendation that established the principles for national policy and action (ILO, 1985). In 1987, ISO published a quality management system standard, which was built on the principles of a company QSM and formed the foundation for future SMS standards. Similarly, OHSA and HSE published a series of industrial regulations. All of them contributed to the foundation of international structural safety standards, which were developed during the next decade.

3.2.4. SMSs and applications

Major accidents and standards started to draw companies' attention to SMSs in a global context (Bowonder, 1987; Mcnutt and Gross, 1989; Tombs, 1988). Since the mid-1970s, Australia put efforts into developing EH&S (environment, health and safety) management and initiatives, such as 'contractor management, quarantine procedures, incident and injury reporting and investigation, etc.' (Kegg, 1998, p. 441). What followed was a shift from individual initiatives to a systematic approach through the development of a safety management system (Kegg, 1998). Especially towards the end of the 1980s, some large companies (e.g. SHELL, Exxon, DSM, etc.) established their first versions of an SMS. They put their safety management activities into a kind of management framework as principles or elements of the safety guidelines for the whole corporation. From then on, safety management systems are widely used in companies to control their risks.

3.2.5. Audit tools

Internal audits aim to review and improve an SMS, while external audits aim to assess legal, regulatory, or certificate compliance (ISO, 2011). Audit tools and the assessment of SMSs are studied along with safety management theories. Based on loss control theory, the 'International Safety Rating System (ISRS)' audit tool was developed in 1978. In order to establish the International Safety Academy (ISA), Bird put forward a management control system with four functions of management: planning, organising, leading and control. This is based on industrial hygiene, loss control, risk management and training of specialists (Bird, 1974; DNV, 2012, 2013). This audit system was then systematically applied to different industries for assessing an SMS.

Under the banner of self-regulation, companies gradually became responsible for devising, installing and monitoring safety management systems (Feyer and Williamson, 1998, p. 134; Hale and Hovden, 1998). By applying an audit system, the effectiveness of an SMS could be further improved (Ashburn and MacDonald, 1987; Wallace, 1990). To summarise, in this period audit tools with assessment methods were developed and used both nationally and internationally (Conrad, 1984; Eisner and Leger, 1988).

3.3. Post 1990

3.3.1. Multi-disciplinary techniques and models

After the 1990s, SMSs became more sophisticated and multi-disciplinary by making use of an increasing number of new techniques, audit tools and standards. These new techniques helped to expand the study of safety management modelling, whereby the models became comprehensive systems rather than just reflecting accident sequences. In particular, two kinds of models were applied: the *accident* model and the *organisational* model. As the study of safety management originally is concerned with the causes of accidents and incidents as well as their prevention, the causation model became more mature; the safety management system is part of an organisational management system, the essence of which is the organisation model.

Thus, modelling SMSs became an important topic with many issues involved. Sometimes, it pertains to more than one model, theory or method. All these models are related to the SMSs at any level, i.e. the theoretical, practical, and standard level. Reason studied complex systems and developed a safety causation and control model involving human factors and feedback loops (Glendon, 1995; Reason, 1990a, 1995a). Another causal model, the Bowtie model, combined with BBNs (Bayesian Belief Nets), were used to model complex systems (Ale et al., 2006, 2009). Furthermore, hybrid causal methodologies incorporating physical & social failure were also extended to management activities and models (Groth et al., 2010; Mohaghegh et al., 2009, 2012; Mohaghegh and Mosleh, 2009). These and other studies on causal models and techniques reflect the current approach to safety management.

Vice versa, multi-disciplinary subjects also provide methodologies and tools for the modelling of risk and management. AcciMap (Svedung and Rasmussen, 2002), Storybuilder (Bellamy et al., 2007a), BowtieXP (Aneziris et al., 2008; Lisbona and Wardman, 2010), and Phonix (Ekanem and Mosleh, 2014; Ekanem et al., 2016) are graphical tools that systematically analyse industrial accidents and hazards. Furthermore, system dynamics as a system engineering technique was applied to SMSs in order to model dynamic factors and their relations (Cook and Rasmussen, 2005; Marais et al., 2006; Yang and Sun, 2010). Others applied the 'systems concept' to safety management and resilience control (Belcastro and Jacobson, 2010; Leveson, 2011). Others applied a system control structure to the model of an SMS (Hale et al., 1997; Waring, 1996). Typically, these tools and models aim to control safety and its management.

Different contexts of SMSs also influence audits or assessment approaches differently. In this period, audit tools were widely used to evaluate SMSs (Bellamy et al., 1993; Cooper, 1998; Glendon, 1995; Hurst et al., 1994; Hurst and Ratcliffe, 1994; Nivolianitou and Papazoglou, 1998; Watson, 1993). There also appeared a number of audit tools only concerned with occupational health and safety (OHS) systems (Emmett and Hickling, 1995; Gay and New, 1999; Lindsay, 1992; Redinger and Levine, 1998). As these multi-disciplinary techniques and models provide methods to calculate potential risks, risk management and assessment is approached here more quantitatively.

3.3.2. Studies of management factors

During the second period (1970–1990), the man-machine-environment system was introduced and traditional safety management factors or risk influencing factors were developed based on these three aspects. After this period, psychological, sociological and organisational factors that influence risks or safety management performance start to appear (Bellamy et al., 2008; Bottani et al., 2009; Makin and Winder, 2009; Øien, 2001; Skogdalen and Vinnem, 2011). Socio-technical factors can be mapped onto the hierarchical system developed by Rasmussen (1997). Having analysed the latent failures in defences, Reason (1995b) emphasised the importance of organisational factors and the need to incorporate these in SMSs and their assessment (Davoudian et al., 1994a, 1994b; Embrey, 1992). Especially human factors and behaviour in SMS became popular topics (Bellamy, 1994; Ranney, 1994; McCafferty, 1995). New methods and techniques also help to model human factors in SMSs (Mearns et al., 2003; Khan et al., 2006; Baranzini and Christou, 2010; Koornneef et al., 2010). Recently, Yang et al. (2017) reviewed the current frameworks for (safety) risk influencing factors and the methods used. Studies of those factors and their influence on risks and SMSs can improve safety performance further.

3.3.3. Standards

Compared to the legislation developed during the second period, an increasing number of international general standards and guidelines have been published; Table 2 summarises some. Actually, different industrial sectors have their own specific standards and regulations, which are published by local and national governments, standard organisations and industrial associations. Although the standards listed in the table could be applied to different industries, the application of an SMS still involves compliance with specific industry safety laws and regulations. Also, these uniform standards are recognised and applied globally.

3.4. Reviews over time

During the development of safety management and SMSs, literature reviews describe this topic from different angles. We simply group these into three levels: theoretical level, practical level, and standard level (Fig. 2 & Table 3).

The theoretical level pertains to the justification, origin and purpose of SMSs. The theories reflect the researchers' perceptions of safety management. The theories and theoretical models support practical SMSs because the basis of an SMS comprises safety, management and system, each having its own theoretical roots. The safety aspect deals with unsafe outcomes and their causes; management in this respect pertains to organisational safety activities; the system provides the framework and the logic for modelling. However, the application of an SMS resides at the practical level.

At the practical level, SMSs are more complex. Some are specific safety management systems, operated within a company or a particular plant. They have different functions, such as collecting information, maintaining (technical) systems or analysing risks. Some general SMSs, especially the SMS framework of large international companies, are also used at the practical level. The advantage is that these general SMSs can be applied in different contexts like in subsidiaries, different regions, and different types of industry. The SMSs at the practical level thus concern both generic SMSs and specific SMSs.

Methods, techniques and audit tools are also developed at the practical level and applied to SMSs. These methods and techniques mostly support the implementation of SMSs. The audit tools are based on models of SMSs to assess the effectiveness or quality of an SMS. All in all, an overview of methods, techniques and audit tools provides insight into approaches to SMSs.

Safety management standards are the guidelines for SMSs published by the relevant authorities. They consist of both generic and industry-specific standards. Issues addressed in the literature are whether these standards are integrated into companies' management systems, whether the companies comply with certain standards and what the effectiveness of these standards is. To some extent, the standards form the basic reference for SMSs of small or medium-sized companies.

In this section, the literature reviewed roughly covers following issues: theories (TH), standards (ST), methods/techniques (MT), audit tool (AT), and SMSs. This overview also shows the historical development of safety management systems. In the beginning, accident theories, methods and techniques were applied most often. Then, standards and audit tools came into the picture. Nowadays, the systemic approach to safety management and the models studying the factors influencing safety or risk are garnering more research effort. However, the SMSs were reviewed from multi-aspects, which is also the aim of this paper.

4. SMS modelling

4.1. Categories of SMS models

As mentioned previously, SMSs are essentially driven by accidents and incidents and the ways to prevent these. With regard to accident or incident analysis or investigation, there are *event models* that depict accident causation mechanisms and that could be used to develop accident scenarios with. These models can be extended further by the insertion of barriers. The term *barrier* comes from Haddon's ten strategies, and they can function as both hardware (physical) and behavioural (involving human action) defences. Barriers are used to prevent accidents and incidents or protect from unwanted consequences. However, event models and barriers are not the full story behind SMSs. *Management system models* are required to explain how to manage safety and how to control risks through the provision of barriers. The management of safety barriers is critical in an SMS, as safety barriers directly prevent unwanted events or mitigate the risk. Consequently, the risk is affected by management's safety performance; i.e. safety management controls the events related to the risk.

Fig. 3 shows the relationship between scenarios, barriers and safety management and also represents the development of models to safety management. According to the definition of a model, the models for an SMS should answer questions about safety management processes. Event models provide accident scenarios, which illustrate the relationship between causes and consequences. In this group of models, the probabilistic analysis of events and consequences determines the

Table 2
Standards for general safety management systems.

Organisation	Industrial sector	Name/year	Aim for
ISO	General	ISO 45001/Under development	Occupational health and safety management systems
	General	ISO 9000 serise/1987, 2008, 2015	Quality management systems
	General	ISO 14001/1992, 1995, 1996, 2004, 2015	Environmental management systems
	General	ISO 31000/2009	Risk management
EU (European union)	Chemical industry (also other industries)	Seveso Directive (Directive 82/501/EEC)/1982 Seveso II (Directive 96/82/EC)/1996 Seveso III (Directive 2012/18/EU)/2012	Control of major-accident hazards involving dangerous substances
	General	(Directive 89/391/EEC)/1996	Guidance on risk assessment at work
BS (BSI Group, British Standard)	General	BS 5750/1979	Quality management systems
	General	BS 7750/1994	Specification for environmental management systems
	General	BS 8800/1996, 2004	Occupational health and safety management systems
	General	BS OHSAS 18001/2007	Occupational safety and health management systems
OHSA (United States)	General	PART 1910 (Standards–29CFR)/since 2001	Occupational safety and health standards

risk of the hazards. If barriers are inserted to prevent unwanted events or harm, the extended accidents model emerges. Barriers have a risk control function, which is directly connected to the management system. The extensiveness and performance of barriers are determined by the safety management delivery processes. The management delivery processes are described in the SMS. Therefore, a complete model for an SMS should contain an events model, barriers and the management system. Accordingly, three categories of models of safety management can be identified. Their input and output are as follows.

1. **Events:** accident models and theories;
   The input is threats or hazards;
   The output is a risk inventory.
2. Events + **Barriers**: the extension of accident models;
   The inputs are risks;
   The outputs are barrier functions and risks.
3. Events + Barriers + **Management**: the models deliver management efforts;
   The inputs are barriers;
   The output is safety performance.

4.2. Events – accident theories and models

Accident models describe causes of accidents and subsequent events and help to develop accident scenarios describing particular risks. The identification of accident scenarios is important for efficient and professional safety management. 'Accident models affect the way people think about safety, how they identify and analyse risk factors and how they measure performance' (Hovden et al., 2010, p. 955). Although accident and risk are considered distinct topics, the study of accidents actually involves research into risks. Kjellén (2000) classified the concept of an accident into four aspects:

– Damage/loss: includes injuries and fatalities, material- and economic losses, reputation, etc.;
– Incidents: subdivided into type (fall, slip, explosion, etc.) and agency (machine, vehicle, tool, etc.);
– Hazardous conditions: covers defective tools, unsafe design, housekeeping, etc.;
– Unsafe acts: covers errors and omissions.

These categories imply that even if no damage or loss would occur, incidents, hazards and/or unsafe acts still remain topics for accident research. Table 4 shows that the literature mainly emphasises either one particular kind or part of accidents.

The accident models not only reveal the causes of accidents but also provide prevention control in the form of defences. The aim of analysing accidents or injuries is to take lessons from the past so as to achieve state-of-the-art safety management, which explains the relationship between those models and safety management. The history of accident models can be traced back to the 1920s and the models are grouped according to different opinions (Khanzode et al., 2012; Lehto and Salvendy, 1991; Toft et al., 2012). To classify accident models in terms of their contents, this paper uses four mainstream groups (Table 4): (1) Simple sequence & complex sequence; (2) Epidemiology & energy transfer; (3) Simple system & social-technical system &

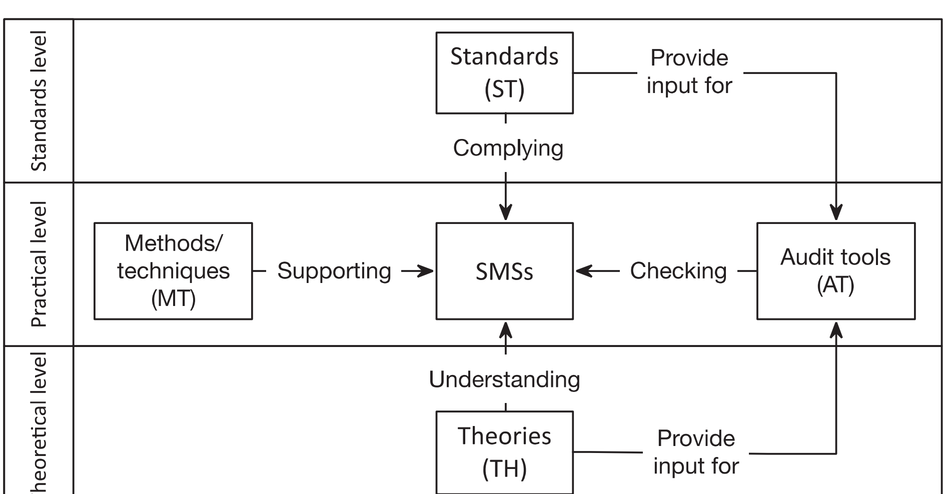


Fig. 2. Issues related to safety management systems.

Table 3
Overview of literature relating to SMSs.

Group	Issue	Title	Contents	Reference
Theoretical Level	TH	*Accident causation theories: A simulation approach*	This paper reviews early age accident causation theories since 1919, including pure chance, biased liability, unequal initial liability, accident proneness, unconscious motivation, adjustment-stress, goals-freedom alertness, domino, epidemiological, specific variables and modelling	Smillie and Ayoub, 1976
		The deviation concept in occupational accident control – I	This paper reviews the causation and control theories, models, and terms by the deviation concept and compares the phases of different process models of accidents	Kjellén, 1984
		Models of accident causation and their application: Review and reappraisal	54 different accident causation models and sixteen methods of application are reviewed	Lehto and Salvendy, 1991
		Accident prevention. Presentation of a model placing emphasis on human, structural and cultural factors	This paper systematically reviews safety interventions for accident prevention. Though it is not related to SMS directly, it shows the behaviour, physical factors of accidents and helps to discover the fundamental theories of SMSs and their influencing factors	Lund and Aarø, 2004
		Highlights from the literature on accident causation and system safety: Review of major ideas, recent contributions, and challenges	This paper's angle is HRO (High Reliability Organising) theory, discusses literature on system safety and accident causation	Saleh et al., 2010
		Safety metaphors and theories, a review of the occupational safety literature of the US, UK and The Netherlands, until the first part of the 20th century	This paper reviews occupational safety theories of three countries at the very early stage of safety science development. Some metaphors are used to show the investigation of accidents and the activities of safety management, for example, Heinrich's iceberg model	Swuste et al., 2010
		Models of Causation: Safety	This paper summarises three kinds of models, which represent three distinct phases from 1920s onwards. They are simple linear models (Heinrich's Domino Theory, and Bird and Germain's Loss Causation Model), complex linear models (energy-damage models, time sequence models, epidemiological models and systemic models) and complex non-linear models (STAMP, FRAM and complexity and accident modelling)	Toft et al., 2012
		Occupational injury and accident research: A comprehensive review	This paper reviews the five stages' development of accident causation theory: accident proneness, domino theories, injury epidemiology, system models, factors affecting injury; and briefly describes injury mechanism models and interventions	Khanzode et al., 2012
		Analyses of systems theory for construction accident prevention with specific reference to OSHA accident reports	This paper reviews and classifies the studies of accident risks, based on Domino theory and OSHA data description	Chi and Han, 2013
		Occupational safety theories, models and metaphors in the three decades since World War II, in the United States, Britain and the Netherlands: A literature review	After the 2010 review paper mentioned here above, this paper continues with describing the occupational safety theories after World War II and during the subsequent three decades, 'The hazard-barrier-target model' and the system method such as 'fault tree' were applied	Swuste et al., 2014
		A review of models relevant to road safety	This paper reviews safety related models and frameworks; and develops seven types of models	Hughes et al., 2015
Practical Level	MT	*Rating accident models and investigation methodologies*	This report reviews fourteen accident models and seventeen different accident investigation methodologies in the selected government agencies	Benner, 1985
		Fault tree analysis, methods, and applications – A review	This paper reviews fault tree construction, application and evaluation including qualitative and quantitative evaluation	Lee et al., 1985
		A causal model of organisational performance and change	This paper summarises the studies for the dimensions of the model, which is built for organisational performance and changes. It provides ten dimensions including leadership, culture, structure, management practices, etc.	Burke and Litwin, 1992
		Safety reviews and their timing	This paper aims to describe the approach of safety reviews but at the same time it summaries and compares some methodologies used in this field (e.g. CHAIR, CHA, PCA, PHA, HAZOP, FEMA, FTA, ETA, What if, PSMSA, PSAudit, Task, HAEA and QRA)	James and Wells, 1994
		Management and culture: the third age of safety. A review of organisational aspects of safety, health and environment	This paper reviews safety management related researches and their institutes or organisations	Hale and Hovden, 1998
		Towards an evaluation of accident investigation methods in terms of their alignment with accident causation models	This paper reviews a series of accident investigation methods within accident causation models. It lists FTA, MORT, MES, CTM, OARU, AEB, SCAT, TRIPOD, ISIM, NSB, WAIT, HSG245, 3CA	Katsakiori et al., 2009
		A review: Advancement in probabilistic safety assessment and living probabilistic safety assessment	This paper summarises the methods of probabilistic safety assessment and living probabilistic safety assessment methods – ESSM (Essential System Status Monitor), DEM (Dynamic Risk Monitor), FTA, ETA, Markov analysis and Risk spectrum software	Zubair et al., 2010
		Risk analysis and assessment methodologies in the work sites: On a review, classification and comparative study of the scientific literature of the period 2000–2009	This paper specifically reviews methodologies used for risk analysis. Authors takes the angle of risk management and its technical uses	Marhavilas et al., 2011
		Safety management for heavy vehicle transport: A review of the literature	This paper reviews safety management interventions and measurements. It distinguishes three groups of relationships between the organizational characteristics and safety results	Mooren et al., 2014
		Risky systems versus risky people: To what extent do risk assessment methods consider the systems approach to accident causation? A review of the literature	This paper reviews the approaches to safety management, especially the methods and tools used for risk assessment. Aligned with Rasmussen's seven tenets, most qualitative and quantitative methods are discussed	Dallat et al., 2016

(continued on next page)

Table 3 (*continued*)

Group	Issue	Title	Contents	Reference
		Risk influence frameworks for activity-related risk analysis during operation: A literature review	This paper reviews recent risk influencing frameworks explicitly. With models and methods, risk or safety influencing factors are analysed. Most of them are project-based, such as MACHINE, SAM, I-RISK, ORIM and so on	Yang et al., 2017
	AT	*Safety management systems: Audit tools and reliability of auditing*	This paper reviews D&S, CHASE (CHASE-II), ISRS, SafetyMap and the MISHA audit method and presents a number of case studies	Kuusisto, 2000
		Are organisations too complex with respect to technical risk assessment and current safety auditing?	This paper discusses how organisational issues affect safety auditing and reviews main theories and summarises the multi-dimensional perspective	Le Coze, 2005
		Measurement properties of occupational health and safety management audits: a systematic literature search and traditional literature synthesis	This paper reviews audit tools on aspects of their conceptual basis, items and output. It contains descriptions of some international audit tools (e.g. D&S, ISRS, CHASE, AIHA ISO9001, SEM, AIHA universal OHSMS, Canadian Pulp and paper, MISHA and Construction Safety Index)	Robson and Bigelow, 2010
		Review of SMS Audit Techniques and Methods – Final Report	This VTT report gives specific information about audit tools used in recent years. It reviews a number of management systems of different industries and audit tools from different organisations	Peltonen, 2013
	SMSs	*A Systematic Review of the Effectiveness of Safety Management Systems*	This paper reviews 37 safety management studies. However, not all of them are SMSs; most of them are dedicated studies and conducted in Asia, Australia and Europe	Thomas, 2011
		Safety management systems from Three Mile Island to Piper Alpha, a review in English and Dutch literature for the period 1979–1988	This paper reviews the theories, metaphors and models in safety management during the period between 1979 and 1988. Especially, this paper shows the use of systems thinking in the development of safety management	Swuste et al., 2017
Standard Level	ST	*Occupational safety and health systems: a three-country comparison*	This paper reviews the OSHSs in Switzerland, the UK and the US based on legislation in different historical, cultural, economic and social terms	Singleton, 1983
		Occupational Health and Safety Management Systems	This paper compares 24 national/state OHSMSs (standards) to a universal international OHSMS	Dalrymple, 1998
		Safety management systems under Seveso II: Implementation and assessment	This paper reviews some safety performance measurements and audits for companies, approaches and some questions in this field. It also illustrates the weight of SMS elements in a different rating system	Mitchison and Papadakis, 1999
		Regulating systematic occupational health and safety management: comparing the Norwegian and Australian experience	This paper reviews OHS-management systems in Norway and Australia, e.g. "the Scandinavian model", "SafetyMAP in Victoria" and compares their implementation in the two countries	Saksvik and Quinlan, 2003
		The effectiveness of occupational health and safety management system interventions: A systematic review	To understand their impact, this paper systematically reviews OHSMSs excluding those systems, which have no accompanying results for outcomes	Robson et al., 2007

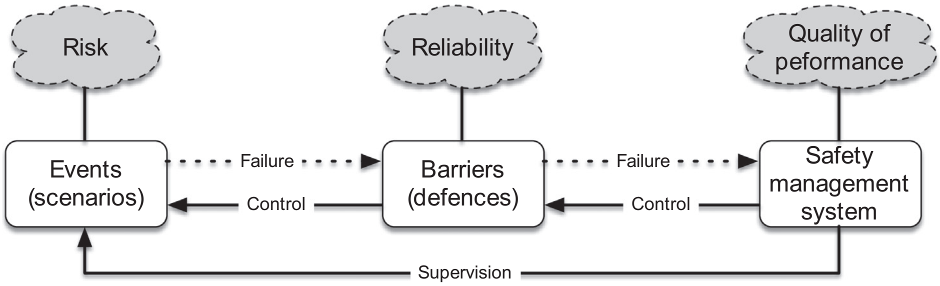


Fig. 3. The relation between scenarios, barriers and safety management.

complex system; (4) Human factor & behaviour & decision making. These categories are discussed below.

4.2.1. *Simple sequence and complex sequence*

Sequential models belong to the early structural accident causation models while the simple sequence model is a metaphor for accidents, described as 'the culmination of a series of events or circumstance' (Toft et al., 2012, p. 3). These simple sequence models are also called linear models. The Domino Model, a typical simple sequence model, originally represents ideas proposed by Heinrich (1931). It distinguishes five stages or factors in the accident sequence, namely (1) Ancestry and social environment (which means undesirable traits of character); (2) Fault of person (which means inherited or acquired faults); (3) Unsafe act and/or mechanical or physical hazard; (4) Accident and; (5) Injury (Heinrich et al., 1980, pp. 22–23). This popular model became the framework for later updated models. With the discovery that inherited characteristics are not useful causal events, Bird proposed the loss control theory by updating the Domino Model to include: (1) Lack of control; (2) Basic causes; (3) Immediate cause; (4) Accident; (5) Injury/damage (Bird, 1974). Lack of control is concerned with management and is an improvement of the sequence models because 'a function of professional management is optimised through five established steps that systematically produce the desired result' (Heinrich et al., 1980, p. 24). This change also shows safety management emphasises the performance of organisational activities rather than finding the inherited shortcomings of humans.

Adams (1976) modified the Domino model that 'retains the concept of operational error and introduces a concept of tactical error', while Weaver (1980) expanded this causal chain by locating and defining the operational error. Besides, Heinrich's book also introduced the *stair step cause and effect* sequence. This sequence model defined the acceptable upper and lower limits and showed step by step how things deviate and cause loss (Heinrich et al., 1980). Borys (2001) introduced the generalised time sequence model, which depicts a simple sequence while structuring the events into a time line. For decades, the simple sequence models have been discussed extensively and provide the foundation for complex theories.

Reason's model, which gained significant popularity after 1990, forms a significant point of departure in the development from single to complex sequence models. The Swiss Cheese model reflects a simple sequence metaphor: an accident is the failure of defences aligned simultaneously in the sequence. Firstly, Reason's model shows 'the relationship between the various human contributions to accidents and the basic elements of production' (Reason, 1990a, p. 479). The sequence encompasses fallible decisions, line management deficiencies, psychological precursors, unsafe acts and accidents. Secondly, he established 'actual and potential feedback loops and indicators associated with each of the basic elements of production' (Reason, 1990a, p. 479). Thirdly, his organisational accident causation model shows that the organisation, workplace, personal or team factors contribute to the occurrence of accidents (the latent failure path), which also illustrates that management decisions and organisational processes can be defences or barriers to prevent accidents (Reason, 1995a, 1995b).

Later studies using the Bowtie model, which can be considered an extension of the event sequence model, focussed on the relations between multiple causes and consequences. The Bowtie model 'allows chains of cause-effect diagrams to be built with a specification of the barriers which can prevent passage from each cause to its effect' (Hale et al., 2004, p. 612). The Bowtie model provides an approach for building accident scenarios; that is, causes, followed by a (potentially) large variety of critical events, one central event, resulting in multiple consequences (Hollnagel, 2008; Markowski et al., 2009). Furthermore, the model provides a control mechanism in the form of barriers placed before unwanted events. Finally, the model connects barriers to (the) management (system) that has to control these barriers. The complex causal Bowtie model is more than just a causation model based on linear sequence thinking; it is associated with accident causation, prevention, control and management issues.

4.2.2. *Epidemiology and energy transfer*

Khanzode et al. (2012) put forward that injury epidemiology theory has a special feature, namely uncontrolled energy as immediate predecessor of accidents. Accidents could therefore also be considered an epidemic phenomenon (Heinrich et al., 1980). For example, Gordon (1949) analysed epidemic data of various areas in the US. He summarised the nature of injuries and identified the principal causes of death. And Suchman's model described epidemiology as predisposition characteristics, situational characteristics, accident conditions, and accidents effects (cited in Heinrich et al., 1980). Haddon (1968, 1972) studied changing approaches to epidemiology and built the Haddon matrix. The columns consist of human (or host), agent, environment; the rows include pre-event, event and post-event. Its columns are often subdivided into physical and sociocultural factors (Phillips, 1970). Finally, Saari et al. suggested that epidemiology is introduced into the study of accident prevention with the following three aims: 'description of the distribution and rate of accidents in human populations; identification of the etiological factors; provision of the data essential for the planning, implementation and evaluation of services' (Saari et al., 1986, p. 300).

Saari et al. (1986) also defined an accident as a series of consecutive events, always triggered by energy. His model consists of four phases, namely, the normal phase (work process is under control), the preceding phase (control is lost during the normal phase), the contact phase (injuring factors release harmful energy) and the injury phase (injury or harm inflicted). In Haddon's theory and other updated models, the agent (e.g. a car, a piece of machinery, a knife, etc.) represents the energy. The energy transfer theory assumes that all hazards involve energy whereby an unexpected energy transfer or release causes the actual accidents.

Gibson (1961) was the first one to propose the energy transfer concept. This concept also refers to the energy damage concept, which focuses on the need for energy to be present for any injury to occur (Borys, 2001). The unexpected energy derives from a destructive energy source or is caused by a lack of critical energy need (Heinrich et al., 1980). Johnson (1973) regards the energy transfer theory as a kind of sequential model. He combined the barrier concept with energy transfer and built the model 'energy and barrier tree' in the form we know as MORT. In this model, the barrier, as injury control mechanism, plays

Table 4
Accident theories and models.

Theory group	Kjellen's accident concept	Industry field	Theory or model name	Model	Method	Description of contents	Reference
Simple sequence	Loss	General	Accident sequence model	Y	QL, QT	Develop the ideas, tools and inspiration to keep person from injuries and economic losses	Bird, 1974; Bird and Loftus, 1976; Wang et al., 1998
		Insurance	Injury level triangle	Y	QL, QT	Minimise loss and build new loss concept and causes analysis	(Sheriff, 1980)
	Incident	General (Insurance)	Domino sequence model	Y	QL, QT	Model of accidents causes and management factors	Heinrich, 1931; Heinrich et al., 1980
		General	Accident causation and the management system	Y	QL	Explore the causes to management philosophy	Adams, 1976, 1977
	Hazard	General	Use of cause-consequence charts in practical system analysis	Y	QL, QT	Outline the main steps of cause-consequence analysis based on the concept of critical events	Nielsen, 1974
		Offshore	The ILCI loss causation model	Y	QL	Provide the audit system management elements	Smith, 1995
	Unsafe act	General	Updated Domino Models	Y	QL	Human characteristics importance in causation model	Weaver, 1973, 1980, 2006
		General	Sequential model of accident occurrence	N	QL, QT	A behaviour-based safety management program focussed on specific work	Lingard and Rowlinson, 1997
& Complex sequence	Incident	General	The complex pattern of the Zeebrugge accident	Y	QL	Model dynamic events to analyse human factor and behaviour	Rasmussen, 1997
		General (Shell)	Tripod BETA incident analysis	Y	QL	Tripod BETA tree describes the incident mechanism in terms of hazards, targets and events	Gower-Jones and van der Graf, 1998; Turksema et al., 2007
		Construction	General model of accident causation; Pattern of Construction accident causation	Y	QL, QT	Identify distal factors and proximal factors	Suraji et al., 2001
		Aviation	Schematic of the causal model	Y	QL, QT	Find causes of incidents and accidents and quantify of the probability	Ale et al., 2006
		General	Combined influence framework	Y	QL, QT	Investigate and understand construction accidents causes	Hale et al., 2012
		General	Accident sequence (phenomenology) and causal basis (etiology) of accidents	Y	QL, QT	Based on sequence events model for near-miss management	Gnoni and Saleh, 2017
	Hazard	Healthcare	Reason's Swiss cheese model	Y	QL, QT	Apply Reason's model following analysis and comparison	Reason, 1990a, 1995a, 2000; Hudson, 2012; Perneger, 2005
	Unsafe act	General	The model bow-tie; PyraMAP, and other triangle MAPs	Y	QL, QT	Based on events model Bowtie, develop function models containing human, organisation, management factors	Bellamy et al., 2007a, 2007b
		Railway	Model of accident causation	Y	QL, QT	Model human failures, technical failures and external intrusions	Kim and Yoon, 2013
Simple system	Loss	General	The deviation theory and models	Y	QL	Define and model deviation by system thinking and then build information system	Kjellén, 1984, 1998; Kjellén and Hovden, 1993
		Equipment	The 'ENKLA' system for the management of information on accidents	N	QL	Aim to classify accidents in specific engineering systems by analysing the data	Backström, 1999; Backström and Döös, 1997; Laflamme et al., 1991
		Chemical process industry	A simple model of incident causation; the Eindhoven Classification model of system failure	Y	QL, QT	Study failure system from near-misses reports	van der Schaaf, 1995
		Hospital	Dynamic safety model	Y	QL	Investigate systemic properties and its potential for creating accidents	Cook and Rasmussen, 2005
	Hazard	Road	The driver-vehicle-environment system	Y	QL, QT	Base on US road casualties, modelling for road accidents factors and mechanism	Kontaratos, 1974
		Aircraft	Hazard modelling research; causal loop modelling;	Y	QL, QT	Specifically model the aircraft hazard, error and unsafe behaviour	Ayres et al., 2013; Downes and Chung, 2011
	Unsafe act	General	Man-machine-environment system (MMES)	Y	QL, QT	Develop interactive system for safety management	Kuhlmann, 1986
		Aviation	SHEL (software, hardware, environment, and live ware) model	Y	QL	Examine the reasons for new human factors training requirements	Johnston and Maurino, 1990

(continued on next page)

Table 4 (*continued*)

Theory group	Kjellen's accident concept	Industry field	Theory or model name	Model	Method	Description of contents	Reference
& Complex system	Incident	Process industry	Socio-technical pyramid & Ideal management loop	Y	QL	The models combine the hierarchy of organizational safety and control loops	Nivolianitou and Papazoglou, 1998
		General	ATSB investigation analysis; AcciMap diagram format; etc.	Y	QL	Develop systems thinking models and techniques	Underwood and Waterson, 2013
	Hazard	Aviation	STAMP: system-theoretic accident model and processes; STAMP-VSM joint model	Y	QL, QT	Analyse accidents and control safety, based on systems theories and techniques	Kazaras et al., 2014; Leveson, 2002, 2004, 2011; Leveson and Dulac, 2005; Leveson et al., 2012
	Unsafe act	Offshore	The control and monitoring loop	Y	QL, QT	Model developed the control from operational level to management level	Bellamy, 1994
		Petroleum	Human factors activities in design	Y	QL	Integrate human factors and engineering into system design	McCafferty, 1995
		Social infrastructure	Conceptual systemic causal model of design error generation	Y	QL	Discuss the dynamic process of design error and causes	Love et al., 2012
		Railway	Model of accident causation	Y	QL, QT	Model human failures, technical failures and external intrusions	Kim and Yoon, 2013
Epidemiology & energy transfer	Loss	General	General injury dynamic according Infor.Mo. model	Y	QL	The model emphasises the energy transfer in accidents causal analysis	Vallerotonda et al., 2016
	Incident	General	The causation and prevention of industrial accidents	N	QL, QT	Discover the basic causes and set up the preventions	Vernon, 1919
		General (Public health)	The epidemiology of accidents	N	QL, QT	Discover the characters of disease and injury according to time	Gordon, 1949
		General (Highway)	Injury epidemiology and categories	N	QL	Develop systematic matrix to study the causes and the contributing factors	Haddon, 1968, 1972, 1973, 1980
		Railway	Integrated framework for the in-depth analysis of HZSCC; HZSCC causation model based on MAERM	Y	QL	Causation analysis is based on modified accident energy release model	Zhou and Irizarry, 2016
	Hazard	Atomic energy	MORT – the Management Oversight and Risk Tree	Y	QL, QT	Present factors and improve system congruous with general system for management of high performance	Frei et al., 2002; Johnson, 1973, 1980
	Unsafe act	General (light metal industry, printing industry, etc.)	Accident and disturbance in the flow of information	Y	QL, QT	Analyse the internal and external factors, and the mechanism of the information processing	Saari, 1984; Saari et al., 1986
Decision model	Incident	Chemical	Multinational vulnerability model	Y	QL	With yes/no questions, this model focus on the global management and operational factors.	Mcnutt and Gross, 1989
& Behaviour theory	Incident	Construction	Accident causation model	Y	QL	Aim is to investigate the production factors that generate hazardous situations	(Mitropoulos et al., 2005)
	Unsafe act	General (Standard)	Integrated behavioural safety framework; Information flow between behavioural safety and the HSMS; etc.	Y	QL	Improve SMS performance and feedback	Fleming and Lardner, 2002

Y – Yes; N – No.

the prevention role that cuts off the unwanted energy transfer. Viner (1991) built an energy damage model to explain that a failure of the hazard control mechanism is equivalent to the loss of control of energy. His model introduced a space transfer mechanism, which brings the energy and the remote recipient together, whereby the recipient boundary is 'the surface that is exposed and susceptible to the energy' (Toft et al., 2012, p. 8). In summary, the epidemiology and energy transfer theory imply that a vulnerable target should be isolated from a harmful energy source (hazard).

4.2.3. Simple system and complex system

The simple systems theory of safety has different emphases: some consider the system objectives, some use the system control concept with consideration for its safety functions, others apply engineering techniques to management control. Firenze's system model (1971) is a man-machine system, composed of the physical equipment, the men who perform functions using the equipment, and the environment where the process takes place. The variables of this system are called 'stressors', which provide information for decision making, since they could lead from risk to accidents (cited in Heinrich et al., 1980; Wiegmann and Shappell, 2012). Rouse's (1981) human-computer interaction in the control of dynamic systems not only provides the structure of a dynamic system, i.e. with feedback loops, it also models the human factors comparably into interactive systems. Kuhlmann (1986) introduced the man-machine-environment system (MMES) in which complex technical systems and interdisciplinary safety tasks are modelled at local, regional and global effect levels. He also emphasises the control loop as an important of a (cybernetic) system. This circle loop consists of a controller, a controlled system and a monitoring device. Waring (1996) in particular explained the system concept in his book on safety management systems. His control paradigm shows the input, process and controller and also specifies Kuhlmann's loop model by applying it to offshore safety management. In the following year, Hale et al. (1997) proposed to use SADT (Structured Analysis and Design Technique) for modelling a safety management system. SADT not only models input and output, but also adds criteria to the control processes, which determine whether a safety activity is successful. Furthermore, resources (nowadays called 'mechanisms'), as part of SADT, include both hardware and people. Based on the systems concept and modelling method, Hale's safety management system combines a framework (SADT) and safety functional logic.

The complex systems theory involves different views and approaches for preventing accidents, controlling risks and also improving safety performance. Leveson (2002) reckons that along with the fast pace of technological change and the changing nature of accidents, the system is becoming increasingly more complex by combining dynamics complexity with decomposition complexity and non-linear complexity. Based on the systems theory and socio-technical system theory, the System-Theoretical Accident Model and Processes (STAMP) enforce safety constraints on system behaviour (Leveson, 2011). This structure follows Rasmussen's hierarchy model whereby the controllers use a process model with control actions and feedback loops (Leveson, 2004; Leveson et al., 2012). This model is used both for root cause analysis and for the dynamic accident process by applying system dynamics.

4.2.4. Human factors, behaviour and decision-making

Since Surry (1969, p. 17) wrote that 'pure accident research declined after 1940 and the study of performance influencing factors has flourished since' (cited in Toft et al., 2012, p. 2), we hardly separate human factors, behavioural or psychological factors and decision-making from actual accident causes. The accident proneness theory, which is commonly named as one of the earliest theories in the history of safety science, primarily shows that a personal trait is an important cause of accidents (Khanzode et al., 2012).

Greenwood and Woods (1919) tested three hypotheses regarding the occurrence of accidents: pure chance, true contagion (an individual who suffers one accident by chance may in consequence have his/her liability to accidents increased or decreased), and apparent contagion (some workers are from the beginning more likely to suffer accidents than others). They conclude that a varying individual susceptibility to accidents exists and that this individual trait can determine the distribution of accidents. Factors that underlie such accident proneness, are identified by James and Dickinson (1950, p. 772) as 'habits and skills, physical characteristics, psychomotor characteristics, mental characteristics and attitudes, and age and experience'. Statistical methods are often used to identify accident proneness at an early stage.

Until the control and modelling of behavioural factors became common practice, studies of the hypotheses of proneness shifted to systematic human factor studies, because efficient defendants are better able to prevent accidents than victims (James and Dickinson, 1950). Kjellén (1984) stated that the human factor theory concerns the probability of human errors that influence equipment, environment and task structure. Reason (1990b) showed underlying causes, intensified psychological research on error and behavioural explanations of error, and discussed approaches to decision-making and problem solving. He established a now popular organisational accident causation model, with performance shaping factors, that is, human factors. Gradually, the notion that human factors are not only individual causes but an integrated part of accident control, is becoming commonplace (Bellamy, 1994; Leonard et al., 2004; Maurino et al., 1995).

For in-depth research on human factors, behaviour-based safety (BBS) management became increasingly popular after 1990. Behaviour-based safety is more likely to be an important strategy of a safety management system rather than a causal factor (Fleming and Lardner, 2002; Nascimento et al., 2010; Salem et al., 2007). From this point of view behaviour research is more a by-product of major accident causation theories and in line with Rasmussen's observation: 'the convergence of human science paradigms towards models in terms of behaviour-shaping work features subjective performance criteria' (Rasmussen, 1997, p. 201).

The Surry model is a decision model, which shows the whole advance process of hazard and injury/damage: perception, cognitive processes and physiological response (cited in Heinrich et al., 1980). It illustrates, within a man plus an environment system, how decisions take shape to release danger. Similarly, the multinational vulnerability model applies the decision tree to get insight into the process underlying an accident in the chemical industry (Mcnutt and Gross, 1989). Since decision models address judgement, choice, and inference (Lehto and Salvendy, 1991), a simple decision model always contains yes/no questions, followed by a choice using a certain kind of (decision tree) operator and then predicts the result. As decision making is one important trigger of incidents, any behaviour or action will affect the safety decision-making in a logical way (Schroder et al., 2007). At present, more systematic methods are applied such as system dynamics, which could provide decision making based on the effect of organisational factors on safety.

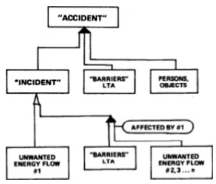
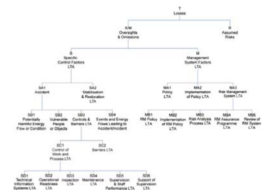
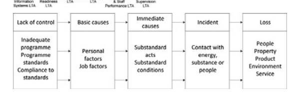
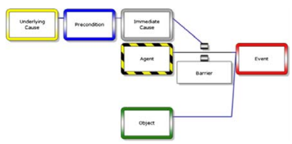
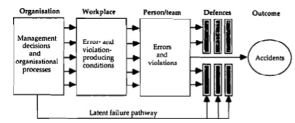
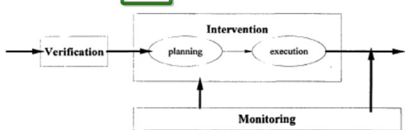
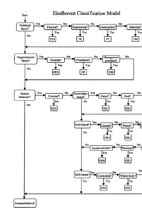
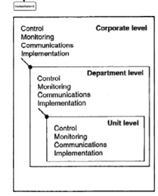
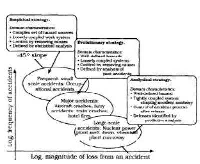
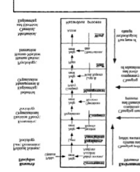
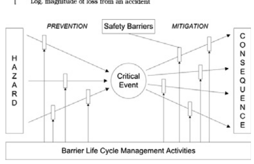
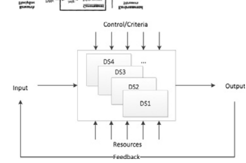
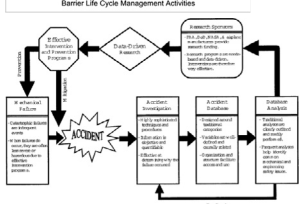
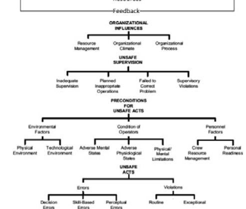
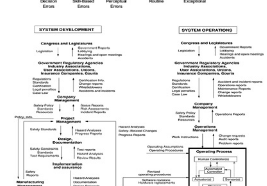
4.3. Extension models – barriers and/or management system

Accident theories and models are the foundation of safety management, so we discuss the barrier and management models based on the events model. Safety barriers are normally considered an extension of accident models, such as MORT, Tripod Beta, Bowtie and so on. However, the development, implementation, maintenance and update of barriers require a systematic management. So, the transition from an extension accident model to a management model is critical for barriers management.

4.3.1. Barriers prevent unwanted events

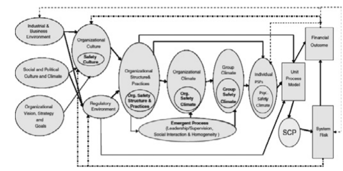
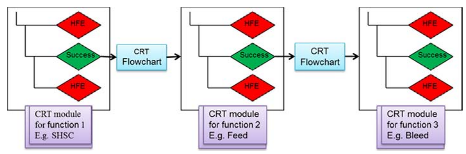
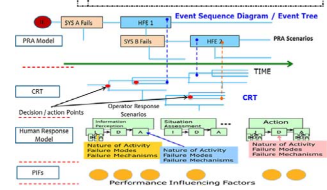
The barriers are functioning to prevent, control and mitigate both critical events and consequences. Some papers review and discuss barriers explicitly on definition, function, and classification (Bellamy

Table 5
Events + **Barriers** + **Management** models.

Model name	*+Barrier*		*+Management*	
	Description	Model shape	Main issues	Model shape
MORT (since 1973)	Energy trace and barrier analysis (and connect MORT analysis this way to the events of the accident)		- Barrier control and other controls - Safety management system - Risk management	
ISRS, also ILCI (since 1974)	Bird's domino theory and loss of control emphasises safety management	(no model shows inserted barriers)	- ISRS 15 key processes	
Tripod (since 1990)	Tripod Beta is based on cheese model; defenses (barriers) are inserted between the causal events		- Latent failure defenses' control - 11 Basic Risk Factors (BRF)	
ECM, also PRISMA (since 1992)	The Eindhoven classification model (ECM) is based on Van der Schaaf's near-miss event model; the control shows the position of intervention		- Technical, organisation, human and unclassifiable factors - SRK-model - PRISMA	
Waring's SMS model (since 1996)	Based on system control, there are risk controls including engineering, organizational, procedural, behavioural, personal protection	(no model shows inserted barriers)	- System resolution and 'nests' - Specific control models at the three levels	
Socio-technical model (since 1997)	Based on defense-in-depth protection, risk management strategies, such as empirical, evolutionary, and analytical strategies, are identified		- The hierarchy of safety management - Adapted socio-technical models applied to different cases	
Bowtie (since 1998)	Bowtie model based on Haddon's HBT-model and Tripod Beta; the barriers are classified and analysed further		- ARAMIS - I-RISK - Hale's SMS Delivery systems: barrier management	
HFACS (since 2001)	Human Factors Analysis and Classification System developed four tiers of barriers, based on Reason's Swiss-cheese model of accident causation; barriers inserted for accident prevention and mitigation		- Emphasise the organizational factors - Four-tier system	
STAMP (since 2004)	Based on causal sequence model, 'protective barriers to control flow after release of hazard. Acceptable downtime according to predicted overall risk of major accidents'		- Socio-technical management model - Hierarchical control loop - Adapted STAMP applied to different cases	
SoTeRiA/ Hybrid model	The causal part of this model is based on events sequence model and uses	(no model shows inserted barriers)	- Model the safety influencing factors - Hybrid modelling technique	

(*continued on next page*)

Table 5 (*continued*)

Model name	+***Barrier***		+***Management***	
	Description	Model shape	Main issues	Model shape
(since 2009)	multiple analysis techniques		- Start with the system risk	
Phoenix (since 2016)	Based on scenario development, the crew-plant interaction (CRT) actually is a kind of behavioural or socio-technical barrier		- Model for quantitative analysis - Performance influencing factors	

et al., 2008; Hollnagel, 2008; de Ruijter and Guldenmund, 2016). Barriers indeed connect the events model to safety management. Table 5 illustrates the role of barriers in the events model and the management structure to control their performance.

In the MORT model, barriers can stop the unwanted energy flow in an event sequence or prevent the incident from intensifying. They are not only physical interventions separated in time or space but also procedures (Johnson, 1973). Even though more complex theories and techniques are used in barrier models, the position of barriers in events models never change. The Tripod Beta and Swiss cheese model just clear the layers of barriers and describe latent reasons for barrier failures, which are then related to their management (Reason, 1990a, 1995a, 2000). The more specific barriers are mapped in the Bowtie extension model, which illustrates multiple ways of accident prevention (Duijm, 2009). Based on this model, barriers are modelled specifically in several projects. The Phoenix model describes three layers of defences. At the top layer, the crew response tree (CRT) directly connects to the control of risk. This CRT is also a method to model the barriers that involve human response (Ekanem and Mosleh, 2014; Ekanem et al., 2016). All in all, the position and function of barriers in the events model is obvious. While the barrier is a very practical and specific concept, how to model barrier systems still needs further study.

The risk is commonly defined in a scenario, which combines the severity of negative consequences and the likelihood of the accident pathway through (series of) unwanted events. To prevent unwanted events and consequences from occurring, safety barriers in the scenario should be functional. Safety barriers can mitigate risks by both decreasing the likelihood of the unwanted event and the severity of the loss. In this way, the management of safety barriers becomes essential for risk control.

4.3.2. *The nature of management models*

The management system purports to deliver the *management factors* to 'complete' the barriers, i.e. provide enough resources and controls to ensure their proper functioning. In the MORT model, the main branches are *specific control factors*, *management system factors* and *assumed risks*; the first two branches are the management components. The management system includes every factor that affect the performance of safety barriers. For instance, the Eindhoven Classification Model classifies incident or accident causes into technical, organizational, human and unclassifiable factors (van Vuuren et al., 1997). HFACS uses a four-tier organisational factors structure (Wiegmann and Shappell, 2001; Lenné et al., 2012). Also, based on the Bowtie extension model, Guldenmund et al. (2006) define seven management factors, also called delivery systems, to identify, implement and support barriers. All in all, the safety management system can and should ultimately control the operational risks.

Another important aspect of safety management models is their *hierarchical structure*. In Waring's SMS model, Rasmussen's socio-technique model and Leveson's STAMP model, the hierarchical structures of management form an essential part of their model (see Table 5). These structures are based on general organisational management systems, but clearly show the change in required safety information at the strategical, organisational and operational level. Evidently, safety management influences are expressed by both individual actions and organisational performance.

The combination with a *control loop* at each level typifies the function and processes of the SMS. Waring's model involves control, monitoring, communications and implementation phases from top to bottom. The STAMP model emphasises the control loop especially at the operational level. Guldenmund et al.'s delivery systems even use the SADT method, of which control is an essential part, to model both barrier and management functions. Control is a central aspect of management in a hierarchical structure.

The main function of a safety management system is to control hazards, by means of safety barriers. So, barrier management plays a pivotal role in safety management. As these practical barriers need their input, resources and controls mostly from higher organisational levels, management models are hierarchically structured. In other words, (generic) safety management is basically safety barrier management.

4.3.3. *Factors that influence safety management*

Research into accidents provides ample information for organisational safety management. Organisational safety studies in particular are meant to show organisational safety management factors and their interrelations. Some accident extension and management models address factors such as human factors, organisational factors, and other performance influencing factors. In current literature, these factors are not linearly related. They sometimes are one or a few latent causal factors affecting risks, barriers, safety performance or any other safety related issue, sometimes they are generic safety management factors that are used also in an audit. A general way of studying factors in SMSs can be summarised as follows:

1. Identify organisational model or factors;
2. Rate or weigh these organisational factors;
3. Design a propagation method or algorithm;
4. Choose modelling techniques;
5. Find the link to risk or other issues;
6. Conduct a case study or some specific application;
7. Improve the approach based on the study's feedback.

There is a series of projects that study how organisational factors affect risks, barriers or safety performance by using a probabilistic assessment method with weighting or rating approaches. The Work Process Analysis Model (WPAM) is a model that incorporates organisational factors for risk assessment (Davoudian et al., 1994a, 1994b). It combines an event tree with an organisational model and identifies a series of organisational factors, which are studied as part of the specific system. It uses an algorithm to study the influence of organisational factors on the safety system. The WPAM demonstrates the impact of organisational factors on a work process and has connected these factors to probabilistic parameters.

System-Action-Management (SAM) is a framework that addresses human and management causes of system failure (Paté-Cornell and Murphy, 1996; Murphy and Paté-Cornell, 1996). These researchers used a quantitative approach to illustrate how human and organisational factors affect the probability of loss. Also, the SAM framework, based on the (binary) event tree, makes use of probabilistic methods.

The Organizational Risk Influence Model (ORIM) applies organisational factors within an organisational model (Øien, 2001). A quantitative model has been built and its algorithm links the organisational model to the risk model (with a focus on frequency).

Studies of organisational safety factors are essentially based on latent accident causes and therefore contribute to the development of safety audits. Because the assessment of an SMS is related to a large number of indicators with information about the relationship between the measurable indicators of an SMS, these studies help to improve effective safety management. For instance, Tripod is based on Reason's accident sequence event model and distinguishes eleven basic (latent) risk factors (Hudson et al., 1994). Another example is the International Safety Rating System (ISRS), based on loss prevention theory, which is used extensively for safety management assessment (Guastello, 1991; Top, 1991). This system uses management factors and combines loss control theory with a management model. In addition, both I-RISK and ARAMIS were safety management and audit projects based on a Bowtie extension model (Papazoglou et al., 2003; de Dianous and Fiévez, 2006; Markert et al., 2013). They are founded on the same principles: a causal event model combined with an organisational model, which are connected through safety barriers. In both these models, management factors are defined through the use of 'delivery systems' (see Section 6).

4.4. Safety, barrier and risk in a business process

Essentially, the safety management system is aimed at business services (Fig. 4). In a business process, like a construction project, the input of raw materials is transferred into a designed construction which is the business output. During the process, risk control is necessary to assure output quality and integrated safety. All sorts of management

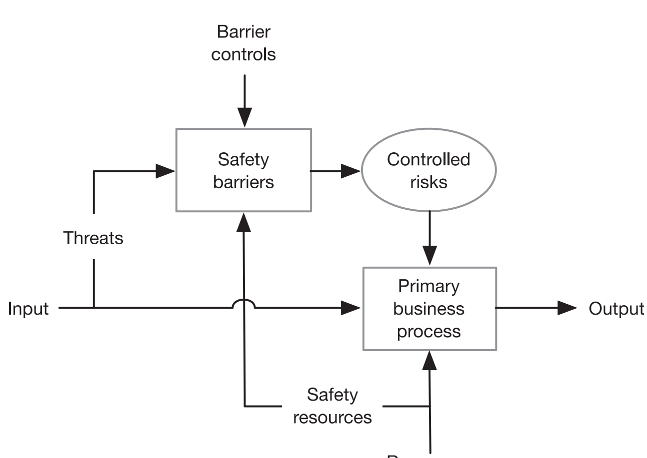


Fig. 4. Safety, barrier and risk in a business process.

delivery are an important resource or mechanism to this process. As risk control is important for the business process, the way to achieve a controlled risk has to be developed.

According to event models, risk control is ensured by safety barriers. The input to these barriers are threats or hazards and the output is controlled risk. These barriers also are supported by safety resources, such as human, organisational and technical resources. By using these resources, all stages of barrier functioning are carried out, which include installation, implementation, maintenance and monitoring of barriers. During these processes, controls and criteria are necessary to avoid the failure of safety barriers. All these aspects, i.e. hazards, safety resources, barrier controls and the barrier processes, are contained in the safety management system. As a result, risk is controlled like a business process. Fig. 4 briefly shows the relationship between safety, barrier and risk in a business process.

5. Purposes of safety management systems

5.1. Control perspective

The main purpose of a safety management system is *control* (Fig. 5). As discussed in Section 3, the control of loss, accidents, hazards and risks is central to safety management (research), so the question arises as to what exactly SMSs have to control and by which means they perform this control function. Fig. 5 illustrates the PDCA (Plan-Do-Check-Act) control process of an SMS and also gives its seven generic sub-systems. A PDCA-cycle is the most common feature of most safety management systems. Originally, the PDCA cycle was proposed by Deming in the 1950s. Since then it has 'evolved into an improvement cycle and a management tool' (Moen and Norman, 2006, p. 7) and is now widely used. Here, not only the management system but also its seven sub-systems use the PDCA-cycle to carry out and improve their functions continuously. Literature on these seven systems is given in Table 6. They are indicated by certain codes, which represent the function of these specific sub-systems and are explained further below.

Policy and plan system (P-1): safety policy is an organisational strategy and the plan is the blueprint of an SMS. Although the policy and plan do not guarantee that the organisation will be accident or incident free, it shows the willingness and attitude of an organisation towards safety activities. Yet, there are few models that identify the safety plan as a separate sub-system, because safety is always a by-product of a project plan, or safety planning is a step in a management system. The safety planning and controlling function describes the processes and interaction between safety planning and safety control. It is proactive regarding measuring and monitoring safety performance (Saurin et al., 2008). That is, if safety policy is the aim, then safety planning is the designed way to achieve the aim.

Information & reporting system (P-2): the information system is supported by a comprehensive analysis capability using mathematical or statistical analysis tools to identify significant relationships between the data and possible risks in the system (Stewart et al., 2009). The reporting system relies on the information system and varies amongst organisations, depending on the different aims and indicators. Some information and reporting systems are based on accident causation models like TRIPOD, such as the 'information flow model' that describes the sequence of sensing, perception, decision-making and action (Saari, 1984). Some of these systems are specifically built to assist a safety management audit system. For example, information from GUARD (Group Unified Accident Reporting Database) can be used to improve the audit system (Koene and Waterfall, 1992, 1994). Others are large data systems for international or industrial safety management, such as MARS (the European Commission's Major Accident Reporting System), PSMIS (Predictive Safety Management Information System), FSMIS (Flight Safety Management Information System) and so on (Table 6). Most information and reporting systems basically provide SMSs with past data to build scenarios and to quantify risks in the safety

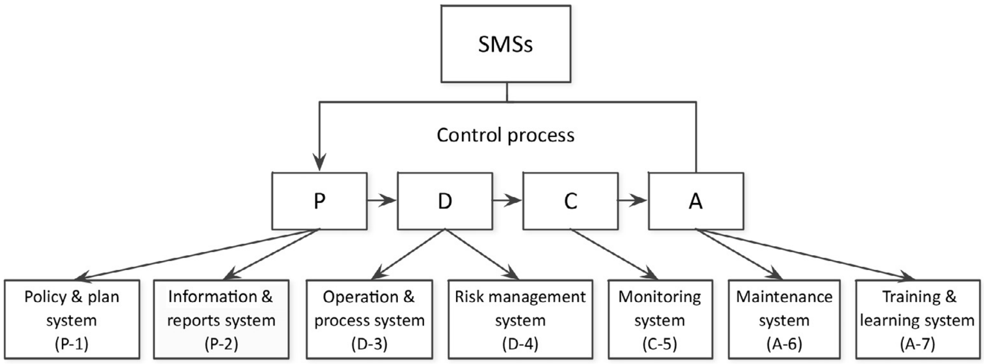


Fig. 5. Safety management systems from a control perspective.

management system.

Operation & process system (D-3): the operating procedure is an element of a process safety management (PSM) framework (Shimada and Kitajima, 2010), as process activities are also the constituent parts of primary business operations. Studies of this function relate to either of the two aspects, operation or process. Indeed, PSM is a broad system and contains all elements with functions of an SMS in, for example, chemical process safety management. PSM provides methods to effectively solve dangerous situations and to prevent accidents within the process framework (96/82/EC). With the aim of safety control, the operation and process system focuses on actual process activities, procedures and operational performance of safety countermeasures.

Risk management system (D-4): risk management refers to the required architecture (principles, framework and process; e.g. ISO 31000) for managing risks effectively; while managing risk refers to applying that architecture to particular risks. This term has been discussed in Section 2 and defined as a component of SMS (Demichela et al., 2004). NASA distinguishes narrow-scope and broad-scope risk management. The former is concerned with hardware risks, the latter is more complex and involves multiple organisations (Dezfuli et al., 2011a, 2011b). Risk management, which involves identifying, assessing, controlling and evaluating safety risks, thus plays a pivotal role in any safety management system.

Monitoring system (C-5): monitoring aims to check or observe the state of the safety performance of an organisation. Real-time information of safety performance can be obtained and analysed during the monitoring process. By using sensors, the monitoring system can obtain certain values of parameters that tell us something about the performance of machines or operators (Zolghadri, 2000). For example, the Prevention Recovery Information System for Monitoring and Analysis (PRISMA) was originally developed to manage human errors in the chemical process industry. It incorporates an causal incident tree, the Eindhoven Classification Model (ECM) and measures for improvement (Dye and van der Schaaf, 2002; Snijders et al., 2009). This system also shows the relationship between information and monitoring. The monitoring system provides an SMS with actual information which is vital for continuous improvement.

Maintenance system (A-6): maintenance in this context always refers to mechanical maintenance. For the entire SMS it means that every component should be maintained regularly to ensure safety. Based on Juran's quality trilogy model (1999), maintenance includes planning, control and improvement. Tucci et al. (2006) established the Deming cycle model for maintenance, introducing a process for maintenance, i.e. planning and execution, data feedback, data analysis and legal, technical and economic solutions. It is obvious that maintenance models emphasise the PDCA cycle; its process of continuous improvement keeps providing an SMS with control measures.

Training & learning system (A-7): training and learning are often regarded as necessary practices in a management system and an accident prevention strategy (Gherardi and Nicolini, 2000; Hale, 1984). Well-organised training and learning activities can also form an independent system. For the sake of safety, many companies actually do set up their own training programs, although some of them can develop into mature systems such as STOP at Dupont (1986). Other learning systems focus on incident learning for feedback and risk control (Chua and Goh, 2004; Cooke and Rohleder, 2006). Training and learning systems are therefore important for the quality of SMSs as they improve the organisation's and its workers' capability regarding safety.

All in all, these seven groups broadly describe the functions of safety management systems from a control perspective. Table 6 describes the literature using the following dimensions: industrial field, name of the system or study, function explanation, model, theory/method or technique and literature reference. The literature shows that a model or a system realises one or more functions of an SMS. They reflect the particular purpose of a control in safety management systems.

5.2. Compliance perspective

Although the control of accidents, losses and defences is considered the main purpose of an SMS, this overview also pays attention to another purpose, namely *compliance* with standards, laws and regulations. For many companies, obtaining a certificate is important and is often a reason in itself to develop and improve SMSs. Some of the more general standards may not provide detailed features of specific operational processes but rather point to topics of significance in the management system (ISO, 2011). Others are industrial major hazard control standards or specific occupational safety standards. Laws and regulations are devised to specifically spell out the norms of safety actions and form a legal framework for acceptable risks. As a result, they provide a distinct view on the study of SMSs in terms of how to develop an SMS that meets the safety requirements set up by different governments, institutions or industries and how to make companies' safety management comply with certain standards.

The literature that relates to safety compliance has three main aspects (Table 7): *understanding, comparison* and *integration*. *Understanding* means by explaining certain standards or legislation, clues are provided as to how the organisational management system can comply with the standards. *Comparison* contributes to a general understanding by showing the pros and cons of certain standards. As different governments or institutions probably use different standards, a comparison could provide users with various views on their suitability. *Integration* means the organisation incorporates required standards or regulations into their own management system for a specific purpose. Beckmerhagen et al. (2003) defines the integration of management systems as 'a process of putting together different function-specific management systems into a single and more effective integrated management system (IMS) [but] the extent of management system "integration" may vary significantly from one company to the other, requiring some workable definition of this term' (p. 214). Normally, organisations can operate more than one formal management system and the above three aspects are all useful for the different development stages.

Table 6
Safety management sub-systems (SMSSs) for controlling.

Group	Industrial field	System name or key words	Function explanation	Life cycle	Model and/or theory	Methods or techniques	Reference
P-1	Construction	Supervising plan	HK government carries out 'supervision plan' to change the safety attitude and culture of construction practitioners		The three-component model of attitudes by Roserberg et al.	Questionnaire	Tam et al., 2001
	Construction	SPC – Safety Planning and Control model	SPC aims to implement an SMS with three principles (flexibility, learning and awareness); this model proposes proactive & reactive performance indicators	Y	SPC model	NG	Saurin et al., 2008
P-2	Light metal & printing	Information flow model	This paper compares two industries' information and based on their data discusses danger zones	NG	The flow of information is dependent on several internal and external factors; error mechanisms in information processing	Probabilistic study	Saari, 1984
	Petroleum	GUARD – Group Unified Accident Reporting Database	The system is designed primarily as a safety management tool for Shell, whereby world-wide data will improve feedback to companies and as such influence the development of safety programs, policies, etc.	Y	Managerial safety control feedback loops Accident feedback loop Management of safety	Computer techniques	Koene and Waterfall, 1991, 1992, 1994
	Nuclear	SAIA – Safety Analysis and Information system	By using a PSA event and fault tree, this information system sets up a probabilistic data bank	Y	Integration of SAIA into the plant management process; functions, structure, and data models	PSA (Probabilistic safety assessment); Fault tree	Balfanz et al., 1992
	General	MARS – European Commission's Major Accident Reporting System	MARS aims to 'collect information related to major industrial accidents in EU Member States in the context of the Seveso Directive'. This system comprises an accident report and data collection, with a special focus on near-miss reporting	Y	Basic structure of the MARS information network Model of human factors identification in MARS, Aviation maintenance check operations and key points of inefficiency Scheme of the taxonomy (Rasmussen);	Computer techniques	Jones et al., 1999; Baranzini and Christou, 2010; Jacobsson et al., 2010
	Aviation (NASA)	IRIA – Investigation and Reporting of Incidents and Accidents	NASA's IRIA has four parts: organisational and system safety; classifying incidents & accidents; keynote address; software issues; reporting and tracking; analysis methods & results and Investigations	Y	Aviation system risk model; Information flow chart; etc.	HAZOP; FT; STAMP; etc.	Hayhurst and Holloway, 2003
	Aviation (NASA)	PSMIS – Predictive Safety Management Information System	This system reduces the time and manpower necessary to perform predictive safety studies by creating predictive SMS software	Y	Barrier analysis; Risk analysis	PHA; CHRDPM	Quintana, 2003
	Construction	A hybrid information and communication technology system	An advanced information and communication system used in the construction field for SightSafety management. To test the system, users and their interaction with the system were observed	Y	Information flow for SightSafety	Micro-Electro-Mechanical Systems (MEMS) and smart sensors	Riaz et al., 2006
	Aviation	FSMIS – Fight Safety Management Information System	Developed by Taiwan Civil Aeronautics Administration (CAA), it uses quantitative methodology to study risk assessment and identify the influencing factors proactively	NG	The hazard regression models	NG	Shyur, 2008
	Aviation	ASRS – NASA Analyses of Aviation Safety Reporting System	This system records accidents in categories and uses tools to analysis their causes. It is based on 'Loss of Control' (Project IRAC)	Y	Loss of control	NG	Reveley et al., 2010
	Chemical Process	OSHA PSM Ontology Design	PSM information system incorporates the PSM elements into a computerised intelligent platform	NG	NG	PHA (Process Hazard Analysis)	Tan et al., 2012
	Oil and gas	EHS MIS – Management Information System	EHS MIS meets the requirement of robust platform for management; it replaces the old incident management system	NG	NG	NG	Heinrich, 2013
	Railway	Railway information system	This system improves near-miss data and combines safety data with GIS data	Y	Data collection and analysis system High-level recording process	GIS	Wullems et al., 2013
D-3	Aviation (NASA)	Safety management of a complex R&D	Safety management is developed for a complex R&D operating system and maintained under safety permit controls	Y	Facility operations management; safety committees framework; elements involved in a comprehensive safety program	System safety tools and techniques	Connors and Maurer, 1975
	Port	SMS in marine operation	This SMS focuses on the barriers of specific operation systems	Y	Bowtie; An integrated SMS	FT; ET	Trbojevic and Carr, 2000

(*continued on next page*)

Table 6 (*continued*)

Group	Industrial field	System name or key words	Function explanation	Life cycle	Model and/or theory	Methods or techniques	Reference
	Oil and gas	PSM for risk management	Risk Management is 'for protection of environment and communities and prevention of major hazards'. This system introduces an effective approach used in PSM process.	Y	Process safety as a 'Three-fold' Issue	Process workflow	Petrone et al., 2010
	Subway	An operation SMS	This paper identifies the failure pattern of a subway operation system and factors affecting subway operation safety system	Y	Subway operation mode map, Bow Tie subway system safety analysis model, subway operation system SMS framework	NG	Dai and Wang, 2010
	Aviation	NASA Safety Control	NASA integrates safety management into the aviation control system. It focuses on how to control the hazards of airplane systems; it also explains a whole hierarchy of management system	Y	Socio-Technical Safety Control Structure Safety Control Structure for ATSA-ITP (Airborne Traffic Situational Awareness – In-Trail Procedure) Control Loop for ITP Flight Crew during ITP, etc.	NG	Fleming et al., 2012; Leveson et al., 2012
	Aviation	Location and consequence model	The technical safety model is based on accidents data; the work on the location and consequence models of airports specifically benefits operation safety	NG	Location and consequence model	Statistics	Ayres et al., 2013
	General	MROI – man, technology, organisational and information	This paper uses control metaphors for a safety management system	Y	Control input-output model	NG	Wahlström and Rollenhagen, 2013
D-4	Construction	Feedback mechanisms model Risk assessment and control model	This paper reviews an incident causation model and gives the result of incidents or accidents' investigation; it aims to build risk assessment and control model	Y	MLCM (modified loss causation model)	NG	Chua and Goh, 2004
	Process (Petrochemical)	Dynamic model of process safety management	Risk scenarios audit models are for risk analysis and show the scenarios and the barriers for protection	Y	Map of scenarios risk process of the plant Model that rep the process safety management audits	NG	Neto, 2008
	Offshore	Hazard management (HSE)	This report discusses the risk management process with regard to aspects of competence and supervision	Y	Bow-tie model, Barrier model, Socio-technical pyramid, Risk based scheme for balancing competence and supervision	NG	Trbojevic, 2008
	Aviation	NASA risk management system	This system consists of Risk-Informed Decision Making (RIDM) and Continuous Risk Management (CRM)	Y	RIDM, CRM, Coordination of RIDM and CRM within the NASA Hierarchy	NG	Dezfuli et al., 2011a, 2011b
	Aviation	FAA SRM	Consistent with ICAO, this system comprises five steps: describing, identifying, analysing, assessing and mitigation of risks	Y	SRM & Safety Assurance Relationship	Risk matrix	FAA, 2012
C-5	Aviation	Monitoring system for the controlled aircraft	This system is designed for aviation safety control, with two levels of mathematical models for major hazards	Y	Monitoring system for the controlled aircraft; RCAM (Research Civil Aircraft Model)	NG	Zolghadri, 2000)
	Construction sites	DSS – Decision Support System	DSS assists construction engineers in monitoring and controlling the excavation conditions that could become hazardous	NG	Disaster-reasoning model development process; Application model for instrumentation monitoring	GIS; computer techniques	Cheng et al., 2002
A-6	General	IMS maintenance system	This paper discusses maintenance activities within the integrated management systems, and how maintenance satisfies system certification	NG	Maintenance engineering activities towards satisfying management systems certification	NG	Bamber et al., 2002
	Gas	A Maintenance Management	A specific maintenance model for gas field safety management system describes the process of maintenance actions	Y	Maintenance System Review; The Maintenance Deming Cycle	FT	Tucci et al., 2006)
A-7	General	Safety training	The purpose is to promote safety-related training and measure the training performance	Y	The training cycle and risk assessment		Cooper and Cotton, 2000
	General	The incident learning system	This paper models a safety and incident learning system to explore its dynamics. The system is expected to move 'safety performance from normal accidents to high reliability'	Y	High-reliability theory, The business and risk systems, 'Disaster dynamics' model, The productive organisational system, The incident reporting system, Safety leadership, etc.	System dynamics	Cooke and Rohleder, 2006

Y – Yes; NG – Not Given (in reference).

Table 7
SMSs studies and models from compliance perspective.

Group	Industry	Contents	Original SMS or standard	Integrated or comparable standard(s)	Reference
Understanding	General	TQM considers the quality program requirements of the ISO 9000 series of standards and the safety management principles embodied in OSHA's VPP and PSM guidelines to create a comprehensive safety management system	TQ(S)M – Total quality (or safety) management	ISO 9000	Adams, 1995; Cooper and Phillips, 1995; Weinstein, 1997
	Drilling	This system contains four aspects: Safety case regulations; PFEER regulations (fire & explosion and emergency response); MAR regulations (fewer substantial implications for drilling contractors); DCR regulations (two main implications for drilling contractors)	UKCS – UK Continental Shelf Regulatory System	HSE regulations UKOOA Guidelines IADC Guidelines	Nelson et al., 1997
	General	This report explains the contributing factors and barriers to OHSMS. It compares QM (Quality Management) with this OHSMS	OHSMS (NOHSC)	QM	Gallagher et al., 2001
	Energy	This system aims to provide uniform guide and activities to improve SMSs	DOE G 450.4-1B; ISMS – Integrated Safety Management System	DOE ordersCFR series	DOE, 2001
Comparison	General	This paper compares SOHSM in Norway and Australia Key objective of SOHSM is 'to promote and monitor programs of internal responsibility for OHS on the part of employer'	SOHSM-systematic occupational health and safety management	ISO 9000 OHS (USA, UK, NSW)	Saksvik and Quinlan, 2003
	Nuclear	This paper compares IAEA GS-R-3, which defines and improves the integrated management system, to ISO quality management system, which satisfies the requirements of the customer	IAEA GS-R-3 (The Management System for Facilities and Activities)	ISO 9001 2008	Biscan, 2008
	General	Based on the type of industry and international standards, this paper addresses SMSs and electrical safety standards in North America including how they can be implemented effectively	ANSI Z10 – Occupational Health and Safety Management Systems & CSA Z1000 – Occupational Health and Safety Management	NFPA 70E-2009; CSA Z462 – 2008; ISO 14001; OHSAS 18001; ILO OSHMS 2001; IEEE 902; IEEE 3007.3; etc.	Floyd, 2011
Integration	Petroleum	Safety improved by new initiatives such as STOP; new trend is to consider integrated system; change safety performance of WAPET	WAPET individual EH&S initiatives	Integrated EH&S MS	Kegg, 1998
	General	Models describe how to integrate standards into a management system and how to make QMS, EMS, OH&SMS fit for management and business systems	Overall management and business systems	ISO 9001 ISO 14001 BS 8800	Wilkinson and Dale, 1999a, 1999b
	Nuclear	This system cares how to integrate standards into a system rather than compliance. For example, it models alignment of ISO 9001 and 14001 using the systems approach	Management system (main elements)	AS/NZS, 1999 Norwegian guideline NTS ISO 9001 and ISO 14001 IEC 60300-1 IEC 60300-2	Beckmerhagen et al., 2002; Beckmerhagen et al., 2003
	Construction	This system aims to integrate standard systems into construction management	QES – Quality, Environmental, and Safety	ISO 9000; ISO 14000; ISO 18000	Koehn and Datta, 2003
	Maritimes	This paper discusses SMS registration and the integration of an SMS with other related management system standards	International safety management (ISM) code	ISO 19001:2000 OHSAS 18001:1999	Pun et al., 2003
	General	This paper discusses the approaches on how to integrate individual systems (QMS–EMS–OHSMS) into IMS and how to build an IMS from start; it describes a model for IMS implementation	Leonardo da Vinci project CZ/98/1/82530/PI/III.1.a/FPI 'Technological Training for SME's'	BS 8800ISO series SEVESO II requirements	Labodova, 2004
	General	This paper reviews papers discussing similarities and differences of SMSs at standard level and papers about IMSs (Integrated management system); it provides an effective implementation approach: a multi-level synergetic model	A multi-level synergy model	ISO 9001 ISO 14001 OHSAS 18001	Zeng et al., 2007
	Process	This paper focuses on 'the integration of health, safety and environment in single management systems', but also discusses two kinds of HSE indicators and problems	HSE (Health, Safety, Environment)	ISO 9000 (1994, 2000) ISO 14000 (2004) BS 8800 (1996) and OHSAS 18000 (2008)	Duijm et al., 2008
	General	This paper discusses the standards, methodologies of IMS; compares companies' QMS & EMS & HSMS in Italy; and finally lists the elements and activities to implement an IMS	QMS & EMS & HSMS	ISO 9000:2000; ISO 14001:2004 OHSAS 18001:1999 SA 8000:2007 BS 7750; BS 8800 French AFNOR 30-200 Spanish UNE 77-201 and 77-802 Italian UNI 10641	Salomone, 2008

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Table 7 (*continued*)

Group	Industry	Contents	Original SMS or standard	Integrated or comparable standard(s)	Reference
	Shipping operations	This paper describes approaches to explore the compliance of ISM (International Safety Management) as well as to assist the ship's management	IQSMS – Integrated Quality and Safety Management System	ISO 9001:2000	Celik, 2009
	General	This paper gives a guideline on and examples of how to integrate certifiable management systems for companies	SMSs of companies	ISO 9001; ISO14001; ISO 18001	De Oliveira, 2013

An integrated safety management system is (much) more advanced than an SMS solely set up for compliance or certification. SMSs started from individual management activities as described in Section 3. They evolved from individual management systems into integrated management systems as safety management is a core organisational issue next to other organisational management considerations. Regarding the form and results of simple *compliance* and *integration*, simple compliance refers to, e.g. an independent environmental management system, quality management system, occupational health & safety system, etc. (NEN, 2013), the indicators of which are to be considered and audited separately; while integration refers to a uniform system whereby indicators of all different aspects are included in the same information system because the quality of management has to be regarded as a whole (Beckmerhagen et al., 2003). Thus, it is evident that a good integrated SMS is more than just obtaining the appropriate certificates as it can, as a whole, improve organisational behaviour.

Moving from an independent safety management system to an integrated safety management system, two approaches are distinguished: one is the integration of, originally, separate systems; another is an integrated system that is developed and implemented from the very start (Labodova, 2004). The first approach is based on traditional management systems, which were originally set up with different management targets. An advanced management system combines these systems into an integrated system with a collection of targets. The second approach means building an integrated management system from the very beginning with comprehensive aims that include safety, security, quality, health, etc. How to obtain an integrated system still depends on the company's actual context. Implementing a management system efficiently is more important than getting a certificate or achieving compliance with standards. Not an integrated system per se but the process of achieving a better safety performance is the aim.

From a compliance perspective, there are several models that describe how SMSs and standards are integrated or aligned, although the original idea comes from quality and environmental management systems (EMS). Adams (1995) introduced total quality safety management and compared traditional management with total quality management (TQM). He argued that safety is an attribute of process quality. Puri (1996) built a framework for integrated EMS/TQM and addressed three specific aspects: management responsibility, process management and support systems. Renfrew and Muir (1998) proposed a management systems evolution model, which outlines the process of integrating into their own management system some ISO standards and some single management systems. This kind of model tries to combine an OH&S management system and a company's management system in either a national or international context (Rasmussen, 2007).

Another group of models shows how to deploy particular standard systems to specific management projects or systems. For example, in order to structure regulations and support guidance, Nelson et al. (1997) established a model with specific safety critical elements for a project SMS; to improve a certain company safety performance, Kegg (1998) deployed an EH&S management system; based on experience with contractors, Griffith and Bhutto (2008) built a model from best-practices for integrated management system (IMS) development, integrating certain ISO standards into business management processes. Another typical example in an operational context is shown in the SMS standard for gas transmission infrastructure and pipeline integrity management (PIMS), called 'architecture of a company management system of transmission system operator (TSO)'. This model illustrates the hierarchy of a company management system (CMS), the safety management system is a constituent part of the CMS, including the specific IMS for different high risk equipment, (design, construction, auxiliary) processes, emergency preparedness and response procedure (EPR), and so on (NEN, 2013). From top to bottom, the management systems actually all rely on technology, documentation and data, and organisation. In summary, from a compliance perspective, safety management systems are expected to contain standards and regulations with multiple aims in their respective fields.

6. Elements of SMSs

6.1. The basic elements – Hale's SMS model

SMSs have many common characteristics in that they are systematic, proactive and explicit (Hsu et al., 2010). Generally, safety management systems refer to a set of procedures connected by logical links. SMSs have general elements in common; they may be used in different industries while their elements are similar; and they are the result of continuous improvement following their life cycles. Fig. 6 shows a complete safety management system following Hale's (2005) model, which is also a generic SMS as these elements can be applied in various industries or organisations.

The generic SMS consists of two main elements: the risk control system and the learning system, each of which can be unpacked to reveal several sub-elements. The generic SMS is influenced through feedback by its own system performance and the societal context in which it operates.

The *risk control* system consists of the following sub-elements or management processes:

Box 1. The *primary and subsidiary business processes* describe the safety management system covering all life cycle phases (LCP) and as such it is responsible for the design, the construction and the technology of the organisation and its output(s).
Box 2. *The risk inventory and analysis in all LCPs and the transitions between them* is concerned with identifying and examining the organisation's hazards, understanding how these can become manifest and can be controlled.
Box 3. *The risk barriers and controls for all LCPs and transitions, plus requirements for their good functioning* is concerned with the implementation of risk barriers and controls. It describes the management system within its particular context and its proper functioning.
Box 4. Finally, *the management system to provide all requirements for good functioning of technical and procedural barriers and controls* contains the so-called delivery systems, which deliver the safety barriers and controls.

The *learning system* consists of the following sub-elements or management processes:

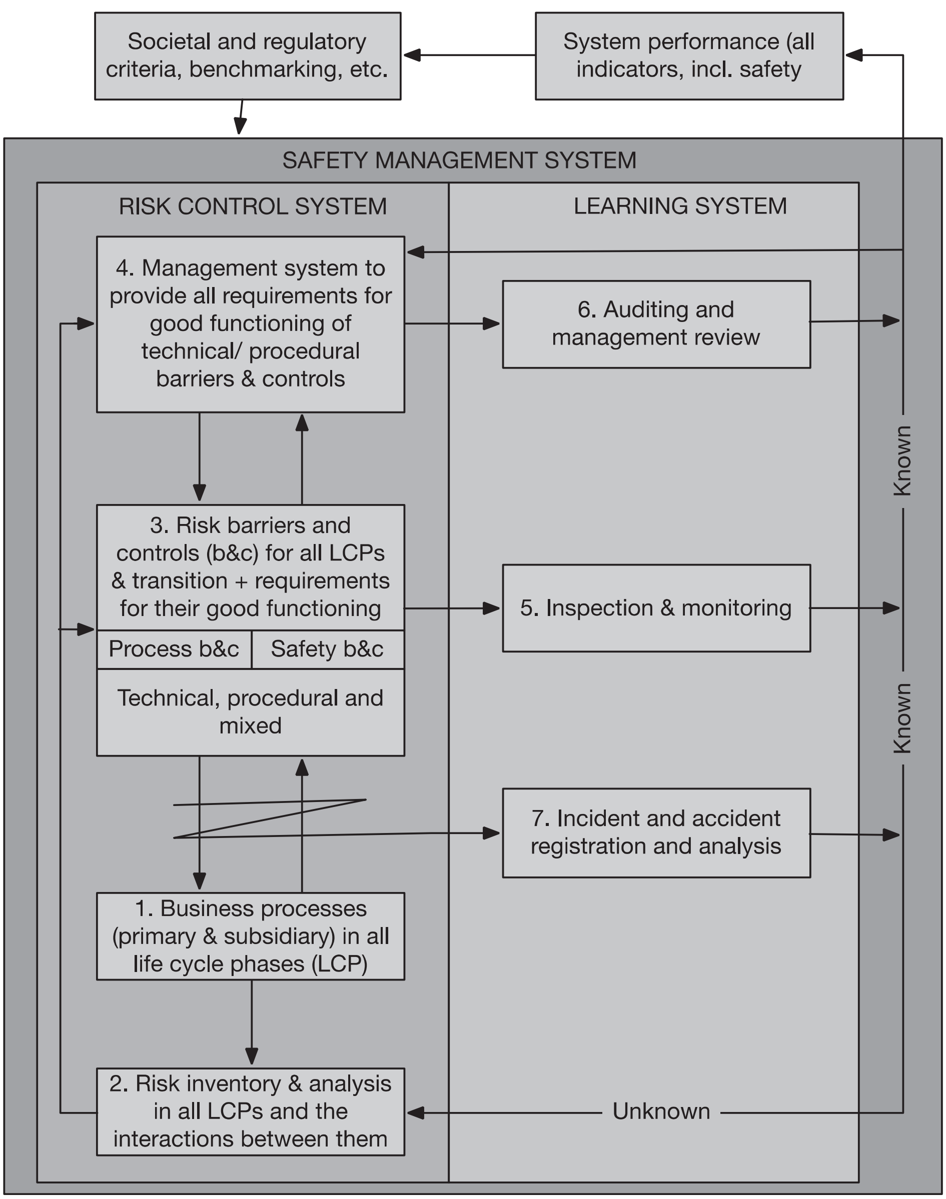

Fig. 6. A generic SMS framework (Hale, 2005).

Box 5. *Inspection and monitoring* is the process that receives real time information from the actual risk controls and checks these.
Box 6. The *auditing and management review* is concerned with the assessment of safety management and their performance, to make continuous improvement possible.
Box 7. The *incident and accident registration and analysis* is the end and also start box in an SMS, as this process is aimed at the identification of hazards and that provides critical information for the management of safety in the organisation.

Box 4 affects both *audit and review* (Box 6) and *risk barriers and control* (Box 3). As for the zigzag line between Box 1 and 3, it indicates that things can go wrong in this process but, at the same time, can be controlled also. So, the system needs *incident & accident registration & analysis* (Box 7), which process evaluates each incident or accident. If they occur, barriers might have failed and *inspection & monitoring* (Box 5) should be carried out more intensely. Otherwise, barriers should be put in place (Box 2, 3 and 4). *Auditing & management review* (Box 6) examines the quality of the delivery systems (Box 4).

Again, Box 4 can be unpacked to show the various *delivery systems* that together should provide barriers and their operators with sufficient controls and resources to function as specified.

4a. Competence and suitability of people;
4b. Commitment and conflict resolution;
4c. Communication, coordination of groups or teams;
4d. Procedures, rules and goals;
4e. Hardware and spares;
4f. Interface and ergonomics.
4g. Availability and planning of people and hardware.

6.2. A comparison of the generic SMS to 43 other SMSs

Normally, the number of elements of an SMS determines the level of detail of a safety management system. Some organisations enter elements into a framework hierarchy of different levels. For example, Lees (2005) built an SMS with twelve main elements and 48 more specific sub-elements. This category of SMSs has thus two levels of elements. However, with respect to the dimensions of this overview, the number of elements do not indicate the effectiveness of these SMSs, but rather show the specification of elements or factors within the framework of an SMS.

SMSs are different from each other for several reasons: (1) as different industries have different safety management problems, their SMSs are based on specific industry criteria and rules; (2) some SMSs or standards are different from SMSs for specific companies because the former are (more) generic and focus on management consistency, while the latter concern a plant, its project management, etc.; (3) the same element in different systems may have a different meaning and scope as a result of different interpretations of particular keywords.

By comparing the elements of different SMSs, their diverse features show the difficulty of modelling an effective generic SMS. An SMS is judged by its efficient and effective implementation. However, how to judge whether one system is better than the other is a thorny issue. Since Hale's SMS is systematic, understandable, applicable, and its elements are developed without any overlap, Fig. 7 uses Hale's model as a benchmark for a series of SMSs.

From the percentages of use of each element in other SMSs (Fig. 7), we can see that the 'Interface and ergonomics' (4f) does not feature in many SMSs and the same holds true for 'hardware and spares' (4e). However, in practice human and machine interfaces, software and hardware are very important for safety. For example, considering the various models of safety management, the MMES and SHEL models indeed emphasise these two elements (Table 4). But based on what has been found in the literature on SMSs, these two elements do not receive much attention (see Table 5).

While accident analysis (Box 7) and risk barriers and control (Box 3) draw much attention from academia, they are overall less deliberated by companies. Indeed, accident registration or analysis and practical measurements for controlling risks may not even be listed as important management elements in some SMS frameworks.

'Audit & management review' (Box 6) is included in most SMSs since it allows for the assessment or evaluation of the effectiveness of a whole SMS and it is therefore more distinct and independent than other elements.

In fact, a complete SMS contains all the elements shown in Fig. 6 but the importance attached to them as well as their position in an SMS framework differ. Fig. 7 shows the percentages with which these elements are used in other SMS models; the full comparison is discussed in a forthcoming paper.

6.3. A discussion of system performance

6.3.1. An SMS provides an assessment framework

In order to assess the effectiveness of the SMS, a clear list of indicators needs to be developed based on the framework of SMSs. The effectiveness of a general SMS is evaluated by a *compliance audit* and a *performance evaluation*. The compliance audit is based on the standardised SMS and its audit methods. It is a way to check if the organisation has the required elements in place and complies with a standard system. This generic audit can hardly use information from operational safety performance because the indicators are too general. However, a good thorough audit requires an effective performance evaluation.

A performance evaluation is difficult for the practice of safety management as key indicators of an SMS are not easy to identify and monitor. There are no principles on how specific a safety indicator should be. The 43 SMSs in Section 6.2 show that generic indicators and specific indicators are both used. However, for some key indicators it cannot be demonstrated that they are actually useful for safety evaluations. Real-time performance information is not fully available or

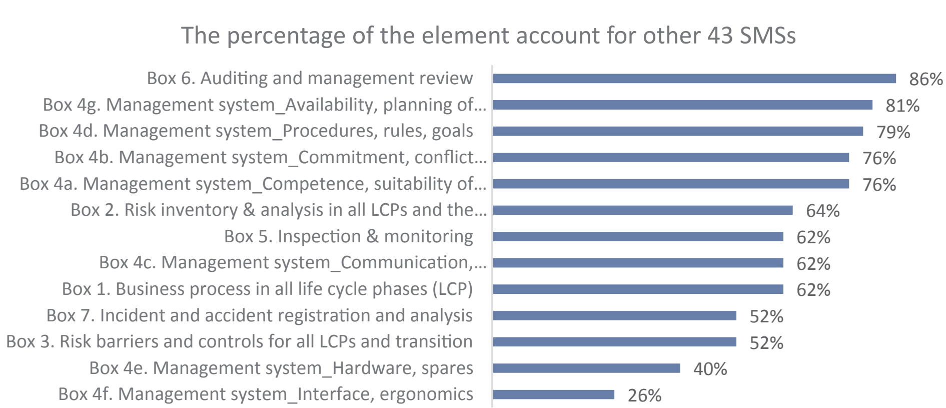

Fig. 7. SMSs elements comparing to Hale's model.

accessible. Regarding the performance of hardware, the failure or success mode of a particular component does not directly express the safety performance of a complex system. The more complex the system, the more affected factors are involved. So, it is hard to judge which barrier failure or barrier absence is critical in a whole safety system. Except for machine indicators, information on some other safety indicators is acquired through peer review and expert judgement. Using these methods requires accurate criteria, which are not easy to develop. In general, the performance evaluation of safety and its management is still a challenging topic.

The traditionally used indicators are the rates and nature of accidents, incidents, injury and other losses. Almost every company reports them in their annual safety report. The traditional outcome measures do not properly indicate the current SMS performance. Nowadays, a thorough analysis of risk, barriers and safety results in more frameworks of indicators. Robson et al. (2007) reviewed the effectiveness of occupational and health safety management system (OHSMS) interventions through the evaluation of three outcome changes: *implementation*, *intermediate outcome* and *final outcome*. The intervention framework is provided by the OHSMS while the indicators are based on the three outcome changes, such as OHSMS implementation over time, safety climate, injury rates and disability-related costs. Haas and Yorio (2016) reviewed performance indicators of health and safety management systems and carried out a survey on SMS elements and practices. They identified three categories of indicators: *organisational performance*, *worker performance* and *interventions*. These kinds of indicators are widely used in the evaluation of many other SMSs as well.

Considering the evaluation of safety management, elements of an SMS are often regarded as indicators, such as insufficient or improper procedures, leadership, commitment, competence, and so on. If one cannot be obtained directly, some other parameters and heuristics are identified when they can represent these general indicators.

An SMS can provide the framework for indicators, which includes every aspect (Øien et al., 2011a, 2011b). The problem is that the general elements sometimes cannot be used as safety indicators. Each element contains complicated control processes and these can affect each other. With various parameters to be monitored in the processes, the key indicators are mostly extracted at an operational level. The more specific the description of an indicator is, the more useful data it generates.

6.3.2. Three kinds of operational assessment in terms of performance indicators

A complete SMS consists of three parts: the events model, barriers, and the management model. Safety performance, therefore, is related to these models. The assessment of the performance can be classified in the following three groups; they contain the key indicators for overall system performance.

INDICATOR GROUP 1 – RISK: Risk assessment based on scenarios

In Hale's SMS, the risk inventory and analysis is an important start for risk control and this information is based on past incident and accident registration and analysis. The analyses apply the event models and techniques. As the original hazard scenarios and risk inventories are critical for an SMS, many specific operational indicators have been developed around these hazards and risks.

INDICATOR GROUP 2 – RISK': Risk analysis after inserting barriers

Modern risk analysis is based on the scenario after safety barriers, defences or interventions are inserted or put into effect. The calculation of event probabilities and consequence severities is with the inclusion of safety barriers. The failures of safety barriers influence the risk level of the basic scenarios. In Hale's SMS, inspection and monitoring focus on the performance information from dynamic barriers and controls, but which also provide (additional) safety performance indicators.

INDICATOR GROUP 3 – MANGEMENT: Delivery systems affect barrier performance

The performance of safety barriers is directly affected by the management systems, i.e. the delivery systems. Good condition of barriers demands a good performance of an organisation on seven aspects (Boxes 4a–4g in Hale's model). Although the assessment of management contains both operational and organisational information, the management is delivered through safety activities and tasks. Management performance is another group of performance indicators for SMS performance.

7. Conclusion

Depending on the perspective taken, there are multiple definitions of a safety management system, but its definition is always concerned with three core issues: 'safety', 'management' and 'system'. *Safety* refers to its opposite: accidents, losses or risks. *Management* connects accident causes to organisational control and actions. *System* refers to a systematic framework or models that provide the logic of safety management. To sum up, an SMS means a system containing management principles and activities for controlling risks and preventing accidents.

Depending on their background, SMSs are either narrowly or broadly defined and developed, each with its own pros and cons. Some provide a definition that is directly based on their own industrial activity or even operational SMSs; their angle is practical and meant to achieve the desired safety performance or meet specific safety policies. Others are more abstract in their definitions of an SMS whereby its constituent parts are elaborated along the lines of traditional management systems directed at the continuous improvement of safety performance. Despite the fact that the content of SMSs always pertains to activities, processes, documented procedures or functional control systems, a clear delineation of an SMS is imperative for its implementation as it determines the required resources as well as the responsibilities of the SMS. An SMS is essentially a mechanism that can be designed in different ways apart from its environment, such as (safety) culture or a certain industrial context. In our overview, the definition of an SMS makes it possible to distinguish it from other such management systems.

Safety management developed along with the improvement of safety theories, practices and standards. An SMS is primarily driven by accident analysis and prevention. Even laws, regulations and standards are prompted by accidents because their consequences raise the public's awareness of safety and their acceptance of risk: as low as possible in a practical sense. The history of safety management also shows increased attention for economic reasons with respect to the development of SMS. Indeed, an effective SMS plays an important role in the assessment of a companies' creditworthiness and its ability to control risk (e.g. through insurances). The overview of the history of SMS development has shown that safety management systems can significantly contribute to the improvement of organisational management as a whole.

The theoretical modelling of SMSs can improve the effectiveness and efficiency of SMS developments. Overall, there are three main groups of models. (1) Accident theories and models describe the events and cause-effect relationships. They provide the means to develop scenarios for risk analysis. (2) Safety barriers inserted in the event sequences are the connection between the accident model and the management model. The barriers show the elaborate ways that safety management systems have for controlling accidents. (3) The management models are important as they show how the safety barriers are to be managed. Subsequently, the risk is controlled. The hierarchical models only show the framework of management, but it is difficult to make sure that the safety systems and barriers are functioning as designed. Therefore, factors that influence risk or barrier failure receive increasing research effort. In terms of a complete SMS, the events model, the events model with barriers inserted and the management model are the three stages for modelling and still three important topics for safety management research.

In accordance with the purpose of setting up an SMS and carrying out research into it, control and compliance are critical. Either at a theoretical level or at a practical level, SMSs are designed to control unwanted events with a high probability or loss. The PDCA control loop is a central idea applied in safety management systems and all its sub-systems. Controls, techniques and data analysis are the main concerns in these sub-systems. In practice, SMSs are popular for their role in compliance management. This given explains why obtaining a safety certificate can sometimes motivate companies to continually improve their SMSs. According to the literature, an integrated management system is more advanced than independent safety systems, as safety is just one of the comprehensive organisation management objectives. In terms of purpose, control is the obvious aim of an SMS for which some functions to prevent accidents need to be fulfilled; a standard complied SMS is the necessary requirement in a global market. The demand for safety of companies ultimately determines the purpose of their SMSs.

Elements of SMSs have a bearing on the definition of safety management, modelling and the actual purpose of an SMS. They can explain the contents of an SMS and the processes of its implementation. Hale's SMS is a comprehensive and well-structured system, which makes it suitable for a comparison with other SMSs. This model provides a tool for assessing the completeness of an SMS. The performance of safety management system can be derived from three groups of indicators: the initial risk based on incident or accident scenarios, the risk' after insertion of safety barriers, and the delivery management for the barriers and controls. These three groups of indicators are not only present in Hale's SMS, but also correspond to the three groups of SMS models.

Throughout the overview, we concluded, grouped and discussed SMSs from five different perspectives: definition, history, models, purpose and elements. All five perspectives contribute to make the management of safety more tangible and efficient. Many SMSs, being a practical industrial topic, have not been elaborated theoretically, so this paper fills this gap and also points out issues especially regarding modelling and the insight into particular SMS elements. Finally, current shortcomings in safety performance assessment have to be solved in a (scientifically) valid yet also practical way.

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