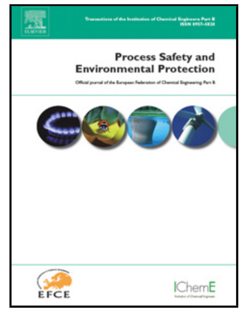

Safety intelligence as an essential perspective for safety management in the era of Safety 4.0: From a theoretical to a practical framework

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Safety intelligence as an essential perspective for safety management in the era of Safety 4.0: From a theoretical to a practical framework

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Keywords: safety intelligence (SI); safety big data; Safety 4.0; safety management; safety decision-making.

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ABSTRACT

In the age of big data, intelligence, and Industry 4.0, intelligence plays an increasingly significant role in management or, more specifically, decision making; thus, it becomes a popular topic and is recognised as an important discipline. Hence, safety intelligence (SI) as a new safety concept and term was proposed. SI aims to transform raw safety data and information into meaningful and actionable information for safety management; it is considered an essential perspective for safety management in the era of Safety 4.0 (computational safety science—a new paradigm for safety science in the age of big data, intelligence, and Industry 4.0). However, thus far, no existing research provides a framework that comprehensively describes SI and guides the implementation of SI practices in organisations. To address this research gap and to provide a framework for SI and its practice in the context of safety management, based on a systematic and comprehensive explanation on SI from different perspectives, this study attempts to propose a theoretical framework for SI from a safety management perspective and then presents an SI practice model aimed at supporting safety management in organisations.

Keywords*:* safety intelligence (SI); Safety 4.0; safety management; safety decision-making

1. Introduction and motivation

Safety management is regarded as the process of realising certain safety functions (Li and Guldenmund, 2018), and it has become an important topic both in academia and in practice over the past decades (Denton, 1980; Hale, 2003; Wang et al, 2017). From an organisational perspective, safety management aims to promote organisational safety and protect people and property within the organisation from unacceptable safety risks (Li and Guldenmund, 2018). Recently, with the increasing global economic uncertainties and owing to global economy in the doldrums, safety management in most organisations is under growing pressure to perform more with less. In addition, there is a constant need to find better approaches to guarantee that safety resources are allocated as effectively as possible while maintaining good organisational safety performance (Wang et al, 2017). Thus, safety information is critical to achieving these targets; it is considered as the lifeblood of organisational safety management because safety information is necessary for effective safety risk prevention and informed safety decision making (Yang, 2012; Huang et al, 2019; Wang et al, 2019). However, safety management (especially decision making, which is the core of safety management) is complex (Gobbo et al, 2018), and requires access to a variety of high-quality safety information (Huang et al, 2018). In the era of information, especially in this era of big data/intelligence/Industry 4.0, it cannot be disputed that safety data and information have become an indispensable resource for and a key successful factor in today's safety management (Gobbo et al, 2018; Huang et al, 2019; Wang et al, 2019; Lee et al, 2019). Therefore, providing the right persons with the right safety information at the right time is vital for the improvement of organisational safety. Moreover, presently, safety science has entered the era of Safety 4.0 (Fig. 1), which is computational safety science—a new paradigm for safety science in the age of big data, intelligence, and Industry 4.0. Its foundation and support are safety informatics (Wang and Wu, 2020a).

In both academia and practice, the processes or activities of gathering and processing data and information to develop strategies and make and implement specific decisions have generally been referred to as intelligence (Gilad and Gilad, 1985; Foshay and Kuziemsky, 2013; López-Robles et al, 2019). In the age of big data, intelligence, and Industry 4.0, intelligence plays an increasingly crucial role in many domains (e.g. military, management, business, security, police, and government), and it has been recognised as an important and potential discipline (López-Robles et al, 2019). Hence, safety intelligence (SI) as a new concept and term of safety informatics was proposed by Wu and Wang (2018). In the stage of Safety 4.0, SI was considered an essential perspective for the safety informatics and safety management practice (Wang and Wu, 2020a). It is defined as the usable and actionable safety information arising from a systematic process for processing safety data and information. SI can ensure that safety decision makers make informed decisions in a wide array of organisational contexts (Wang and Wu, 2019; Patriarca et al., 2019). In an organisation, SI can integrate various safety data and information from internal and external sources and convert them into actionable safety information to provide an effective support for safety management

(Wang and Wu, 2019). This is a key feature of SI.

In the stage of Safety 4.0, intelligence as a concept or a term is beginning to enter the field of safety science. However, intelligence as a discipline has a quite long history in many areas (López-Robles et al, 2019). In fact, in the field of safety science, SI has existed since before it was proposed as a safety concept. Currently, there are numerous safety management practitioners that consciously or unconsciously engage in various SI practices. For example, various present technologies (e.g. safety information systems, safety big data, and artificial intelligence) and approaches (e.g. evidence-based safety management, data-driven safety management, and safety knowledge management) related to SI have been widely applied to safety management practices to produce valuable SI to support safety management process (Sherehiy and Karwowski, 2006; Wu et al., 2014; Wang et al, 2017; Huang et al, 2018; Gobbo et al, 2018). Safety managers carry out the safety risk identification, analysis and evaluation to gain valuable SI for safety risk prevention and control. However, the implementation of SI practices in the organisation is often haphazard. SI can provide various benefits to safety management, which can be summarised into eight key aspects as follows (Turban, 2008; Foshay and Kuziemsky, 2013; López-Robles et al, 2019; Wang and Wu, 2019):

(a) accelerating safety decision making,
(b) accessing safety information (e.g. supporting for a systematic safety data and information collection, providing useful safety information for safety decision-making, making safety data and information reliable and special, increasing the quality of safety information, and avoiding unnecessary safety data and information),
(c) improving safety (safety performance),
(d) reducing and managing safety risk (e.g. identifying, analysing, assessing, and predicting the safety risk and improving the understanding of safety risks),
(e) increasing safety management effectiveness and efficiency (e.g. systematically promoting organisational safety management process; identifying the strengths, weaknesses, opportunities, and challenges of safety management; as well as assessing and improving safety management efficiency and effectiveness),
(f) promoting safety information sharing (such as improving flow and dissemination of safety information),
(g) enhancing safety performance management, and
(h) saving safety management time and cost.

Moreover, in the age of big data, organisation face safety data and information overload. However, safety information has no value if it is not relevant, up to date, accurate, reliable, and actionable. SI can process the safety data and information collected to provide the most relevant, accurate, useful, and actionable safety information to safety managers or, more specifically, decision makers (López-Robles et al, 2019; Wang and Wu, 2019).

Although SI has the above potential benefits for safety promotion and safety management, many organisations have not yet effectively and normatively implemented the SI practice. Furthermore, studies on SI to guide SI practice and promote further research of SI barely exist. To the best of our knowledge, only five representative papers in English in the safety science domain focused on SI. Wu et al. (2014) provided a review of recent advances in the field of using intelligence tools (such as early warning systems and data mining) for enterprise risk management. Patriarca et al. (2019) highlighted that SI is an incremental proactive safety management method for holistic aviation safety performance. Since 2018, Wang and Wu (2020a), two Chinese safety & security scholars, published some academic articles on SI. However, only few non-Chinese safety scholars and practitioners discovered their studies on SI as their papers were published in Chinese and in Chinese journals. To introduce the concept of SI to the rest of the world, Wang and Wu (2019) published a paper in English in 2019, which discussed and explained the basic issues regarding SI, such as its definition and scope. In 2020, they provided a brief review on the Chinese literature on SI (Wang and Wu, 2020a). Bruenisholz et al. (2019) stressed the importance of intelligence in fire prevention and suggested that the data from unknown and deliberate fire events should be used to produce valuable intelligence to support fire prevention. Although studies (including the authors' Chinese publications) on SI have been performed in recent years, a universal framework for SI is still missing. This seriously hinders the effective implementation of SI in an organisation and the future study on SI. Therefore, this study aims to present a framework for SI to promote its future studies and practices. Moreover, it should be clarified that this study is different from the authors' previous articles on SI in Chinese (interested readers can gain a brief understanding on the authors' Chinese SI literature in a review paper by Wang and Wu (2020) in English) and has not been published in any Chinese journal.

This paper is organised as follows. Section 1 introduces the research progress and background of the study. Section 2 provides a systematic and comprehensive explanation about SI from different perspectives. Section 3 proposes the theoretical framework for SI. Section 4 presents how to a practice the framework for SI in an organisation. Finally, Section 5 draws conclusions from the analysis and proposes the limitations of the study.

2. What is SI?

When people first hear the term intelligence, they think of military or defence intelligence. Although the roots of intelligence may have been with the military (Ruggles and Brodie, 1947; Schultz et al., 1994), the essence of intelligence applies to all organisations—that is, how organisations can improve their decision-making processes (López-Robles et al, 2019). Intelligence is considered as the collection, analysis, interpretation, and dissemination of data and information to be used for decision-making processes (Kahaner, 1996; Turban, 2008). Presently, in intelligence studies, intelligence has been extended to become an umbrella term that includes uses, tools, infrastructure, and practices to enable access and analysis of data and information, thereby improving organisational performance and decision making (López-Robles et al, 2019; Turban, 2008).

From an organisational safety management perspective and based on general definitions of intelligence (e.g. Yovits and Kleyle, 1993; Turban, 2008; Calof and Skinner, 1999; Rouach and Santi, 2001), Wang and Wu (2019) define SI as the usable and actionable safety recommendations gained through safety data and information processing; SI can influence organisational safety management. Specifically, "safety management" in this definition of SI implies "safety decision-making" as the core of safety management is safety decision making (Wang et al., 2017; Huang et al., 2018). A simple definition is that SI is safety information that has been processed such that it can be helpful to safety managers (safety makers) in making decisions. Therefore, SI is an essential component to making safety decisions (e.g. safety goals and policies). It simplifies safety data and information analysis and safety knowledge discovery, rendering it possible for safety decision makers in an organisation to more easily access, comprehend, analyse, collaborate, and act on the useful safety data and information for safety decision making, anytime and anywhere.

According to the SI definition of Wang and Wu (2019), in fact, SI also is an umbrella term similar to intelligence; in other words, SI has multiple meaning. We believe that SI is a product, process, tool, and capability, which are explained in Sections 2.1–2.4, respectively.

2.1 SI as a product

Intelligence professionals emphasise that, if intelligence gathered is not usable (or actionable), then it is not intelligence (Turban, 2008). Thus, SI is the usable and actionable safety information (including safety knowledge) and is the actionable output ascertained by the safety management needs prescribed by an organisation. SI is the product arising from the collection, evaluation, collation, analysis, integration, and interpretation of all available data and information related to one or more aspects of safety, which has direct or potential significance for the safety management of an organisation, such as the development and execution of safety plans, policies, decisions, and safety risk controls. In other words, SI is a product of processed (analysed and interpreted) safety data and information.

2.2 SI as a process

First, to help safety decision makers make safety decisions and to improve an organisation's safety, SI is a process that produces and disseminates actionable SI by planning; systematically, ethically, and legally collecting; processing; and analysing safety data and information from the internal and external environment of an organisation. Key constructs or stages of the SI process are as follows (Wang and Wu, 2019; Brummer et al., 2006):

(a) planning and direction, i.e. focusing on the SI needs of an organisation's safety managers (safety decision makers) and safety issues of the highest importance to senior safety management of an organisation,

(b) safety data and information collection, i.e. the focused collection of safety data and information from various internal or external sources of the organisation,

(c) safety data and information sorting, capturing, and storing; i.e. dividing safety data and information types from different perspectives, and based on the certain rules, and using various methods and technologies for capturing key safety information from physical and electronic safety management records,

(d) safety data and information analysis, i.e. converting safety data and information into actionable SI on which safety decisions may be made, and

(e) SI reporting and dissemination, i.e. reporting and communicating the results of the SI process or project to those in the organisation with the authority and responsibility to act on the findings.

According to the above discussion, the process of SI is illustrated in Fig. 2, demonstrating that the process is cyclical, with a series of interrelated steps. Safety data and information analysis is the key step for converting raw safety data and information to safety decision supporting information. From an information chain perspective, SI is a process by which organisations gather safety data and information, convert them into SI (namely, usable and actionable safety information and knowledge, or safety recommendations), and, then, ideally apply these data in their safety decision-making processes to improve their safety performance. In other words, SI, as a process, is the action of harnessing and transforming fragmented safety data and information into actionable information or knowledge about safety objectives and recommendations of an organisation and applying them to help an organisation achieve safety management success. Moreover, to make SI more targeted and effective, SI planning and direction should be adjusted according to the SI needs of safety decision makers and other SI users in an organisation.

Second, SI is a safety data- and information-driven process that combines safety data and information storage and gathering with safety data, information, and knowledge management to provide input for safety decision-making processes.

Third, as processing safety data and information should rely on software and information technology, SI is a software- and technology-driven process; it allows organisations to analyse raw safety data and information from multiple sources, extracting insights that lead to more effective safety decisions.

Finally, from the perspective of safety management, SI is a process for supporting safety decisions. Thus, it embodies safety management processes based on well-informed safety decisions, which lead to high safety performance level within an organisation. In other words, SI is a significant part of the safety management process.

2.3 SI as a tool, technology, and technique

First, SI is an effective tool (or a technology) for transforming safety data into safety information, safety information into safety knowledge, and safety knowledge into safety decisions, which drive effective actions for safety management. It encompasses data warehousing, safety analysis (including safety risk analysis) tools, and safety data/information/knowledge management. Specifically, SI comprises various architectures and techniques such as database, data warehousing, and data mining, which transform raw safety data into useful safety information and knowledge to provide safety decision support. Meanwhile, various information technologies are key enabling technology for SI. For example, SI uses a machine learning technology that can identify correlated information (relationships between things that change in an organisation' safety management system for no articulate reason) to intelligently predict safety information, thus making things clearer for organisational safety managers. Therefore, recently, rapid advances in information technologies such as database management, data warehousing, and big data mining and the application of these information technologies in safety management have further embarked the use of SI in safety management (Fig. 3). This implies that SI as a tool for processing and analysing the collected safety data and information requires many tools originally developed by many disciplines, such as safety science, data science, information science, computer science, and artificial intelligence science.

Second, SI is a powerful tool and technology to analyse incident and safety event causalities and perform organisational safety diagnoses as it offers a safety data- and information-driven approach to link organisations' strategic safety goals and policies into tactical safety procedures and operational safety actions.

Third, any organisation's safety executive or safety manager who desires greater safety management success in his or her organisation should consider incorporating SI technologies, to improve the quality and efficiency of safety management. SI technology allows safety decision makers to make quicker, more informed decisions based on highly accurate and valuable safety data and information.

In summary, SI is a set of tools, technologies, and techniques that enable an organisation to transform its safety data into timely and accurate information for the safety decision process to be made available to the right persons in the most suitable form.

2.4 SI as a capability

First, SI is an organisation's capacity for safety data and information collection and processing. Second, it is an organisation's ability to solve safety problems because SI focuses on safety problem solving, which is the direct objective and task of safety management. Third, SI is an organisation's capability to understand and forecast risks and changes related to safety in a timely manner to take appropriate actions against them. This capability involves foresight and insight on safety management. For example, SI can identify impending safety changes in an organisation, which may be positive, representing safety improvement opportunities, or negative, representing safety threats or challenges. Certainly, SI can represent the following numerous capabilities:

(a) capacity for safety learning (e.g. gaining new safety information and understanding the latest safety research evidence),
(b) ability to adapt to and reshape an organisation's safety management environment,
(c) ability to understand safety management factors (such as hazards, incidents, unsafe behaviours, safety culture, and safety resources) and to act appropriately upon understanding, and
(d) capability of adding more intelligence to the safety management activity of organisations.

2.5 Summary

According to the above analysis, as a safety management term, SI is a contemporary safety management idea and approach that combines methodologies, processes, architectures, tools, technologies, techniques, and capabilities to transform raw safety data and information into the SI product (namely, meaningful and actionable safety information) for safety decision making. It can play a vital role in promoting an organisations' safety and improving the organisational safety performance by identifying safety risks and new safety promotion opportunities, highlighting hazards and potential safety threats, revealing new safety management insights, and enhancing safety decision-making processes. Therefore, SI is a top priority for most organisations in the era of big data and intelligence.

3. Theoretical framework for SI

3.1 Main task (objective) of SI

SI focuses on safety data and information from a very wide view, allowing organisations to predict future safety events and use them to make effective safety decisions as every safety decision is based on certain assumptions. Therefore, SI primarily aims to provide safety decision support for specific safety goals defined in the context of safety management activities considering the organisational safety management framework. Specifically, SI is used by safety decision makers to obtain comprehensive knowledge regarding the organisation's safety and safety management and of the factors that affect them, as well as to define and support their safety strategies, policies, standards, rules, procedures, etc. The goal is to enable data- and information-driven safety decisions to improve the effectiveness of safety decisions, enhance safety performance, and respond more quickly to safety risks and changes.

Regardless of the SI-related information technology or mean organisations use, the organisational safety managers should focus on the ultimate value of SI: it allows people at all levels of an organisation to access, interact with, and analyse high-value safety data and information to identify safety risks (hazards), improve safety performance, discover safety promotion opportunities, and manage safety effectively, efficiently, and confidently. In other words, SI primarily aims to formulate a sound, fact-based, and rational safety decision-making mechanism for safety management action.

3.2 Foundation of SI

The black arrow in Fig. 4 indicates the traditional safety information cycle, which is "Safety data→Safety information→SI→Safety wisdom" (Wang and Wu, 2019). Safety data are a collection of raw value safety elements or facts used for calculating, reasoning, or measuring. They may be collected, stored, or processed; however, they are not placed into a context from which any meaning can be inferred. Safety information is the result of collecting and organising safety data such that it establishes relationships between safety data items, thereby providing context and meaning. SI is the processed safety information that provides insights for safety information. The distinction between safety data (quality) and safety information (quality) is particularly evident in the SI context. The main task of SI is to provide high-quality safety information for safety decision making of organisations using essentially a two-stage approach: (i) identification, collection, storage, and maintenance of safety data (e.g. in large safety data warehouses or safety data marts) and (ii) retrieving, analysing, processing, and conveying (communicating/presenting) safety data in a way that is useful for safety decision makers using various SI forms (see Section 3.3). The hierarchical relationship of safety data and safety information indicates that safety data quality is a prerequisite or antecedent, but is not a guarantee for safety information quality (Wang and Wu, 2019).

According to the traditional safety information cycle, the production process of SI is transforming safety data into safety information (including safety knowledge) and safety information into SI, which can drive effective safety decisions. SI decision support mainly relies on empirical safety information based on safety data. In addition to this empirical background, producing SI uses different types of safety knowledge and theories for useful safety information generation. In the era of big data, safety data can also be directly transformed to SI by big data analytics. This is implied by the blue arrow in Fig. 4. Therefore, information regarding safety, as well as safety data collected from multiple sources, is used to form the basis of what is known as SI. Safety data and information regarding SI activities comes in an organisation from both external and internal environments. Internal safety data and information include input safety data and information (e.g. safety investment), process safety data and information (e.g. data and information from safety monitoring and inspection), and outcome safety data and information (namely, various key safety performance indicators). External safety data and information include national safety laws and regulations, official safety standards and accident reports, safety research evidence, and other safety data and information from external environments.

Based on the objective of SI and as shown in Fig. 4, SI seeks to achieve the safety data and information value through targeted collection and analysis of partial (various locations) safety information in an organisation. Fig. 5 shows the process of achieving the safety data and information value (safety wisdom in the future).

3.3 Types of SI

Safety management requires safety managers to make a set of interconnected and successive safety decisions over time (Huang et al., 2018). In the long-term, safety managers decide the possible safety investments, strategies, policies, and safety management systems to select or adapt to best fulfil organisational safety goals. In the medium term, safety managers make some tactical safety decisions. For example, they develop safety plans, procedures, resources, and prevention and control methods for preparing, guiding, and optimising the online safety risk prevention and control in an organisation. However, descriptions of tactical safety decision are not sufficient to trigger daily operational safety management activities. Thus, safety managers must define specific ways to execute their tactical safety decisions. In other words, in the short term, safety managers need to make operational safety decisions, which may result in daily safety management operation orders to be executed. Therefore, we suggest reconsidering safety management as a safety decision-making process in which decisions and adaptations are made continuously and sequentially over time (strategic safety decisions/tactical safety decisions/operational safety decisions) to simulate reality more closely. In fact, Hale (2003, 2005) and Winge et al. (2019) have expressed a similar opinion and believed that the structure of a good safety management system must include a safety problem-solving cycle at three levels (operational, tactical, and strategic). Moreover, Hale (2003) highlighted that these three safety problem-solving levels have different time dynamics, from seconds up to days at the first level, weeks and months at the second, to 3–5 years at the third.

Three types of management are distinguished: strategic, tactical, and operational. An approach to reduce the complexity of safety management involves distinguishing it into strategic, tactical, and operational safety management with each of the levels using its own safety management tools. Based on this and the above understanding, safety management also can be divided into three types (Fig. 6): (i) strategic safety management (i.e. long-term safety decision-making processes of safety managers, resulting in safety investment and long-term safety management system decisions), (ii) tactical safety management (i.e. medium-term safety decision processes of safety managers resulting in updating the safety management system), and (iii) operational safety management (i.e. short-term safety decision-making processes of safety managers resulting in daily online safety risk prevention and control). As SI support is required for all types of safety management (safety decision making), an organisation must produce three different types of SI for safety management—strategic, tactical, and operational (Fig. 6)—and deliver them to the team in need of that specific type of SI. An organisational SI system can address all three types of SI, or it may only address a subset of these types, depending on the requirements and availability of safety data and information. Each SI type serves a different safety management type and purpose, as well as targets a different safety manager group. When traversing the SI cycle, understanding who the target audience is for a piece of SI system is important, and the report must be geared to the audience. In other words, SI needs to be actionable by the target safety manager group and safety management type.

As outlined in Fig. 6, the different types are hierarchical in nature with strategic SI at the top. Strategic SI is SI for the managers at the highest levels of organisational safety management. It is designed to help senior safety managers understand the large picture surrounding an organisation's safety factors and consider the improvement of an organisation's safety appropriately and effectively. Strategic SI should focus on long-term trends surrounding safety risks, safety technologies, safety culture, or potential safety threats to an organisation. Strategic SI is a forward safety management thinking mechanism and relies heavily on safety prediction and estimation, thus anticipating future organisational safety and safety management based on past safety management actions or expected safety capabilities. Effective strategic SI requires safety managers (or more specifically, safety analysts) with deep safety management expertise, considerable safety management insights, abundant management experience, as well as willingness to understand and adapt to changes in a highly dynamic safety management environment.

If strategic SI is designed for an organisation's safety leaders, then safety leaders on the safety team use tactical SI. Tactical SI focuses on safety risks and threats and attempts to answer the what and when questions by providing safety information regarding safety plans, procedures, and techniques. It is an assessment of the immediate safety management capabilities of an organisation. It focuses on safety risk assessment (including hazard identification), as well as the weaknesses, strengths, opportunities, and challenges of safety management. Effective tactical safety risk assessment and safety management analysis of an organisation allow those in direct control of the safety risks to allocate crucial resources for safety-critical tasks in the most effective manner and to engage in the online safety risk management at the appropriate time using the right safety plans and procedures.

Operational SI focuses on all daily safety management activities of organisations. Operational SI within the realm of safety management is geared toward, unsurprisingly, the online safety risk managers. It is real-time or near real-time SI, often derived from technical means and delivered to organisational members who are in direct control of safety risks engaged in online safety risk management activities. Operational SI is immediate and has a short time to live. The immediacy of operational SI requires that safety managers (or more specifically, safety analysts) have instant access to the safety data and information collection systems and can transform safety data and information into SI in a short time and in a high-pressure environment.

Based on the above analysis, strategic SI focuses on an organisation's safety management strategies and long-term safety investments, goals, and policies. While tactical SI focuses on safety plans, procedures, and resources, operational SI focuses on all daily and online safety risk management activities of organisations. Operational SI mostly differs from strategic and tactical SI for safety management and promotion purposes at both the level of detail required and in the timeliness of the safety data and information. Operational SI may involve accessing a transaction system directly or through a safety data warehouse that is updated in near real-time multiple times throughout the day. Strategic and tactical SI for safety management and promotion purposes may also occur in near real time; however, they can also be based on weekly, monthly, or yearly safety and information. Meanwhile, the three types of SI feed off each other and each has impact on the other type. Strategic SI drives the requirements for tactical SI, which drives the requirements for operational SI. Therefore, SI provides a data-driven approach to link organisations' strategic safety goals into tactical safety policies and operational safety actions. Certainly, a successful operation may change the tactical SI picture, and numerous successful operations may change the strategic safety outlook.

3.4 Styles of SI

The architecture of SI depends on its specific applications. Through investigation of SI practice in organisations, we found that SI usually can be divided into five styles: (i) safety reporting, (ii) safety analysis (including safety risk analysis), (iii) safety querying, (iv) safety statistical analysis and safety data mining, and (v) safety early warning (Wu et al., 2014; Turban, 2008). The five styles are explained in detail in Table 1, but organisations need to provide special tools for each style.

3.5 Conceptual SI model

To provide a clear and comprehensive understanding of SI to researchers and practitioners, a conceptual SI model is highly necessary. However, a conceptual model for SI does not exist. This led us to develop a conceptual model for SI, and the proposed comprehensive model for SI is shown in Fig. 7.

The conceptual SI model as shown in Fig. 7 is a comprehensive model, which includes six units. The first unit shows different organisational safety management (safety decision-making) levels, which were explained in Section 3.3. This guided the authors in creating the requirements for our SI pools. The second unit in the model indicates SI pools where all collected safety data and information are transferred through the safety data and information. The SI gathered in these pools can provide support for organisational safety management (safety decision making). In Section 3.3, according to the different categories (levels) of safety management or safety decision making (see the first unit of Fig. 7), three types of SI (i.e. strategic, tactical, and operational) are distinguished. Hence, three main components exist, which need to be considered for the second unit (see the second unit of Fig. 7). In other words, the SI pools in the second unit are mapped by considering the three organisational safety management (safety decision making) levels. The third unit shows the organisational SI team. A satisfactory and ideal SI team should include both intelligence and safety professionals. The fourth unit is related to how the organisational SI team can contribute to organisational SI practices or activities. Intelligence professionals usually lack sufficient knowledge and skills for safety management; similarly, safety professionals lack the necessary intelligence knowledge and skills. Therefore, intelligence professionals in the organisational SI team should receive safety training (namely, basic knowledge and skills training for safety management), and safety professionals in the organisational SI team should receive intelligence training (such as intelligence awareness and literacy training). The fifth unit in the model is SI action, which is a collection of the safety data and information for producing SI. The last unit in the model indicates SI objectives, which were explained in Section 3.1.

4. Practical framework for SI

4.1 Importance of SI in safety decision making

Simon (1959), a Nobel Prize winner in economics and a famous decision-making scholar, stated that information (or more specifically intelligence) is fundamental and affects each decision. Therefore, he proposed three major stages of the decision-making process: intelligence (intelligence gathering and analysis, such as situation analysis and problem identification), design (uncovering, developing and analysing various possible solutions), and choice (evaluating the options, and selecting the best ones). Simon’s decision-making model is a commonly accepted view and serves as the basics for decision-making research and practice (Sadovykh, Sundaram and Piramuthu, 2015). Many researchers (e.g. Huber and McDaniel, 1986) followed Simon’s model or even based further studies on Simon’s view. For example, Simon’s model was extended by adding additional phases. Based on Simon’s model, more complete steps of the decision-making process were developed, which include intelligence, design, choice, implementation, and control (Kilvijarvi and Tuominen, 1999; Sadovykh, Sundaram and Piramuthu, 2015). According to this view, we developed a safety decision-making model, as shown in Fig. 8.

According to Fig. 8, the safety decision-making process can be structured and ordered in five phases from a SI perspective: SI, safety solution design, safety solution choice, safety execution, and safety monitoring and review. SI is where the safety decision maker identifies the safety problem and its cause(s), collects safety data and information regarding the problem, and converts the collected safety data and information into useful and actionable SI for safety problem solving. The second phase includes development, recognition, and understanding of possible safety management alternatives and consequences of the future safety decision. The third phase is the selection of one from a feasible set of safety management solutions, wherein the identified safety management alternatives are narrowed down to the best utility option that leads to a safety decision maker’s choice. The fourth phase is the implementation of the decision made in the third phase. In the last phase—safety monitoring and review—the implementation of the safety decision and changes of safety risks and safety management are monitored and evaluated and the safety data and information collected in this stage are fed back to the first stage to adjust and improve future safety decisions. Moreover, SI flows and activities run through the entire safety decision-making process. Therefore, SI is the prerequisite and foundation for safety decision making and plays a vital role in safety decision-making processes.

4.2 SI practice framework for supporting safety management

4.2.1 Comparison of the SI practice and safety management processes

On the practical level, to provide effective support for safety management, an organisation requires an organic integration of SI practice and safety management practice. Therefore, before proposing an SI practice model, we should make a brief comparison of the SI practice process and the safety management process. In fact, the SI practice process and the safety management process are very similar. For example, SI practice and safety management cycles share common attributes because of their common objectives of supporting safety policy and safety decision making with the analysis of pertinent safety data and information. Moreover, both SI practice and safety management rely on a cycle focused on the analysis of safety data and information. Therefore, an increased understanding of the safety practices by SI professionals could provide insights for improving SI practice, and a greater knowledge of SI practice processes could help safety managers enhance the safety management practices. According to the SI practice cycle (Wang and Wu, 2019) and safety management cycle (Hale, 2003; Wang et al., 2017; Li and Guldenmund, 2018; Wang et al., 2019) (Fig. 9), this study compares their similarities as follows:

(a) The first stage in both the SI practice process and safety management process begins with scope establishment. In initial step of the SI practice process, the safety policy and solution areas where SI can contribute are identified and prioritised. The first step of the safety management process determines the requirements, constraints, and priorities for safety decision or policy targets to be supported by safety management.

(b) The second stage in both the SI practice process and the safety management process includes a major focus on gathering safety data and information. The second step of the SI practice process focuses on collecting safety data and information and preparing them for analysis. In the second step of the safety management process, safety managers collect safety data and information for identifying safety problems (such as cataloguing and categorising various safety problems to be considered) and of safety problem analysis in the next phase.

(c) In the third phase, analysis is performed in both the SI practice process and the safety management process. In the third step of the SI practice process, safety data and information are analysed for production of SI. The third step of the safety management process aims to analyse and evaluate the characteristics, causes, and consequences of safety problems based on the systematic analysis of the collected safety data and information and, then, to analyse and assess results of the safety problems.

(d) The goal of the fourth step of both the SI practice process and the safety management process is to produce various products to meet the needs of safety managers. In the fourth step of the SI practice process, the priority of SI is determined, and SI is packaged to form SI products (namely, safety solutions or recommendations) to meet the needs established by the safety decision makers who require SI support. The objective of the fourth step of the safety management process is to formulate feasible safety solutions (from the SI perspective, their essence is the SI product) and to prioritise the safety solutions. The development of safety management alternatives involves identifying various safety management options that support the safety decision makers and safety policy goals and assessing the advantages and disadvantages of each option. The methodologies may differ between the SI practice process and that of safety management; however, the common target is to produce analytical products that meet the defined needs of safety managers (namely, safety policy, and decision makers).

(e) The final stages of both the SI practice process and the safety management process focus on application and accomplish very similar functions. The final step of the SI practice process is dissemination and application. In this phase, the SI products are distributed to the safety decision makers and other safety managers requiring SI, and the safety managers use the SI product for supporting safety decision-making and other safety management activities. In the safety execution step of the safety management process, safety managers decide and implement safety solutions to address safety problems by providing the assessment of safety management options to solve appropriate safety problems.

(f) Both the SI practice process and the safety management process are followed by a feedback step which involves monitoring and reviewing their effectiveness. The implementation of SI practice and safety management work and changes of safety risks and safety management are monitored and evaluated, and the safety data and information collected are fed back to the first stage to adjust and improve future SI practice and safety management systems. In other words, the common objectives of the SI practice and the safety management involve obtaining the processed safety data and information, providing them to those who need it to make safety decisions, and receiving feedback on the products and additional needs. Moreover, both the SI practice and safety management emphasise continuous improvement using the feedback mechanism.

4.2.2 SI practice model supporting safety management

The approach or concept of “intelligence-led safety management” provides a framework that applies the SI concepts intrinsic to safety management to address the SI needs of safety managers (Wang and Wu, 2019). In other words, intelligence-led safety management provides an SI practice framework for supporting safety management. Intelligence-led safety management is described as a safety management philosophy, idea, approach, and process to find and apply SI to proactively drive and guide strategic, operational, and tactical safety decisions for safety problem solving and improvement of safety management (Wang and Wu, 2019). Intelligence-led safety management suggests that the application of SI processes provides an added value to the safety decision-making process for improving safety. Moreover, intelligence-led safety management can effectively address the existing gaps in the SI products available to support safety decision making (Wang and Wu, 2019).

There are three important principles for providing a basis for intelligence-led safety management, which are as follows: (i) SI products are required to support safety management (including the safety decision-making) process, (ii) safety decision makers need to clearly communicate their SI needs, and (iii) the SI practice process is highly similar to the safety management process (see Section 4.1). According to the first and third principles, in fact, intelligence-led safety management represents a fusion of the SI practice process and safety management practice cycle. Based on the connotation of intelligence-led safety management, safety decision-making model developed from an SI perspective (Fig. 8), and comparison of SI practice and safety management cycles (see Section 4.2.1) (as well as by referring to the key factors influencing the intelligence practices in the organisation), we developed a model for intelligence-led safety management in the organisation (Fig. 10). This model is an SI practice model for supporting safety management in the organisation and shows how the SI practice process and safety management process are combined to promote safety management (including safety decision making) driven by SI.

The intelligence-led safety management process occurs within the context established by organisational safety leadership and safety managers (especially those ultimately responsible for organisational safety management decision making). The context provides boundaries for intelligence-led safety management efforts. To promote the implementation of intelligence-led safety management in an organisation, several factors influencing SI practice in the organisation need to be considered to frame the safety management context, which mainly comes from nine aspects (Fig. 10) (Wang and Wu, 2019; Shamim et al., 2019; Wang et al., 2019; Yang, 2012; Pellissier and Nenzhelele, 2013). These factors are the following: (i) safety management process and structure (such as safety management goals and objectives, safety risk tolerance, safety decision scope and criticality, safety managers and stakeholders, and safety policies and procedures on SI), (ii) availability and quality of safety data and information, (iii) the awareness and culture of safety intelligence (e.g. the understanding of the importance of SI practice, attitudes of organisational leaders and safety managers towards the SI practice and safety information sharing, organisational safety culture, and organisational intelligence culture), (iv) focus of leadership on SI (a leadership focus on the SI practice is positively associated with intelligence-led safety management capabilities), (v) intelligence literacy of safety managers, (vi) SI infrastructure (including the hardware, software, and network), (vii) SI human resources (including intelligence professionals with high safety management abilities and safety professionals with intelligence literacy), (viii) technical assistance (such as the use of information technology in safety management and technologies to support SI practice), and (ix) lack of time. The information relevant to these factors must be shared with those involved in the organisation’s SI practices and safety management activities to improve the efficiency and quality of intelligence-led safety management.

Because the phases of the intelligence-led safety management process (Fig. 10) have been explained in Sections 2.2, 4.1, and 4.2.1, they were not analysed in detail in this section. Certainly, interested readers can find more deep and specific discussions on them in the articles of Wang and Wu (2019). In addition, the hub of the intelligence-led safety management process is communication. A shared understanding of intelligence-led safety management and its associated factors is achieved through consistent communication with those charged with safety decision-making and analysing and producing judgements throughout the process.

5. Conclusions and limitations

In the era of big data, intelligence, and Industry 4.0, safety science has entered the era of Safety 4.0, and SI has emerged as a new concept and term. SI has various potential benefits for safety promotion and safety management and is considered an essential perspective for safety management in the era of Safety 4.0. Although the concept of SI has been proposed, many organisations have not yet effectively and normatively implemented the SI practice, and studies on SI to guide the SI practice and promote further research on SI barely exist. Specifically, a universal framework for SI is still missing. The present research attempts to present a framework for SI from a safety management perspective as SI aims to provide meaningful and actionable information for safety management. We highlight that SI is an umbrella term and is a product, process, tool, and capability related to safety management. Moreover, this study proposes a theoretical framework for SI and then presents an SI practice model to support safety management in organisations. We present a framework for SI and lay a solid foundation and provide useful guidance regarding SI practices and studies in the future. Certainly, this study lacks the necessary quantitative analysis and case studies, which should be carried out in the future to improve the SI framework.

Declaration of Interest Statement

Article Title: Safety intelligence as an essential perspective for safety management in the era of Safety 4.0: From a theoretical to a practical framework

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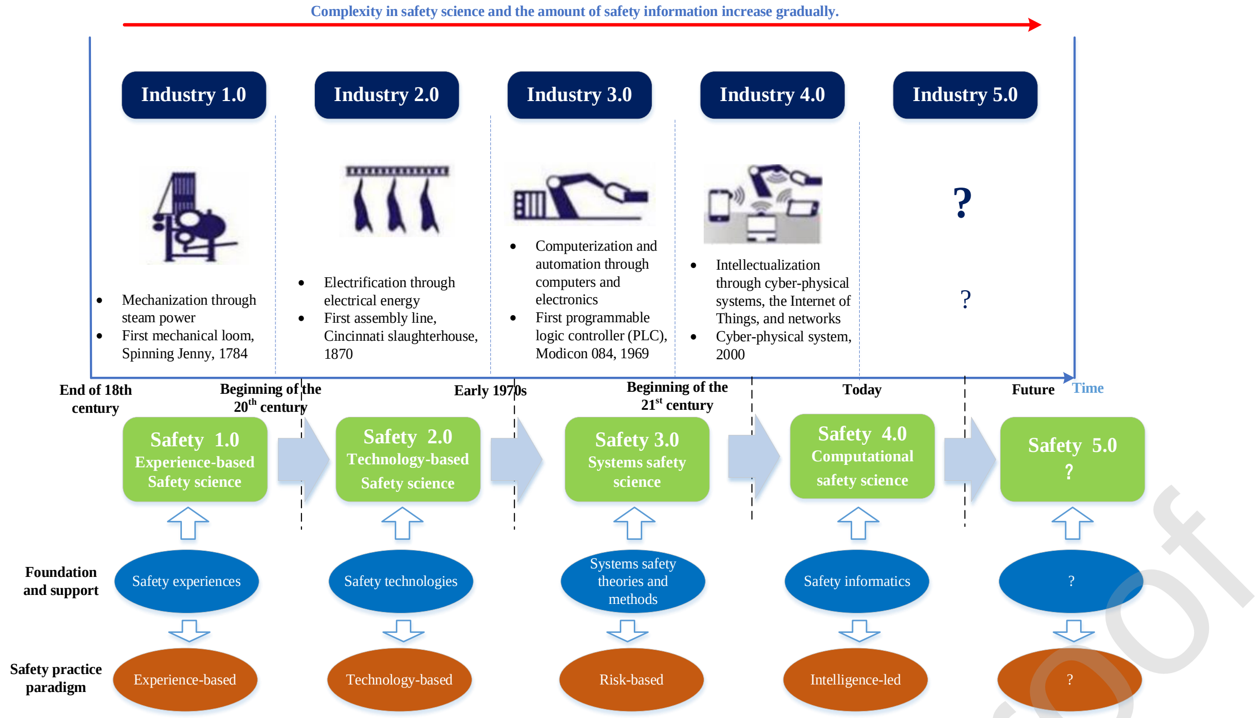

Fig. 1. Development process of safety science (revised from Wang and Wu (2020a)).

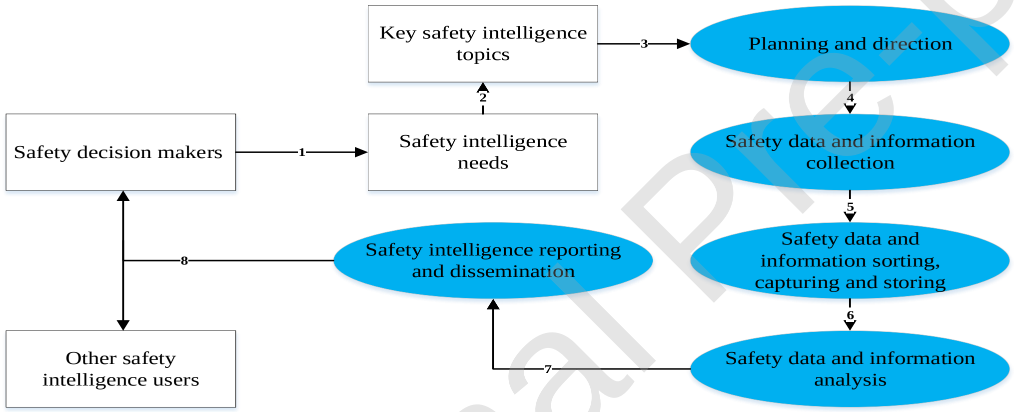

Fig. 2. The SI process cycle.

Technologies	Main objectives	Core techniques	Strengths	Limitations
Safety database system	On-line transaction processing	Relational database, normalization	Safety management process data, safety data storage	Low speed, safety data irregularity, and security
Safety data warehousing	On-line analytical processing	Star schema, snowflake schema, data mart	Historical safety data, ad-hoc queries	Cost of extraction, transformation, and loading
Safety data mining	Safety knowledge discovery	Association, clustering, classification	Safety big data, safety data analysis	Variety of safety data and high dimensionality
Safety intelligence	Safety decision support	Data warehousing, data mining, data visualization	Safety performance management	Identifying causality between safety predictors and outcomes

Fig. 3. Comparison among various information technologies used in safety management.

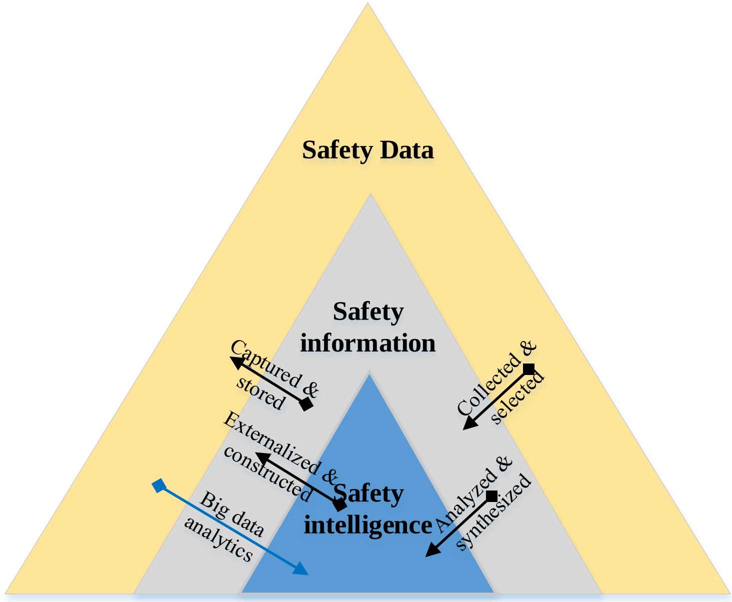

Fig. 4. Interrelationships of safety data, safety information, and SI in the era of big data (adopted from Wang and Wu (2020b)).

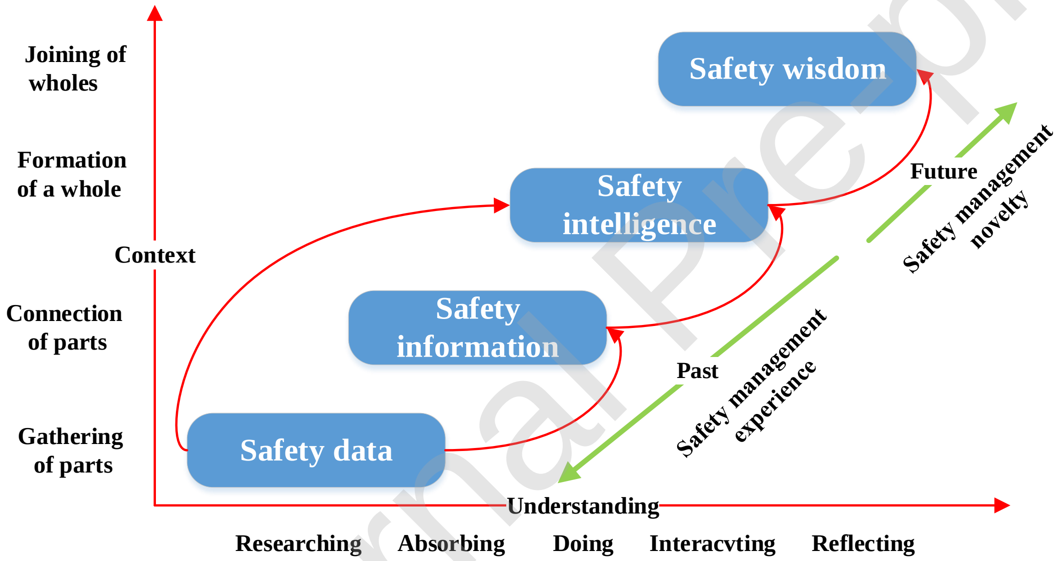

Fig. 5. Achieving of the safety data and information value in safety management in the era of big data.

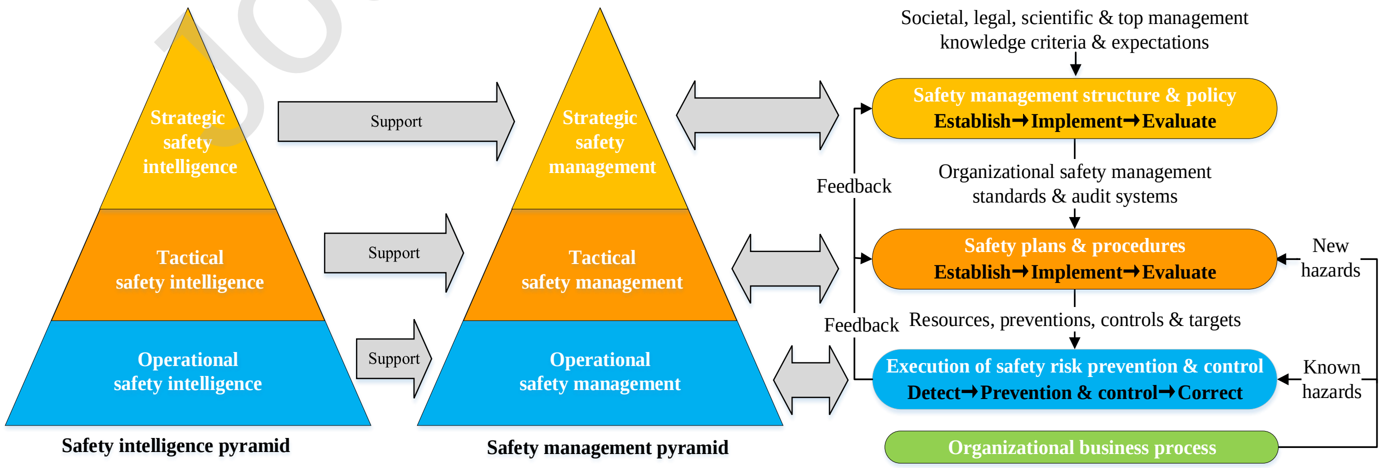

Fig. 6. SI and safety management pyramid (Hale, 2003).

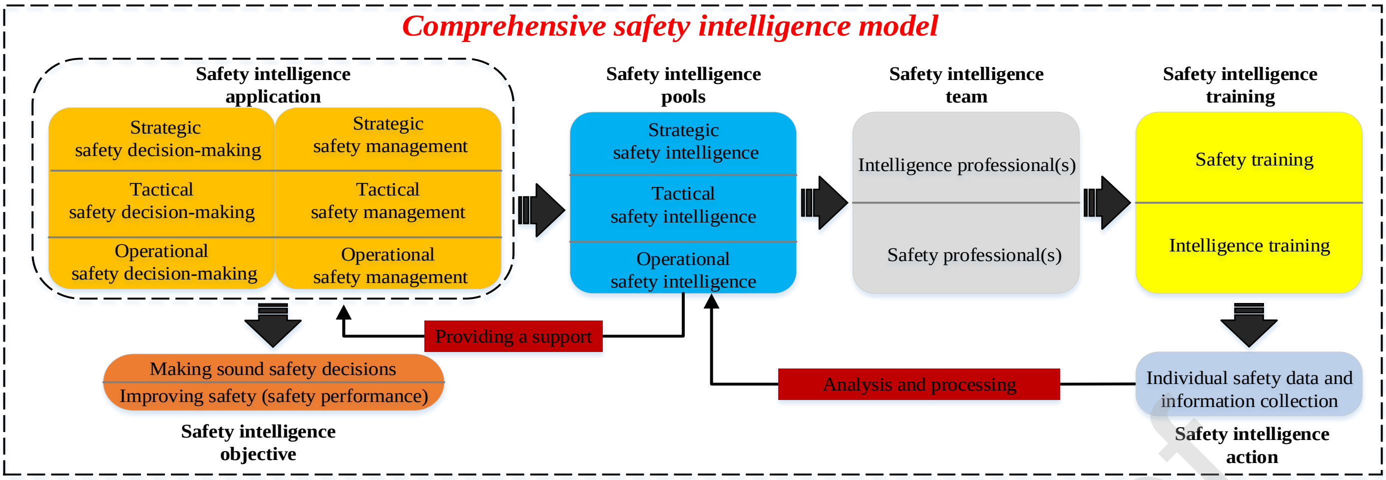

Fig. 7. Proposed conceptual SI model.

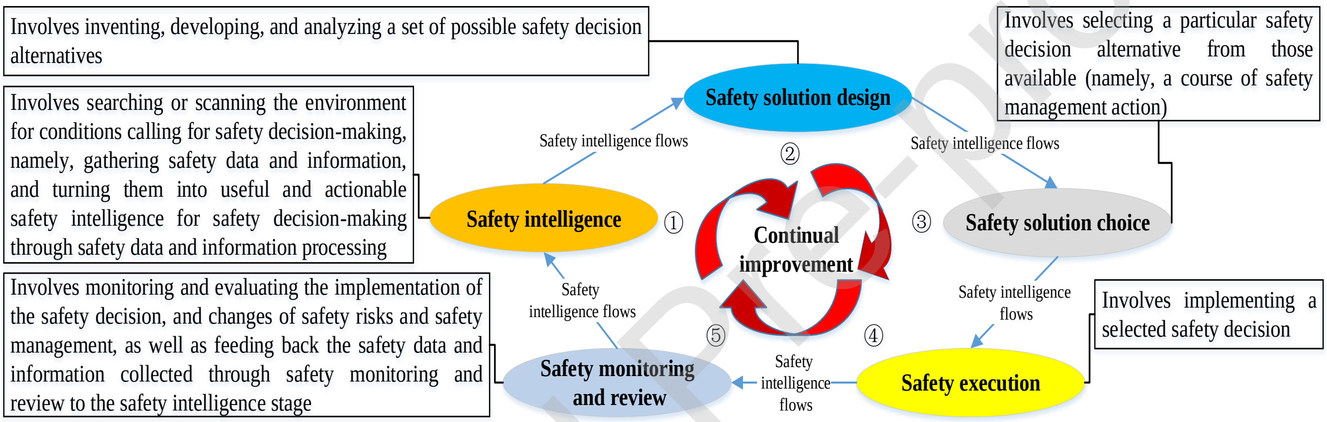

Fig. 8. Safety decision-making model developed from a SI perspective.

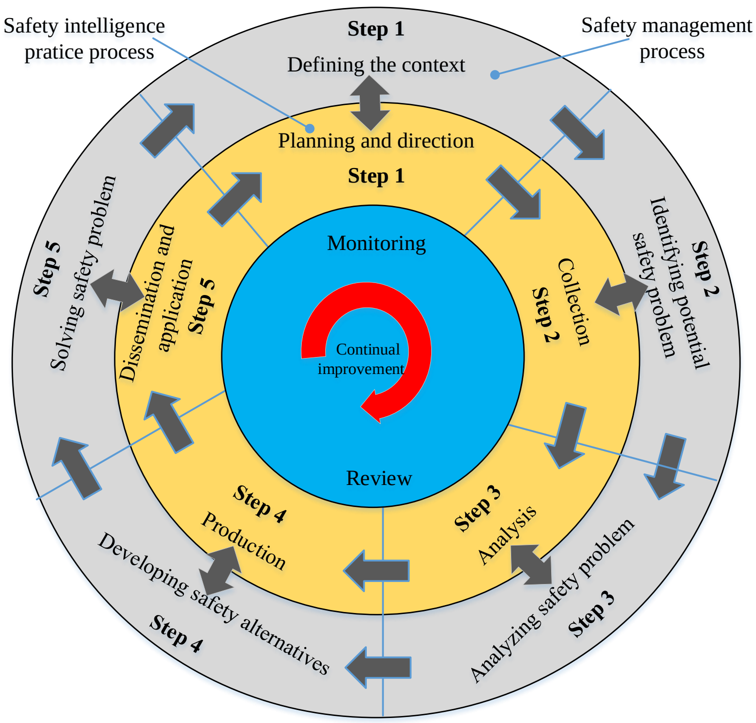

Fig. 9. Comparison of the SI practice and safety management cycles.

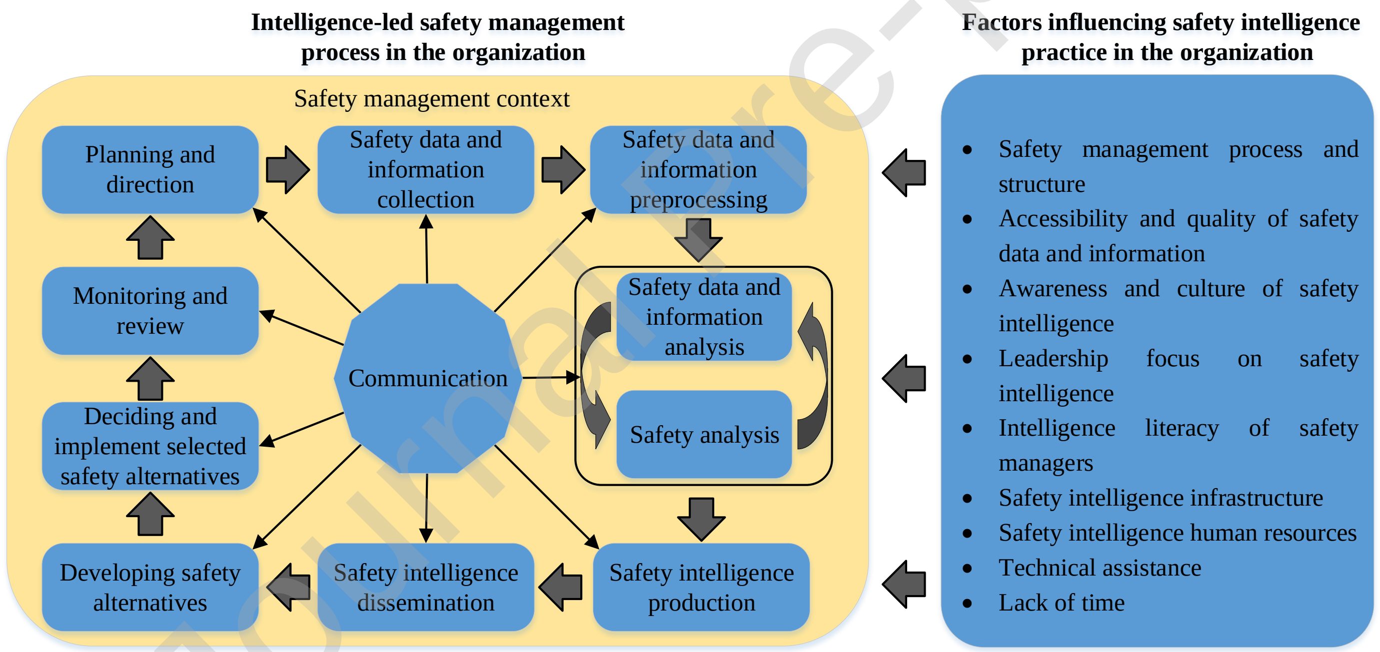

Fig. 10. SI practice model supporting safety management in the organisation.

Table 1. Styles of SI.

No.	Style	Explanation
1	Safety reporting	Broadly deployed safety report (such as the safety check report and the safety risk assessment report) formats for safety reporting and scorecards or dashboards targeting SI users, such as safety decision makers in an organisation.
2	Safety analysis (including safety risk analysis)	Online analytical processing (OLAP) slice-and-dice analysis (also known as cube analysis) of limited safety data and information sets, targeted at safety managers and others (such as frontline employees) in an organisation who need a safe environment for basic safety data and information exploration within a limited range of safety data and information.
3	Safety querying	Full investigative query into all safety data and the automated OLAP slice-and-dice analysis of the entire safety database (or safety information system). Targeted at safety information explorers and power users.
4	Safety statistical analysis and safety data mining	Full mathematical and statistical treatment of safety data for purposes of correlation analysis of factors influencing safety, safety trend analysis, safety performance analysis, and safety prediction. Targeted at the professional safety information analyst team, which usually consists of professional information analysts and safety professionals.
5	Safety early-warning	Proactive safety report delivery and safety early warning to organisational safety managers and other members based on schedules or event triggers in the safety database (or safety information system).