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IMPROSafety: A risk-based framework to integrate occupational and process safety

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ABSTRACT

Occupational Safety and Health (OSH) and process safety are traditionally separated by a fuzzy perimeter, and the need to adopt different management approaches is emphasised in the literature. However, OSH and process safety complement rather than replace each other, and their integration may achieve total safety excellence of organisations. The existing studies about this integration focus on various aspects of the risk management process and provide different types of outputs. In such a context, this paper has the objective to propose IMPROSafety (Integrated risk Management for PRocess and Occupational Safety), a risk-based framework to integrate OSH and process safety. We expand the traditional risk definition considering scenario identification, its occurrence probability, and its consequence severity, to also include other dimensions, i.e. the temporal evolution and spatial extension of the scenario, and the number of workers involved. The framework covers all the steps of the risk management process: hazard identification is performed thanks to the bow-tie chaining structure and the application of the energy theory perspective, risk estimation via quantitative analyses of the considered dimensions, risk evaluation by means of the ranking of each dimension and an overall risk level, and risk treatment through a proper safety measure identification. A case study about three real events occurred in the steel and iron industry in the last decades is used to test the IMPROSafety framework. The investigation of six scenarios highlights the most dominant event sequences and risk dimensions that should receive prioritised attention for developing effective risk reduction controls.

1. Introduction

Organisations face a range of ongoing safety-related challenges in order to protect the occupational safety of workers from harm and injuries and to prevent process safety events resulting in adverse effects on workers, local communities, and the environment (Bitar et al., 2018). Occupational safety is also called “personal safety” or “personnel safety” (Baker et al., 2007; Energy Institute, 2011; Mataqi and Srikanth Adivi, 2013; Tang et al., 2018), “traditional safety” (Anderson, 2005), “workplace safety” (Aldrich et al., 2015; Tanjin Amin et al., 2019), and is referred to as “conventional safety” in the nuclear sector (Clay et al., 2020). Complete locutions for indicating this domain are Occupational Safety and Health (OSH) or Occupational Health and Safety (OHS). The term “process safety” originates in the United States (Hopkins, 2009), and is strictly related to the prevention of major accidents. Synonyms of this locution are “asset integrity” and “technical integrity” (Energy Institute, 2011; Hopkins, 2009; Swuste et al., 2010).

Different authors (Gobbo Junior et al., 2018; Khan, 2015; Tanjin Amin et al., 2019) emphasises that process safety differs from occupational safety. This is not only a statement, but also represents a good practice and a suggestion (Khan et al., 2015; Mataqi and Srikanth Adivi, 2013). The distinction between them became clear after World War II, when the two evolved as relatively independent domains (Swuste et al., 2016b). However, there is a fuzzy perimeter between process safety and OSH (Leclercq et al., 2018), and general confusion and misconception about these domains, their features, differences, and similarities are noticed (Aldrich et al., 2015; Andersen and Mostue, 2012; Theophilus et al., 2018). This confusion can arise from the general consideration according to which a major accident can also represent a significant OSH concern, leading to personnel injuries and fatalities to people, and an OSH incident can also be a major accident (Andersen and Mostue, 2012; Brocal et al., 2018; Fleming and Fischer, 2017; Kjellén and Albrechtsen, 2017).

It is recognised that process safety and occupational safety are

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equally important to the success of organisations (Mataqi and Srikanth Adivi, 2013). In fact, non-negligible ethical issues related to the quantification of the number of lives affected by an accident and the value of a life (Holen et al., 2019) should be properly taken into account. Furthermore, some authors (Knowles and Vaughen, 2020; Mataqi and Srikanth Adivi, 2013) agree that the integration of process safety and occupational safety allows ensuring good safety performance and achieving total safety excellence of organisations. Leclercq et al. (2018) highlight that, although process safety and occupational safety are often distinguished in the literature and practice, there is an acknowledged advantage in their integration.

In such a context, a holistic view based on a risk-based approach (Mataqi and Srikanth Adivi, 2013) focusing on the hazards that led to the accidents (Holen et al., 2019) could be adopted. Therefore, this paper has the objective to propose IMPROSafety (Integrated risk Management for PRocess and Occupational Safety), a risk-based framework to integrate OSH and process safety. Such a framework responds to the need for a holistic safety assessment and management tool that can support managers, practitioners, and researchers (indicated in the rest of the paper as "analysts") in the safety-related decision-making processes about risk prevention and mitigation.

The remainder of this paper is organised as follows. Section 2 summarises the background of the study, and the cornerstones of OSH and process safety. Section 3 details the literature review on the existing studies proposing an integration between OSH and process safety. The IMPROSafety framework is presented in Section 4, and its application to a case study related to three real events in the steel and iron industry is described in Section 5. The case study results, and the main features and limitations of the framework are discussed in Section 6, while concluding remarks are provided in the final section.

2. Background

2.1. Occupational safety and health

In this work, the locution OSH is preferred over the term "occupational safety" in order to also include the concept of occupational health. A precise description of occupational health is provided by Niu (2010). OSH regards the area of safety addressing the safety and health of workers (Tang et al., 2018). It deals with hazards that are more directly related to and affect one individual worker at a time, for each occurrence (Baker et al., 2007; Clay et al., 2020; Luna, 2016; Swuste et al., 2010). Its focus is the prevention of injuries, occupational illnesses, and fatalities of individual workers while doing jobs (Murphy, 2017; Khan, 2017; Vallerotonda et al., 2018), but not necessarily directly linked to the primary work task (Grote, 2012). ISO (2018b) defines an OSH risk as the "combination of the likelihood of occurrence of a work-related hazardous event(s) or exposure(s) and the severity of injury and ill health that can be caused by the event(s) or exposure(s)". Therefore, OSH hazards give rise to incidents or exposures resulting in injury and ill health, including disease, illness, and death (ISO, 2018b). Typical examples of OSH-related hazardous events are slips, trips, collisions, falls, crushing, struck against, vehicle incidents, electrocutions, burns, cuts, falls from height, while exposures are linked to the possible contact with a machine, the presence of airborne chemicals or noise, or working in awkward postures (CCPS, 2008; Clay et al., 2020; Hopkins, 2009; Klein and Vaughen, 2017; Mataqi and Srikanth Adivi, 2013; Murphy, 2017; Tang et al., 2018). OSH hazards are more easily identified (Morrison et al., 2011), and OSH risks are more easily monitored and managed (Astrup et al., 2016).

Incidents and exposures related to OSH have low or medium consequences with minimum escalation potential (Astrup et al., 2016; DNV GL, 2014), and occur in a working life context relatively often (Astrup et al., 2016; DNV GL, 2014; Hovden et al., 2010). For this reason, they can be termed as high-frequency (or likelihood), low-consequence (or severity) events (Anderson, 2005; Kubascikova, 2015; Luna, 2016; Mataqi and Srikanth Adivi, 2013). This is depicted in Fig. 1 by means of the blue arrow.

Astrup et al. (2016) and DNV GL (2014) consider incidents and exposures connected to OSH as single-linear chains of event in contrast to process safety-related accidents. Jørgensen (2016) use (provocatively) the term "simple accidents" in order to underline that such accidents are perceived as trivial, common or traditional, and they seem to be rather simple to explain. However, there are many and complex (also latent) hazards and causes leading to occupational incidents and injuries, and the combination of precursors characterising the triggering of these hazards is difficult to observe or be aware of Jørgensen (2016). Moreover, multiple factors contribute to incidents and exposures and influence their occurrence, including humans, technologies, environment, and organisation (Zarei et al., 2021). According to Reason (2016), incidents and exposures related to OSH can be assumed as individual accidents: they are larger in number (compared to organisational accidents), affect either individual workers or individual items of equipment, and are associated with activities in which the workforce is in close contact with the hazards.

2.2. Process safety

Process safety is a disciplined framework for managing the integrity of hazardous operating systems and processes by applying good design principles, engineering, and operating and maintenance practices (ANSI, 2016; CCPS, 2010b; Nesa and Hadikusumo, 2017). Process Safety Management (PSM) focuses on the prevention of, preparedness for, mitigation of, response to, control of, and restoration from process hazards that may result in the (unexpected) release of chemicals, (hazardous) materials, or energy from a process associated with a facility (CCPS, 2007, 2010b; Khan et al., 2010, 2015, 2016; Matthews, 2012). Therefore, process safety is focused on the prevention and mitigation of unintended toxic releases, fires, explosions, and accidental chemical releases in the process industries involved with the manufacturing, handling, and storage of hazardous chemicals (Murphy, 2017; Theophilus et al., 2018).

Process safety hazards are those arising from the processing activity in which a plant may be engaged (Energy Institute, 2011; Hopkins, 2009; Mataqi and Srikanth Adivi, 2013), and typically are hidden inside the complex process systems (Lakhiani et al., 2016; Prior, 2017). Process safety accidents could result in serious multiple injuries and fatalities,

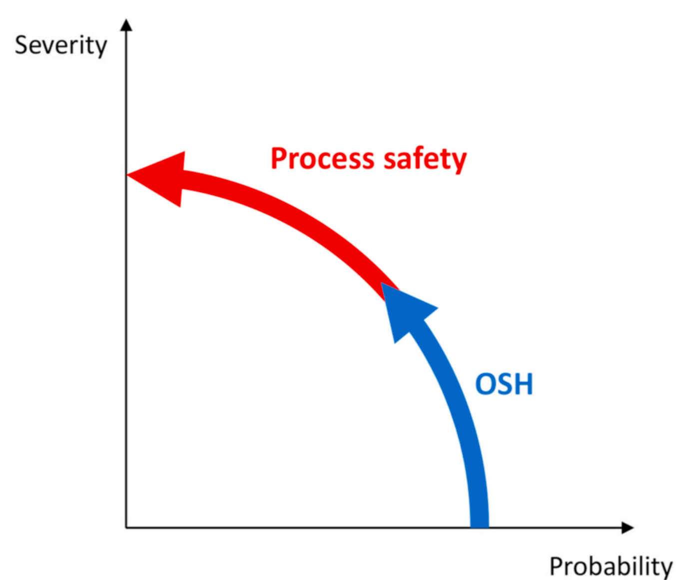

Fig. 1. OSH and process safety in severity-probability graph (Note: OSH = Occupational Safety and Health).

property damage, asset losses, lost production, substantial economic and financial losses, and environmental impacts (Baker et al., 2007; CCPS, 2010b; Gala et al., 2016; Khan et al., 2016). For a detailed list of potential consequences of such accidents, refer to Klein and Vaughen (2017).

Process safety concerns the prevention of major accidents (or major accident hazards) (Energy Institute, 2011; Hunter and Wolf, 2015; Kerin, 2019; Mataqi and Srikanth Adivi, 2013; Tang et al., 2018). In the literature, several definitions of major accidents can be found (e.g. CCPS Energy Institute, 2018; DNV GL, 2014; European Union, 2012; ILO, 1993; ISO, 2016; PSA, 2013; UK Secretary of State, 2015). For instance, in accordance with European Union (2012) and UK Secretary of State (2015), a major accident is an occurrence such as a major emission, fire, or explosion resulting from uncontrolled developments in the course of the operation of any establishment, and leading to serious danger to human health or the environment, immediate or delayed, inside or outside the establishment, and involving one or more dangerous substances. Elements of major accident definitions can be found in Baalisampang et al. (2018), and their characteristics, descriptions, and references are summarised by Holen et al. (2019).

Major accidents are rare events (Holen et al., 2019; Johnson, 2012), but with high impacts (Saadawi, 2018). For this reason, process safety accidents can be termed as low likelihood (frequency) with high consequence (severity) events (Clay et al., 2020; Kubascikova, 2015; Luna, 2016; Mataqi and Srikanth Adivi, 2013), as graphically shown in Fig. 1 by means of the red arrow. The consequences may be immediate or delayed, and there is a potential for escalation (Astrup et al., 2016; DNV GL, 2014; Holen et al., 2019). Such potential for escalation is indicated by the term “domino effect”, i.e. a chain of accidents (Khan and Abbasi, 1999), and the triggering of secondary events by a primary event such that the result is an increase in consequences or area of an effect zone (CCPS, 2000).

Process safety and major accidents are usually caused by multiple events or simultaneous barrier failures that coincide and collectively result in a loss of control and in an accident (CCPS, 2010b; CCPS Energy Institute, 2018; Chen et al., 2015; Santos et al., 2019). These events are characterised by a relative complexity of their development (Paltrinieri and Khan, 2016), multi-linear chain of events (Astrup et al., 2016; DNV GL, 2014), and nonlinear patterns (Vallerotonda et al., 2018). Consequently, they are hard to predict (DNV GL, 2014; Holen et al., 2019). Such features recall the ingredients describing a normal accident proposed by Perrow (1999): (1) an unexpected interaction of multiple failures in (2) a tightly coupled system that allows cascades of failures beyond the original failures. Taking into consideration Reason’s perspective, process safety accidents can be seen as organisational ones: organisational accidents are often catastrophic events, can have devastating effects on uninvolved populations, assets and the environment, occur very rarely, and are hard to predict and control (Reason, 2016).

2.3. Differences between OSH and process safety

Clear differences between OSH and process safety have been well documented (Clay et al., 2020). Hopkins (2009) underlines that the distinction between OSH and process safety is really a distinction between different types of hazards. This is related to the mechanisms of causation highlighted by Kerin (2019): while both process safety and OSH are concerned with a potential loss of control of hazardous energy, process safety is usually about managing higher levels of energy. The different precursors and origins of these types of incidents and accidents are also pointed out by Anderson (2005), and Swuste et al. (2016a). Moreover, the scale of potential consequences distinguishes process safety from OSH: while process safety accidents are less common than incidents and exposures related to OSH, their consequences are more likely to be severe (Kerin, 2019). Indeed, OSH events are less devastating in size and usually influence fewer people than major accidents (Andersen and Mostue, 2012).

It is largely acknowledged that process safety has to be dealt differently from OSH (Khan, 2015), and the approaches dedicated to their hazards and risk management processes are different (Astrup et al., 2016; Bennet and Wilson, 2010; CCPS, 2008; Clay et al., 2020; DNV GL, 2014; Johnson, 2012). The presence of an effective OSH management system does not ensure and does not mean the presence of an effective process safety management system, and vice versa (Baker et al., 2007; Luna, 2016; Saadawi, 2018; Stricoff, 2012). Good safety performance based on OSH metrics does not reflect and does not necessarily translate into good process safety performance (Aldrich et al., 2015; Luna, 2016). Kerin (2019) describes in depth the key differences in terms of focus, hazard identification, risk assessment tools, and outcomes. For instance, process safety can be based on data-driven, analytical semi-quantitative, and quantitative risk assessment tools, whereas hazard identification and risk assessment in OSH domain usually feature a combination of qualitative and semi-quantitative methods informed by data from a range of sources.

Indicators and metrics for OSH and the ones for process safety are different (CCPS, 2010b; Hopkins, 2009). Process safety indicators refer to issues arising from the scenario in which the entire organisation is engaged, and are related to processing activities, including process disturbances, barrier quality, root causes and precursors of loss of containment; OSH indicators make it possible to assess the effectiveness of measures to enable workers to avoid risks, which are not included in the management of process-related dangers (Barbosa et al., 2019; Patriarca et al., 2019). Moreover, OSH metrics are well established and widely used (Luna, 2016); on the contrary, process safety indicators are difficult to establish (Astrup et al., 2016) and universally agreed upon ones are lacking (Baker et al., 2007; Stricoff, 2012). Since major accidents occur relatively infrequently, the data collection for process safety is difficult and past process safety accidents have limited value in predicting future process-related events (Baker et al., 2007; Prior, 2017). For all these reasons, OSH and process safety require different behaviours, skills, competences (Grote, 2012; Knowles and Vaughen, 2020; Luna, 2016; Sutton, 2008) and remedies.

2.4. Overlaps and correlations

Although the above differences, there are overlaps and correlations between OSH and process safety (Clay et al., 2020; Kerin, 2017, 2019; Khan et al., 2015; Kubascikova, 2015; Vallerotonda et al., 2018). Such overlaps can be identified in the following aspects:

- safety culture, attitude, and leadership practices (Klein and Vaughen, 2017; Mataqi and Srikanth Adivi, 2013);
- tools or requirements in terms of safe work systems, procedures, and training (Kerin, 2017);
- knowledge of human failures in the form of violations and human error (Prior, 2017);
- root causes of the incidents and accidents in terms of deficiencies in the systems (Baker et al., 2007);
- sources of potentially damaging energy in terms of hazards (Kerin, 2019);
- same process disturbances both accelerating major accident scenarios and inducing OSH scenarios (Swuste et al., 2016a);
- similar collection and analysis of basic data for some situations (Prior, 2017);
- similar objectives of risk assessments, i.e. to understand the nature of the risk for developing and implementing controls (Kerin, 2019);
- enhancements achievable by means of layers of defences built into the system to control the hazards (Lakhiani et al., 2016).

Regarding hazards, Bellamy (2015) contradicts the Hopkins’ statement according to which the distinction between OSH and process safety is related to the different types of hazards (Hopkins, 2009). Specifically, Bellamy (2015) highlights a link between these domains that is represented by the hazard, and explores the direct and underlying causes of incidents and exposures related to OSH to consider the potential for using that information for preventing the catastrophic and major accidents.

The identification of these overlapping aspects can be a valuable starting point to raise awareness, ensure improved management of both process safety and OSH risks, and optimise both the domains (Kerin, 2017, 2019). OSH and process safety complement rather than replace each other (Luna, 2016). To prevent future hazardous events and exposures, the same attention should be dedicated to both the disciplines in order to raise the overall level of safety (Gala et al., 2016; Grote, 2012).

3. Literature review

The literature review had the purpose to identify those studies proposing an integration between OSH and process safety. Studies dealing with only one of the two safety domains and/or written in languages different from English were not considered. On the contrary, studies proposing an original approach, whose main intent is not to combine OSH and process safety but implicitly consider both the domains, were included in the results. In this work, we extended the systematic review of the scientific literature recently proposed by Stefana and Paltrinieri (2020). For this purpose, we searched for scientific publications in the relevant electronic (bibliographic) databases for the topic under investigation (i.e. ScienceDirect, Scopus, Taylor & Francis, Web of Science), and technical reports, books, and specialised guidelines. We defined and used various combinations of keywords (e.g. "occupational safety", "health and safety at work", "process safety", "major hazard", exposure, "occupational incident", "occupational exposure", "major accident"). The list of references in each retrieved study was checked through a manual examination to capture any additional interesting documents. We rated the relevance of the documents by reading the full-text. The results of the literature review were critically analysed in order to identify the main features of the existing approaches proposing an integration between OSH and process safety.

A wide spectrum of studies able to integrate OSH and process safety is available in the literature. Table 1 proposes a brief description of them. In order to identify the main types of approaches, we grouped these studies in the following categories: (1) adjustment of an existing method, (2) combination of existing methods, (3) integrated management system/risk management, (4) new method or tool.

The majority of the approaches propose an integrated management system/risk management, or a new method or tool for combining the two safety domains. Integrated management systems are developed and described to identify the links and ties between the existing OSH and process safety management programs, leverage on them, and integrate occupational and major accident aspects in an only management system. Some of these studies include bow-tie representations (Agnello et al., 2014; Pitblado and Tahilramani, 2010; Vaughen et al., 2015), others refer to specific directives or requirements of well-known safety-related standards (Brocal et al., 2018; Leino, 2002). Two approaches (Vallerotonda et al., 2016; Yu et al., 2017) focus on analyses of incident and accident data in order to investigate their causal factors, individuate useful information about occupational and major accident aspects, harmonise them in an integrated management system, and thus improve safety performance.

The studies presenting a new method or tool mainly propose a quantitative risk index (Chen and Yang, 2004; Gnoni et al., 2010; Gnoni and Bragatto, 2013; Papadakis and Chalkidou, 2008; Wang et al., 2012). In such indices, the relevant parameters and factors are explicitly mention. For instance, Chen and Yang (2004) mention the probability of danger, the frequency of work exposure, the number of persons at risk, and the maximum probable loss or severity, Gnoni and Bragatto (2013) the percentage of the working time spent by each worker in any unit, hazards, accidental scenarios, and the effectiveness of measures to

Table 1
Overview of existing approaches integrating OSH and process safety.

Type of approach	Reference	Description
Adjustment of an existing method	Ale et al. (2014)	Dynamic risk management support tool based on Bayesian Belief Nets and on CATS model. Analysis of various risk-contributing factors (such as a runaway reaction in a thermal cracker, overflow in a storage tank, pipe rupture in a jetty-arm, and occupational risks), their logical combination in a top node called "output" risk, and consideration of influences related to human factors and management factors.
Combination of existing methods	Amir-Heidari et al. (2016)	Comprehensive risk assessment for identifying significant risks, by means of past research and accident statistics, questionnaire and interview to experts for risk identification, selection of important risks and influencing factors, semi-quantitative structured methodology, risk matrix, and analysis of controls for risk assessment. The methodology considers all kinds of risks, analyses three levels of risk, and defines seven categories of consequences.
	Boncan (2014)	Combination of bow-tie risk assessment tool with Job Hazard Analysis in order to develop a clear method for communicating personal and process safety risks at the job site, highlighting the key tasks and activities that are required for reducing the potential for employee injury from either cause, personal, or process safety.
	Collins (2010)	Systematic and rigorous framework to integrate Job Safety Analysis (JSA) into Process Hazard Analysis (PHA) techniques, considering potential modes of operation (also non-traditional ones), process-related and people-related initiating events or upsets that can result in consequences of concern.
	Gerbec et al. (2017a, 2017b)	Approach to jointly integrate and enhance safety, quality and productivity in the production environment characterised by rare, new, or complex processes by combining different methods for the description and analysis of plant and operations, including Task Analysis, 4D process simulation, hazard analysis, and Pareto optimisation. The safety analysis generates a list of risks (e.g. procedural, OSH, and process safety) and additional safety measures as outputs. The main aim is to identify potential hazards and areas for improvement both in terms of process safety and efficiency. Comparative risk assessment by means of Bayesian (Belief) Network (BBN) and Integrated Dynamic Decision Analysis, and comparative Cost Effectiveness Analysis of the original and optimised procedure alternatives.
	Marhavilas et al. (2019)	E-HAZOP framework that integrates Hazard and Operability

(*continued on next page*)

Table 1 (*continued*)

Type of approach	Reference	Description
		(HAZOP) study with Decision-Matrix Risk Assessment (DMRA) technique and Analytical Hierarchy Process (AHP) to identify critical points and potential hazards and prioritise risks in industry. The framework consists of the following separate steps: (1) hazard-source identification by using HAZOP analysis, (2) risk quantification, (3) risk evaluation by means of AHP and DMRA, (4) safety related decision-making to reduce risk. The results of the framework application are the priorities and ranking of hazards.
Integrated management system/risk management	Agnello et al. (2014)	A simplified model to support galvanic industry for an integrated management system based on specific procedures of OSH and major accident hazard. Safety Management Models for Small Sized Enterprises (SMEs), and Safety Digital Representation. The model includes a bow-tie representation, and is implemented in a web-based tool for the application of the procedures with a mobile reporting of anomalies and near misses.
	Brocal et al. (2018)	Identification and analysis of the links and transitional spaces between the risk management of occupational and major accidents involving hazardous substances in manufacturing processes, from a regulatory and technical perspective. Establishment of correspondence among the structure of the management systems included in Framework Directive, individual directives, international standards, and Directive Seveso III, in order to develop models integrating the management systems.
	Lee et al. (2011)	Integrated Health, Safety (occupational and process), and Environmental (HSE) management system, with foundational and framework standards, a rigorous process for global standard development, and target key performance indicators. The system is derived from a basic quality model driven by key management processes, and contains best practices and company's experience.
	Leino (2002)	Quality, Occupational Safety, and Health Management System, which is designed to comply with the safety liabilities and the requirements of OHSAS 18001. It is composed of risk assessment and safety instructions, responsibilities of personnel involved in the management of major hazards, procedures for systematic assessing of major hazards. An intranet-based plant-operating manual is developed.
	Pitblado and Tahilramani (2010)	Web-based solution based on Microsoft® Sharepoint for an integrated risk management (facility and process risks), including procedures, performance, bow-tie reports, hazard and effects risk registers, Key Performance Indicators (KPIs), safety culture, incidents, emergency response plans, quizzes, and surveys.
	Vallerotonda et al. (2016)	Analysis of accidents and comparison of results by means of the application of Infor.Mo and Root Cause Analysis (RCA) in order to investigate their main technical and organisational causes, identify the critical elements of the Safety Management System (SMS), individuate useful information about occupational and major accident aspects, and to harmonise them in an integrated SMS.
	Vaughen et al. (2015)	A guideline to propose a process through which an organisation could develop or improve the ties among its existing process safety, occupational safety, personal health, environmental, quality, and security management programs. It is based on the Plan, Do, Check, Act management life cycle approach, the Bow-tie barrier analysis, and the Risk-Based Process Safety concepts.
	Yu et al. (2017)	Study of potential extension of current Safety Management Systems (SMS), such as Process Safety Management (PSM) and Safety and Environment Management Systems (SEMS). By means of analysis of OSHA incident data, and identification and categorisation of causal factors of incidents, development of an integrated SMS containing personal protective equipment, equipment design/selection, inspection and maintenance, written procedure, hazard assessment, hazard communication, work practice, training, and emergency response planning to improve safety performances of drilling and servicing operations and integrate both process and personnel safety.
New method or tool	Casson Moreno et al. (2016)	Specific checklist for performing a first step in bioprocesses hazard identification and screening the possible criticalities related to bioprocesses, based on engineering process, operating procedures, and plant layout.
	Chen and Yang (2004)	Predictive Risk Index (PRI) based on regular observation of unsafe acts or conditions, considering the probability of danger, the frequency of work exposure, the number of persons at risk, and the maximum probable loss or severity in order to monitor the current safety performance and predict the occurrence of several incidents in the plant.
	Gnoni et al. (2010)	Approach based on area characterisation (also by means of a questionnaire), combined risk analysis for estimating two separate indices for the OSH hazard and MAH analysis, and criticality evaluation according to an

(*continued on next page*)

Table 1 (*continued*)

Type of approach	Reference	Description
		integrated risk level for obtaining a Criticality Index to assess plant criticality due to both OSH and MAH hazards.
	Gnoni and Bragatto (2013)	Semi-quantitative risk index derived by the standard ISO 12100 for assessing hazard elements and safety measures, and for representing the criticality level characterising each job profile during a shift at Seveso plants, which depends on the percentage of the working time spent by each worker in any unit, hazards, accidental scenarios, and the effectiveness of measures to mitigate consequences.
	Jørgensen (2016)	Information (INFO) cards to make it easy and available for workers and managers, and to cover all hazard sources and connected information: generic (needed in all kinds of risk situations), cross-cutting, and specific (for specific risks) safety barriers. The basis of this tool is that different hazard sources need different safety barriers and different management delivery processes.
	Leclercq et al. (2018)	Formalisation of the coexistence of different hazards (e.g. energies), and harmonised characterisation of hazard for every accident occurring in a sociotechnical system. Damage production model, based on a common energy-based hazard characterisation, where energies external to human (process energy) are distinguished from human's movement energies (personal energy).
	Papadakis and Chalkidou (2008)	Individual Occupational Risk (IOR) index based on the quantitative risk assessment principles for the control of major accident hazards as a function of the frequency of a released hazard at the workplace, the probability of an employee being present at that workplace, the extent of consequence zones of an event connected to the released hazard, and the human vulnerability to the consequences of that event.
	Wang et al. (2012)	Risk-Based Maintenance strategy, composed of system scope identification (subsystems and facilities), risk assessment (failure probability estimation and consequence analysis), risk evaluation (definition of a risk index based on weight factors), and maintenance planning. A semi-quantitative Failure Modes and Effects Analysis (FMEA) based on subjective information derived from experts, a single risk index, and Analytic Hierarchy Process (AHP) are used in the approach.

mitigate consequences, and Papadakis and Chalkidou (2008) the frequency of a released hazard at the workplace, the probability of an employee being present at that workplace, the extent of consequence zones of an event connected to the released hazard, and the human vulnerability to the consequences of that event. In addition to the proposal of risk indices, a new method or tool regards a common energy-based hazard characterisation through the definition of a damage production model (Leclercq et al., 2018).

Other studies develop risk assessment and management approaches based on existing methods. For example, Boncan (2014) combines the bow-tie tool with Job Hazard Analysis, Marhavilas et al. (2019) use Hazard and Operability (HAZOP), Decision-Matrix Risk Assessment (DMRA), and Analytical Hierarchy Process (AHP) techniques. The latter study proposes a structured framework consisting of the typical risk management steps, i.e. identification of the hazards, risk quantification, risk evaluation, and measures to reduce risks.

The literature review highlights that the available approaches for integrating OSH and process safety are characterised by several focuses and perspectives, examine various aspects of the risk management process, and provide different types of outputs. Therefore, there is the lack of a standardised approach that considers the multiple differences and overlaps between OSH and process safety.

4. The IMPROSafety framework

4.1. Objectives, general principles, and terminology

The IMPROSafety framework has the objective to integrate OSH and process safety in a standardised approach able to describe risks and scenarios traditionally classified as occupational or process ones. This framework goes beyond such classification to develop a holistic safety perspective that addresses the differences and overlaps existing between the domains. The framework allows implementing the same methods and techniques and following common steps to identify, assess, and manage OSH and process hazards and risks. By means of the IMPROSafety framework, analysts are able to recognise the most critical factors characterising the scenarios of interest and contributing to a specific risk. Furthermore, they can identify and adopt the most urgent measures for achieving a tolerable risk.

The proposed framework covers all the steps of the risk management process, as displayed in Fig. 2, and described in ISO/IEC Guide 51 (ISO

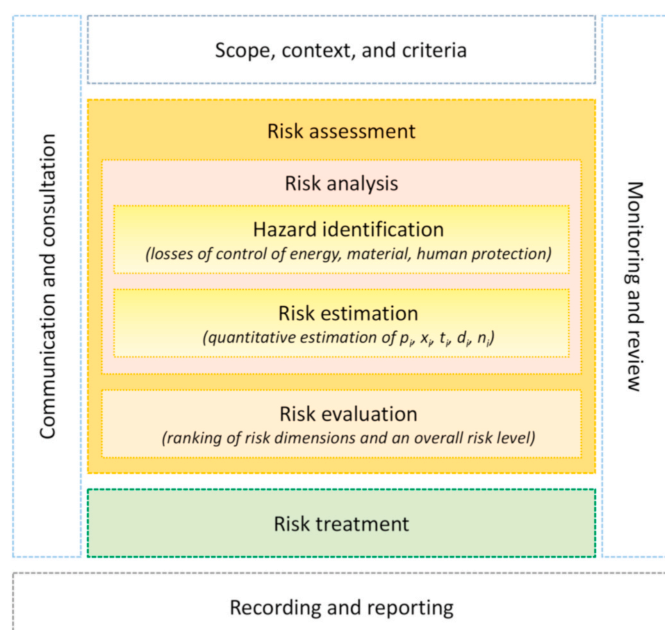

Fig. 2. Risk management process in the IMPROSafety framework, based on ISO/IEC Guide 51 () and ISO 31000:2018 (ISO, 2018a) (Note: p_i = probability of that scenario; x_i = severity of the consequence of that scenario; t_i = temporal evolution of that scenario; d_i = spatial extension of that scenario; n_i = number of workers involved).

IEC, 2014) and ISO 31000:2018 (ISO, 2018a). The terms and concepts at the basis of the framework are reported in Table 2, while the details of the steps of risk analysis, evaluation, and treatment are provided in the next paragraphs. The methods and techniques used in the risk assessment are described adopting the scheme employed by the International standard IEC 31010:2019 (IEC and ISO, 2019): (1) overview, (2) use, (3) inputs, (4) outputs, and (5) strengths and limitations.

In our framework we consider "risk treatment" and "risk reduction" as synonyms.

4.1.1. Risk definition and dimensions

To develop the IMPROSafety framework, we consider the definition of risk proposed by Kaplan and Garrick (1981): the risk is a set of triplets (s_i, p_i, x_i), with i = 1, 2, …, N, where s_i is a scenario identification or description, p_i is the probability of that scenario, and x_i is the consequence or evaluation measure of that scenario (i.e. the measure of damage). A risk analysis answers the following three questions: (1) what can happen? (i.e. what can go wrong?), (2) how likely is it that occurs?, and (3) if it does happen, what are the consequences? (Kaplan and Garrick, 1981). To answer these questions, we would make a list of outcomes or "scenarios" (Kaplan and Garrick, 1981). Kaplan and Garrick (1981) state that "in the case of a single scenario the probability times consequence viewpoint would equate a low-probability high-damage scenario with a high-probability low-damage scenario - clearly not the same thing at all". This is the case when typical scenarios and risks of OSH are compared with scenarios and risks traditionally categorised as process safety (Fig. 1). The assignment of similar ratings to these different risks could confuse analysts during the management process.

Therefore, to capture the peculiarities of both OSH and process safety (summarised in the Background section), the IMPROSafety framework is based on a revision of the definition of risk proposed by Kaplan and Garrick (1981), taking inspiration from the parameters and factors mentioned in the literature (e.g. Chen and Yang, 2004; Gnoni and Bragatto, 2013; Papadakis and Chalkidou, 2008). We assume risk as a set of sestet (s_i, p_i, x_i, t_i, d_i, n_i), with i = 1, 2, …, N, where:

- s_i is a scenario identification or description;
- p_i is the probability of that scenario;
- x_i is the severity of the consequence of that scenario;
- t_i is the temporal evolution of that scenario;
- d_i is the spatial extension of that scenario;
- n_i is the number of workers involved.

In our framework, these dimensions are the key parameters and factors for understanding risks and scenarios related to both OSH and process safety.

In fact, the consequences on workers may occur over different time periods in both the domains. They can be immediate as a result of an incident, accident, or exposure (e.g. burn, cut, death), be delayed, happening distant in time from the incident, accident, or exposure (e.g. hypoacusis, permanent brain damage, cancer, death). The consequences can accumulate over a period of exposure: e.g. the health consequences of exposure to a chemical may depend on the dose to which the person is exposed, as reported by IEC and ISO (2019). CCPS (2000) highlights that the consequences on human beings may be expressed as the long-term health effects arising from a single exposure that does not cause immediate serious injury or fatality, or health effects of chronic exposure over a long time period. Gnoni and Bragatto (2013) include the time spent by a worker in a unit (i.e. the exposure time) in their approach as one of the parameters affecting both OSH and process safety. To capture all these aspects, we introduce a dimension of risk related to the temporal evolution of the scenario, from the beginning of the cause to the occurrence and existence of the consequence. This dimension permits accounting for the exposure duration, the delays between the exposures and the consequences, the persistence of the consequences, and the time between different events composing a scenario.

The spatial extension of the scenario should be included in the set of the risk dimensions for taking into account the distant effects of the impact and the damage area extension. It appears particularly interesting when the cause of the critical event is external to the unit or plant under investigation. Indeed, potential causes may also derive from external circumstances that could produce adverse impacts on the unit or plant under study, or undesired events at the boundary of the unit or plant. This dimension is also relevant for differentiating scenarios in which an individual must be close to the event for a fatality to occur from the situations in which the hazard (e.g. chemical air contamination, toxic gas) may endanger people at a greater distance (CCPS, 2009). In the literature, a similar parameter (i.e. the extent of consequence zones of an event connected to the released hazard) can be found in the index proposed by Papadakis and Chalkidou (2008).

However, the consideration of the only spatial extent of the scenario does not provide information on the number of workers potentially affected by the consequences. This appears relevant in the following cases:

- process safety accidents;
- health effects on long time periods (e.g. several workers can breathe toxic substances for several years, but they are located in the same geographical point in a company);
- confined space incidents (the spatial extent from the cause to the consequence is limited, but the number of workers potentially involved in the scenario may be higher than 1).

Therefore, we explicit a dimension related to the total potential number of workers affected by the studied event. A similar parameter is also included by Chen and Yang (2004) in their index. Papadakis and Chalkidou (2008) report the use of "the number of personnel involved in the accident" in an expanded version of the RSPE (Risk - Severity - Frequency - Exposure) approach that permits handling the consequences to more than one worker under a more sensitive scale.

Table 2
Terms and definitions at the basis of the IMPROSafety framework.

Term	Definition	References
Hazard	Potential source of harm, which can be a risk source.	ISO (2009); ISO IEC (2014)
Harm	Injury or damage to the health of people, or damage to property or the environment.	ISO IEC (2014)
Hazardous event	Event that can cause harm.	ISO IEC (2014)
Hazardous situation	Circumstance in which people, property, or the environment is exposed to one or more hazards.	ISO IEC (2014)
Consequence	Outcome of an event affecting objectives.	ISO (2009; 2018a)
Risk management	Coordinated activities to direct and control an organisation with regard to risk.	ISO (2018a)
Risk assessment	Overall process comprising a risk analysis and a risk evaluation.	ISO IEC (2014)
Risk analysis	Systematic use of available information to identify hazards and to estimate the risk.	ISO IEC (2014)
Risk evaluation	Procedure based on the risk analysis to determine whether tolerable risk has been exceeded.	ISO IEC (2014)
Risk treatment	Process to modify risk.	ISO (2009)
Risk reduction measure - protective measure	Action or means to eliminate hazards or reduce risks.	ISO IEC (2014)

4.2. Hazard identification

The identification of hazards allows highlighting possible malfunctions of the systems, individuating hazardous conditions in plants, processes, or materials, outlining undesired situations, and describing potential scenarios associated with the undesired situations and their consequences (CCPS, 2010a; Villa et al., 2016). During the hazard identification, both normal and abnormal process conditions should be considered (CCPS, 2008). The hazard identification step in the IMPROSafety framework employs a modified version of the bow-tie diagram.

The bow-tie technique is a tool to integrate broad classes of cause-consequence models (Bellamy et al., 2007). It is particularly useful to analyse accidents (Ale et al., 2008; Lisbona and Wardman, 2010), and to understand how unwanted events can occur (CCPS Energy Institute, 2018). Bow-tie analysis provides a systematic structure to facilitate an understanding of risks associated with a facility, scenarios for threat and consequence pathways, and the barriers and degradation controls deployed against the risks (CCPS Energy Institute, 2018). In accordance with Mannan (2012), "the bow-tie diagram is a risk assessment method that is used to identify critical events, build accident scenarios, revise causes of accidents, and study the effectiveness and influence of safety barriers in the diagram". Indeed, it provides a pictorial representation of the relationships between hazards, initiating events (or threats), controls, and consequences (Cockshott, 2005). It is centred on a critical event (Khakzad et al., 2012, 2013; Villa et al., 2016), which represent "the release of a hazardous agent" (Bellamy et al., 2014; Lisbona and Wardman, 2010) or, more generally, a loss of control event (Jan Manuel et al., 2012). The centre of the bow-tie should be selected with care because it is crucial for the analysis (Bellamy et al., 2007). Besides the critical event, other key elements of a bow-tie are: hazard, threats, consequences, prevention and mitigation barriers, degradation factors, and degradation controls (CCPS Energy Institute, 2018). It gives an overview of multiple plausible scenarios, in a single picture (Murphy and Hatch, 2020). In fact, a particular trajectory in the bow-tie is a scenario (Johansen and Rausand, 2014). A scenario is "an unplanned event or incident sequence that results in a loss event and its associated impacts, including the success or failure of safeguards involved in the incident sequence" (CCPS, 2001, 2008, 2009). In other words, scenarios can be represented by the combinations of their starting and ending points, i.e. cause-consequence pairs (Baybutt, 2003). Therefore, the top event is shared by multiple possible scenarios (de Ruijter and Guldenmund, 2016). A detailed explanation of this method can be found in CCPS Energy Institute (2018), while an interesting review is provided by de Ruijter and Guldenmund (2016).

We adopt an advanced feature of the bow-tie diagram, called "bow-tie chaining" (CCPS Energy Institute, 2018). In this structure, a single bow-tie may act as a single ring in a long chain of events, where each event is simultaneously the cause of the following event and the consequence of the previous one (Tarantola et al., 2018). The top event or the consequences of one bow-tie can become causes or contribute to (or even become) the top event of another bow-tie (ICES, 2014).

The bow-tie chaining at the basis of the hazard and scenario identification in the IMPROSafety framework is modelled thanks to the application of the energy theory perspective. We take inspiration from the energy-based hazard characterisation and the topic of the loss of control of energy used by Leclercq et al. (2018). Therefore, we consider the energy model pioneered by Gibson (1961) and then developed in the Hazard-Barrier-Target model by Haddon (1973, 1980), by assuming that the risks in process safety and OSH both stem from the potential for uncontrolled releases and/or unwanted contacts with energy (Fleming and Fischer, 2017). These models assume the presence of different energy sources (i.e. hazards), multiple barriers, and some victims that are vulnerable targets (e.g. persons, environment, property). A transfer of energy more than body injury thresholds causes injury to a person (Gibson, 1961). Detailed descriptions and examples about the energy model are provided by Kjellén (2000) and Kjellén and Albrechtsen (2017). The application of the energy model in the framework for accident analysis proposed by Kjellén (2000) and Kjellén and Albrechtsen (2017) appears particularly interesting for our purpose. In such a framework, an accident occurs when a target is exposed to an uncontrolled transfer of energy and sustains damage, and an injury or damage is the result of an uncontrolled flow of energy reaching the victim, which thus is exposed to this energy flow (Kjellén, 2000; Kjellén and Albrechtsen, 2017). The severity of the injury or damage is dependent on the type and amount of energy and the way it reaches the target (Kjellén, 2000).

Our bow-tie chaining structure is schematically represented in Fig. 3. It is composed of two categories of centre events, as follows:

- loss of control of energy and/or material, which is the hazardous event that causes the release of energy and/or material, and has the potential to expose certain targets to the energy flow;
- loss of control of human protection, which is the transfer and interaction of the energy and/or material released to the human target.

We intend as "loss event" a point in time when an irreversible event occurs that has the potential for loss and harm impacts; this represents the "point of no return" for a scenario (CCPS, 2008). In our bow-tie version, there can be more than one event related to the loss of control of energy and/or material (that we can also call "loss of control of the hazardous energy" or "loss of control over the hazard") in order to capture possible domino effects. This appears interesting for intercepting scenarios in which a first hazardous event does not necessarily result into immediate consequences on workers and can evolve into a different loss of control of energy and/or material event. Therefore, the consequences of the loss of control of energy and/or material potentially impacting on workers become the cause/threat of the following bow-ties, which can be centred on another loss of control of energy event or loss of control of human protection. In the process safety perspective, a typical example of this event is the loss of containment of a hazardous material (CCPS, 2010a; Luna, 2016; Mannan, 2012; Morrison et al., 2011; Murphy, 2017; Pitblado and Nelson, 2013; Saadawi, 2018). The loss of control of human protection causes the exposure of the workers to the hazard, and represents the contact/interaction of the energy and/or material released with the vulnerable target (i.e. workers). Therefore, the loss of control of energy is the centre event of the first bow-tie, while the loss of control of human protection the centre event of the following bow-ties. This because our focus is on consequences in terms of injuries and damages on workers and on-site personnel. The impacts on other targets (e.g. off-site population, environmental receptors, assets, business, production, reputation) are indicated after the bow-tie(s) centred on the loss of control of energy and/or material.

Between the causes and the centre events, and between the centre events and consequences, different intermediate events can be placed. Furthermore, the bow-tie diagram can be displayed assuming the presence of safety barriers (mitigated risk) or supposing that no safety barriers are installed (unmitigated risk). A safety barrier is "physical and/or non-physical means planned to prevent, control, or mitigate undesired events or accidents" (Sklet, 2006), or "a physical entity, a technical, hardware, procedural or organisational element in the working environment that aims either at preventing something from happening (e.g. the centre event) or at mitigating the consequences of something that has happened" (Aneziris et al., 2013, 2014). Bow-ties show prevention barriers, which stop the top event from occurring, and mitigation ones, which reduce the consequence severity when the top event occurs (CCPS Energy Institute, 2018). In Fig. 3, we report safety barriers, but not degradation factors and controls.

The bow-tie technique has been largely used for hazard identification purposes. It has been utilised to identify the potential major accident scenarios of a facility during the Accidental Risk Methodology for Industries (ARAMIS) project (Mannan, 2012), and to assess occupational risks (Aneziris et al., 2008a, 2013). The bow-tie also represents the key model for the development of the tool Storybuilder to represent accident sequence events, classify and analyse past accidents, identify prevention and protection mechanisms, and quantify the risks of activities and the combined risk for a job or profession in terms of probability and damage

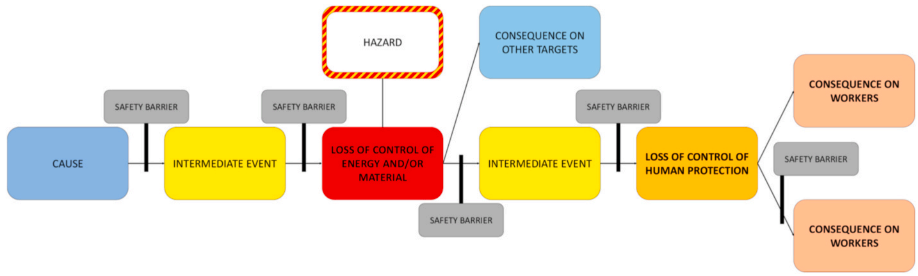

Fig. 3. Bow-tie chaining for identifying OSH and process safety scenarios.

(Bellamy et al., 2006, 2007, 2008). This tool has been applied to analyse both major accident hazards and OSH scenarios (Jan Manuel et al., 2012; Lisbona et al., 2012). Leclercq et al. (2018) highlight that the bow-tie representation of an accident may be used for hazardous substance risk management under the Seveso III directive, but it may also be used as a tool for comparing incidents and exposures related to OSH based on their seriousness.

Bow-ties can also be used to test the adequacy and relevance of existing barriers, and to assist in deciding if additional barriers and degradation controls are required (CCPS Energy Institute, 2018). They demonstrate that sufficient controls are in place for the effective management of hazards and risks, and support the identification of actions to strengthen degraded barriers and degradation controls (Mannan, 2012; CCPS and Energy Institute, 2018). Therefore, the pinpointing of existing safeguards not only indicates the risk control measures already taken, but also makes it easier to identify additional measures that may be required (Baybutt, 2003). Finally, bow-ties can also be used dynamically to reflect the current status of knowledge and information when new data becomes available (Paltrinieri et al., 2014). An example of the dynamic procedure for atypical scenario identification through bow-ties can be found in Ustolin et al. (2019).

Inputs include historical data, past near misses, incidents, and accidents, expert opinions, and literature information in order to individuate the causes and consequences of the events, and the safety barriers that might modify them. Valuable pieces of information are derived from the investigation of traditional and non-traditional, normal and abnormal operation modes, e.g. production activities, inspection and maintenance tasks, start-up, planned and temporary shutdowns, non-routine maintenance tasks, temporary activities, and emergency operations.

The outputs are a graphical representation about the identified scenarios, the events and their logical relationships, causes, operation modes, potential consequences, and safety barriers. Note that our bow-tie structure allows only qualitative identification of scenarios.

The proposed bow-tie diagram combines the strengths of a traditional bow-tie analysis and the ones of a bow-tie chaining structure. Therefore, the strengths are summarised as follows:

- it provides a clear representation of the scenarios under investigation, in terms of events, causes, and consequences (IEC and ISO, 2019);
- it identifies the safety barriers that can be implemented to prevent a critical event from happening and/or to mitigate its effects after it has occurred (Mannan, 2012);
- it considers different hazards;
- it displays multiple top events in an event sequence (CCPS Energy Institute, 2018), and the connection of consequences (upstream) that become threats (downstream) (Murphy and Hatch, 2020);
- it shows the potential domino effects in a scenario (Tarantola et al., 2018).

The limitations of our bow-tie chaining structure include the following issues:

- it cannot depict a situation where pathways from the causes to the event are not independent (IEC and ISO, 2019);
- it can be difficult to introduce all the elements of a scenario in complex situations.

4.3. Risk estimation

The scenarios, the events and their logical relationships, the causes, the potential consequences, and the safety barriers obtained in the hazard identification step are deeply considered in order to estimate the risk. For this purpose, we provide a quantification of both the entire set of dimensions in our definition of risk (Section 4.1.1), and a concise value about the risk of each scenario under investigation. The method employed for this step comprises: (1) scales to transform estimates and categories representing each risk dimension into numerical values, and (2) graphs to visualise and compare the most critical parameters contributing to the risks for a range of workers from the occurrence of a specific scenario.

Proper identification and determination of different parameters on which the risk dimensions depend should be carried out. For example, the probability of the scenario is a function of the probability of the cause (i.e. initiating event), the probability of intermediate events, the probability of the critical events, the probability of a person being present in the area affected by the event (i.e. probability of exposure, occupancy), the possibility to avoid or limit the harm, the vulnerability of the worker, conditional probabilities or modifiers, and failure probabilities of the related barrier functions (CCPS, 2001, 2008, 2009; ISO IEC, 2014; Paltrinieri et al., 2017). The temporal evolution of the scenario is affected by the warning time of each event composing the scenario, the duration of exposure, the time required for the occurrence of the consequence, and the period of time needed for activating safety barriers.

The estimation of risk dimensions can be supported also by means of mathematical models and data about past exposures, near misses, incidents, or accidents. For instance, the probability of the scenario can be quantified by means of Fault Tree Analysis (FTA). The estimation of consequences can be performed using several mathematical and empirical models (Villa et al., 2016). Source models for assessing the loss of containment of hazardous substance and the related physical effects can be employed (e.g. Ustolin et al., 2021), as well as physical-mathematical models for estimating the spatial distribution of damage. Regarding the spatial extension of the scenario, Mannan (2012) underlines the possibility to derive analytical expressions giving the variations of the intensity of the effects with the distance from physical models for different hazards.

To assess the consequences on workers, the different classifications and levels of the severity of damage and harm suggested by the literature can be adopted, for instance:

- no injury, recoverable injury, permanent disability, death (Aneziris et al., 2008b);
- recoverable injury, permanent injury, fatality (Aneziris et al., 2014);

- illness, permanent disability, injury, death (Johansen and Rausand, 2014);
- first-aid injury; lost-time injury, permanent disability, fatality - one person, fatality - two or more persons (Kjellén, 2000).

A largely employed classification of accidents and incidents at work is the so-called Reporting of Injuries, Diseases and Dangerous Occurrences Regulations (RIDDOR) by HSE (2013), which provides the categories of death, specified injury to worker (e.g. amputation of an arm, unconsciousness), over-seven-day injury to worker, occupational disease (e.g. carpal tunnel syndrome, cancer), dangerous occurrence (e.g. explosions, fires). In the IMPROSafety framework, the severity of the consequences is estimated for a single worker and is based on the following types: (1) first-aid injury, (2) temporary and recoverable injury, (3) illness/disease, (4) permanent partial disability, (5) permanent total disability, and (6) death.

All these risk dimensions can be plotted on different graphs: Fig. 4 and Fig. 5 show a multidimensional overview and a radar chart, respectively, of two possible scenarios. In Table 3, some proposed scales of the risk dimensions are reported.

In Fig. 4, the risk defined as the traditional combination between the frequency of occurrence and the severity of consequences is placed. Then, this risk can be better described by means of further dimensions related to the number of workers exposed, temporal evolution, and spatial extension of the scenario under investigation. Each axis can be arbitrarily divided into different levels and scales. An example of such levels is proposed in Table 3, which is also useful for obtaining Fig. 5. The axes in Fig. 5 represent the dimensions that we use to define risk in an integrated perspective between OSH and process safety. The two visualised scenarios are characterised by different levels of the risk dimensions. The green contour is defined by Scenario A: its area shows that the risk dimensions tend to focus more on the severity of the consequence of the scenario. The blue contour is defined by Scenario B, which is characterised by lower values of severity, but higher values for the probability of the scenario and the number of workers involved with respect to Scenario A. For each scenario, the polygon area can be calculated by means of trigonometric relationships, and this can be considered as a proxy of the risk. In Fig. 5, the lower risk is associated with Scenario B.

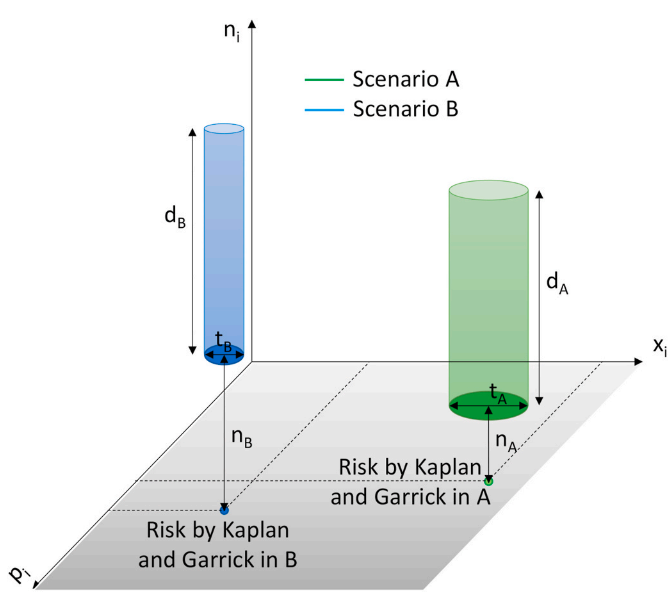

Fig. 4. Multidimensional graph for risk estimation (Note: p_i = probability of that scenario; x_i = severity of the consequence of that scenario; t_i = temporal evolution of that scenario; d_i = spatial extension of that scenario; n_i = number of workers involved).

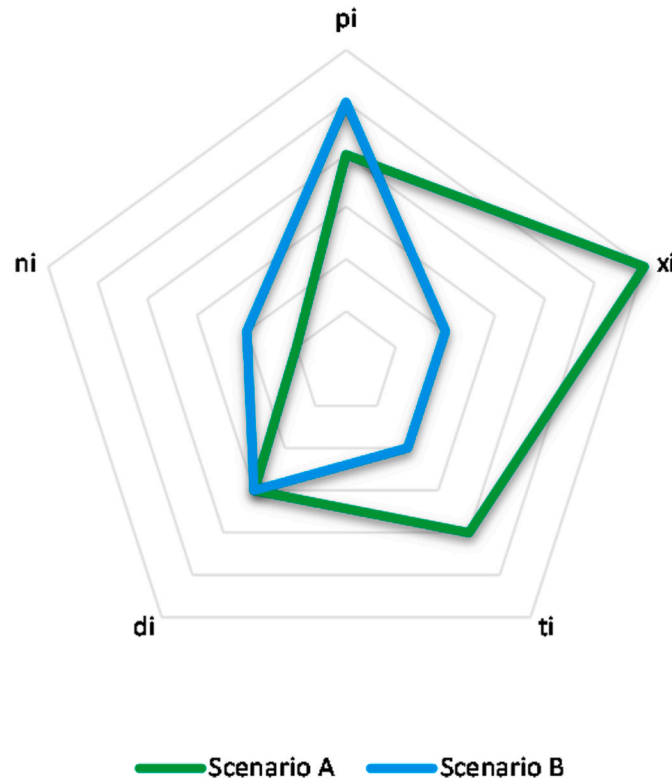

Fig. 5. Radar chart for risk estimation (Note: p_i = probability of that scenario; x_i = severity of the consequence of that scenario; t_i = temporal evolution of that scenario; d_i = spatial extension of that scenario; n_i = number of workers involved).

The method provides a measure for the different risk dimensions and for a concise value of the risk. It permits comparing different possible scenarios, analysing a specific scenario over time, and examining unmitigated and mitigated risks. The graphical tools can also be used for displaying the criticality of some parameters in comparison to risk tolerability/acceptability levels (deriving from regulations, standards, best practices, or companies).

The inputs include the different scenarios previously identified, the details of their constituent events (e.g. in terms of probability, duration, spatial impact), and the effectiveness of existing safety barriers. Physical measurements, and data about past exposures, near misses, incidents, or accidents, when available, give valuable inputs to the risk estimation.

The outputs are estimates of the five risk dimensions for each scenario under investigation: the probability of occurrence, the severity of the consequence, the temporal evolution, the spatial extension, and the number of workers involved. Such estimates are scales assigned to each dimension based on their determination. Furthermore, a value representing the overall risk is obtained.

The strengths of the proposed method for the risk estimation can be summarised as follows:

- the understanding of the dimensions that mainly affect the risk;
- the consideration of different risk dimensions not commonly taken into account;
- the ease of communicating results;
- the possibility to customise the scaling of the risk dimensions according to the type of industry or organisation;
- the opportunity to improve the risk dimensions separately.

On the contrary, the method presents the following limitations:

Table 3
Proposed scales for the risk dimensions (Note: p_i = probability of that scenario; x_i = severity of the consequence of that scenario; t_i = temporal evolution of that scenario; d_i = spatial extension of that scenario; n_i = number of workers involved).

	1	2	3	4	5	6
p_i	<5%	≥5% and <10%	≥10% and <30%	≥30% and <60%	≥60% and <80%	≥80%
x_i	First-aid injury	Temporary and recoverable injury	Illness/disease	Permanent partial disability	Permanent total disability	Death
t_i (min)	<10	(10,1000(	(1000,5000(	(5000,50,000(	(50,000,100,000(	≥100,000
d_i (m)	<1	(1,5(	(5,10(	(10,100(	(100,1000(	≥1000
n_i	1	)1,3(	(3,5(	(5,10(	(10,20(	≥20

- the difficulty to select a proper model for estimating a specific dimension;
- the complexity and resources required to quantify some risk dimensions (e.g. the probability of the scenario);
- the involvement of personnel with specialised competences in the use of mathematical models;
- the identification of adequate scales;
- the arbitrary of the scale selection;
- the presence of different uncertainty sources that can impact the results.

4.4. Risk evaluation

Risk analysis provides an input to the risk evaluation that involves comparisons between the results of the risk analysis and the established risk criteria to determine where additional action is required (ISO, 2018a). The risk criteria are terms of reference that can be derived from standards, laws, policies, and other requirements (ISO, 2009). To conduct the risk evaluation step, we use the ranking method.

The ranking permits producing ordered lists of the risk dimensions and of the overall risk value, sorted according to their scales obtained in the risk estimation step (Section 4.3). In our approach, the ranking allows identifying the most significant risk contributors and the most critical risks for each scenario to effectively address them. Therefore, it supports the decision-making process about the need and definition of the most urgent measures that should be adopted. Through the ranking, analysts may focus on a single dimension of interest and/or on an overall evaluation obtained by combining all the dimensions. If the risk is evaluated as not tolerable, a step of risk treatment is required.

Risk rankings can be used to help prioritise recommendations, determine if a recommendation needs to be made, determine how quickly recommendations should be implemented, distinguish between hazard scenarios, and screen scenarios for a more detailed analysis (Baybutt, 2003).

The inputs are the estimates of the risk dimensions and of the concise risk value, and the risk criteria previously defined.

The outputs are rankings of the risk dimensions previously estimated and of the concise value for the risk. The ranking can be relative or absolute. It also provides information about the acceptability of certain risks and the need to perform a risk treatment step.

Ranking is an advantageous method because of the following strengths:

- the immediate visualisation of the risk dimensions and risks requiring a priority attention;
- the opportunity to improve the risk dimensions separately;
- the ease of use;
- the support for decision-making processes;
- the provision of inputs to the subsequent step of risk treatment.

The limitations of this method are summarised as follows:

- the sensitivity to risk estimation results;
- the difficulty to its applications in assessments composed of a large amount of scenarios.

4.5. Risk treatment

Based on the results of the risk assessment process, analysts perform the risk treatment step, in which options for addressing risks are selected and implemented (ISO, 2018a). Some measures to control (i.e. prevent or mitigate) the risks could be adopted, and their effectiveness and performance should be assessed. In addition, safety measures should be defined in terms of safety barriers and related generic safety functions.

A deeply and combined examination of the scenario evolution, the outcomes of the risk analysis, and the most critical dimensions obtained by means of the ranking permits guiding analysts during the risk treatment. For instance, according to Hale (2002), the slower the speed of development of the scenario, the more effective the recovery mechanisms we can put in place.

Analysts may rely on different classifications and hierarchies of controls, including the well-known ten countermeasure strategies by Haddon (1973) or the energy-based hierarchy of controls by Fleming and Fischer (2017). When considering the possible measures, a Cost-Benefit Analysis (CBA) aids the decision-making process on risk reduction actions (Paltrinieri et al., 2012a).

5. Case study

In this section, we propose a case study in order to preliminarily test the IMPROSafety framework. The case study regards the analysis of three events occurred in the steel and iron industry in the last decades. The operations usually carried out in this industry may expose workers to a wide range of hazards, and lead to injuries, diseases, and adverse effects (Stefana et al., 2019, 2020).

5.1. Description of events

5.1.1. Event 1

On 12th April 2006 an unwanted event occurred at the Elkem Thamshavn plant furnace #1. This event happened due to a water leakage in the cooling system at one electrode in the furnace. The amount of water in the furnace achieved a critical level (i.e exceeded the safe limit) and was mixed with the hot charge material. As consequence, the water flashed into steam. The material in the furnace got wet and was mixed with the hot charge. This provoked the cooling of the hot charge and the formation of a huge amount of water vapour, which was mixed with the combustible process gas in the furnace. This caused the prime eruption and the flow out of the vapour and process gas from the furnace.

During the event, three sequential eruptions from the furnace happened, and the second one was the most violent. The sequential eruptions were created by the primary eruption that lifted the charge and created an intensive mixing of the water, the wet charge material, and the hot charge material. Water vapour was mixed with combustible process gas, glowing raw material, and charge material. As result, flames flowed out from the furnace doors and poured into the surrounding area. One worker died after severe burns four weeks later, two other operators received minor injuries, and the furnace was damaged in the hood and the electrode systems. A detailed description of the event can be found in Tveit et al. (2008).

5.1.2. Event 2

At 11:35 p.m. on 20th February 2012 a severe water vapour explosion occurred in an indoor moulding pit of the Steel Casting Plant of the Heavy Machinery Co. Ltd., a part of the Anshan Iron and Steel Group in the Liaoning Province in northeast China. The cavity was lined with a thick water-proof concrete layer placed inside of a whole-welded steel box. The explosion happened during the casting of a stainless-steel conical ring (whose weight was about 90 tonnes), basement of a water turbine, in the sand moulding pit. The preparation of the sand mould started on 14th January, before a 7-day holiday break, and was completed on 19th February. The casting of the stainless steel ring started on 20th February. Two steel ladles, each charged with 90 tonnes of molten stainless steel, were used during the casting. Before pouring was started, the sand mould had been dried for 8 h. After about 30 min of pouring of the molten stainless steel into the mould, an abnormal buzzing sound could be heard from the interior of the pit. Suddenly, the entire sand mould and its content of molten stainless steel were lifted at least 5 m up in the air, shattered and thrown around. Thirteen people were killed, six seriously injured, and eleven moderately/slightly injured. The explosion caused serious damage to the power supply system, various pipelines, the gantry crane, and the excavator.

This event was initially caused by the seepage of the ground water into the pit through the eroded holes in the steel lining and cracks in the concrete layer, and the moistening of the sand during the holiday break. When the completed sand mould received the molten stainless steel, the sand and water were exposed to a substantial heat flux from the hot metal. The water rapidly evaporated causing a pressure increase throughout the sand bed in and below the mould. In other words, when the molten steel met the wet sand, a sharp pressure build-up of the cavity was generated by the rapid superheated water vaporisation. Further details of this unwanted event can be found in Li and Ji (2016), and Xu et al. (2020).

Water vapour explosions are usually categorised as Rapid Phase Transition (RPT) (Aursand et al., 2020; Odsæter et al., 2021; Ustolin et al., 2020a). Xu et al. (2020) define it as a sand casting explosion, in particular as a Boiling Liquid Expanding Vapour Explosion (BLEVE). BLEVE is a physical explosion that can be formed by a superheated liquid stored in enclosure spaces, such as inside a liquefied gas vessel. However, during a BLEVE there is not direct interaction between different substances (e.g. water and molten metal). Instead, the explosion manifests after the catastrophic rupture of the tank with consequent expansion of the compressed gaseous phase together with the flashing of the liquefied gas due to the depressurisation (Ustolin et al., 2020b). It seems that the analysed scenario recalls the chain of events of a confined RPT explosion instead of a BLEVE one. RPT is an atypical accidental scenario (Ustolin et al., 2019), which is an accident scenario not captured by conventional hazard identification techniques and risk analysis processes because of deviation from normal expectations of unwanted events or worst-case reference scenarios (Paltrinieri et al., 2012b).

5.1.3. Event 3

In 2017, an unwanted event occurred in a fiberglass tank of the purification system of an Italian company specialised in galvanic treatments of metals (cadmium and nickel). The tank was open at the top, and had a height equal to 2.20 m and a diameter to 1.70 m. It is a confined space, since it (1) is large enough and so configured that an employee can bodily enter and perform assigned work, (2) has limited or restricted means for entry or exit, and (3) is not designed for continuous occupancy (OSHA, 2011).

The purification system required periodic maintenance interventions in order to clean and eliminate limestone deposits from the sand filters. The tank had the objective to store the solution used for the maintenance interventions for a specific period of time. The tank was washed with well water when the solution was removed from it, and then cleaned manually by a worker for taking off any muddy residue at its bottom. Therefore, the worker entered the tank by means of a metal ladder. After a few seconds, the worker experienced early adverse health effects, nausea, vomiting, and breathing difficulties, but he was unable to leave the tank, although the help from an attendant stationed outside. When the alarm was raised, the company owner intervened and entered the tank for rescuing the worker. The owner exhibited the same symptoms and was unable to leave the tank. When the worker and the owner were extracted from the tank, some resuscitation attempts were carried out by medical personnel. However, the worker died a few days later the event, and the owner was recovered in 56 days.

The unwanted event was caused by the presence of chlorine vapours at the bottom of the tank, which are released by the acid solution for the maintenance interventions. The used hydrochloric acid and the vapours from the acid solution are harmful if inhaled, and may cause eye damage and respiratory irritation. ACGIH (2019) specifies the possibility to Upper Respiratory Tract (URT) irritation caused by this chemical (CAS 7647-01-0), and a Threshold Limit Value – Short-Term Exposure Limit (i.e. TLV STEL, a 15-min time weighted average exposure that should not be exceeded at any time during a working day) equals to 2 ppm.

The cause of the unwanted chain of events was not precisely identified, but a human error about the dilution of the hydrochloric acid in the water was assumed. A description of this event can be found in Informo database by Istituto Nazionale per l'Assicurazione contro gli Infortuni sul Lavoro (INAIL), which is available on https://www.inail.it.

5.2. Hazard identification

The hazard identification step was performed by means of the bow-tie chaining described in Section 4.2. The obtained bow-ties are shown in Fig. 6, Fig. 7, and Fig. 8. Specifically, Fig. 6 displays the event occurred at Elkem Thamshavn in 2006, Fig. 7 the event at Steel Casting Plant in the Liaoning Province (northeast China) in 2012, and Fig. 8 the event in an Italian company specialised in galvanic treatments of metals in 2017. In these bow-ties, we also included some examples of safety barriers. Note that due to graphical constraints, Fig. 6 depicts the scenarios from the cause to the consequences of the second eruption, although in Elkem event three sequential eruptions happened.

Due to the lack of precise information about the causes, we assume that the failure of furnace water cooling system provoked the event 1, the eroded holes in the steel lining and concreate layer of the pit the event 2, and an error in the dilution of the solution the event 3.

In event 1 and event 2 the hazard was the material incompatibility: in event 1 there was a chemical reactivity between the water and the hot charge, and in event 2 a large temperature difference and thermal energy content of the molten metal compared with the ground water. Water is not a reactive nor flammable substance, but becomes hazardous if kept under high pressure especially in a superheated status. In event 1, when the control of the chemical reactivity hazard was lost, an uncontrolled chemical reaction occurred. In this case, the loss of control of energy was the eruption. In event 2, when the control of the thermal energy hazard was lost, an uncontrolled and substantial heat flux happened. In this case, the loss of control of energy was the RPT explosion. In event 3, the hazard was correlated with the inherent properties of the hydrochloric acid: this chemical is corrosive and irritant, and the exposure to it may produce severe adverse health effects to workers. In this case, the loss of control of energy was the presence of significant concentrations of hydrochloric acid and its vapours in the tank. These losses of control of energy represent the "points of no return" for the scenarios under investigation.

After the loss of control of energy, a loss of control of human protection took place, causing the interaction between the energy released and the human target. In the events under investigation, the losses of control of human protection were the following:

- the contact between workers and the eruption products (e.g. flames) flowed out from the furnace doors (event 1);

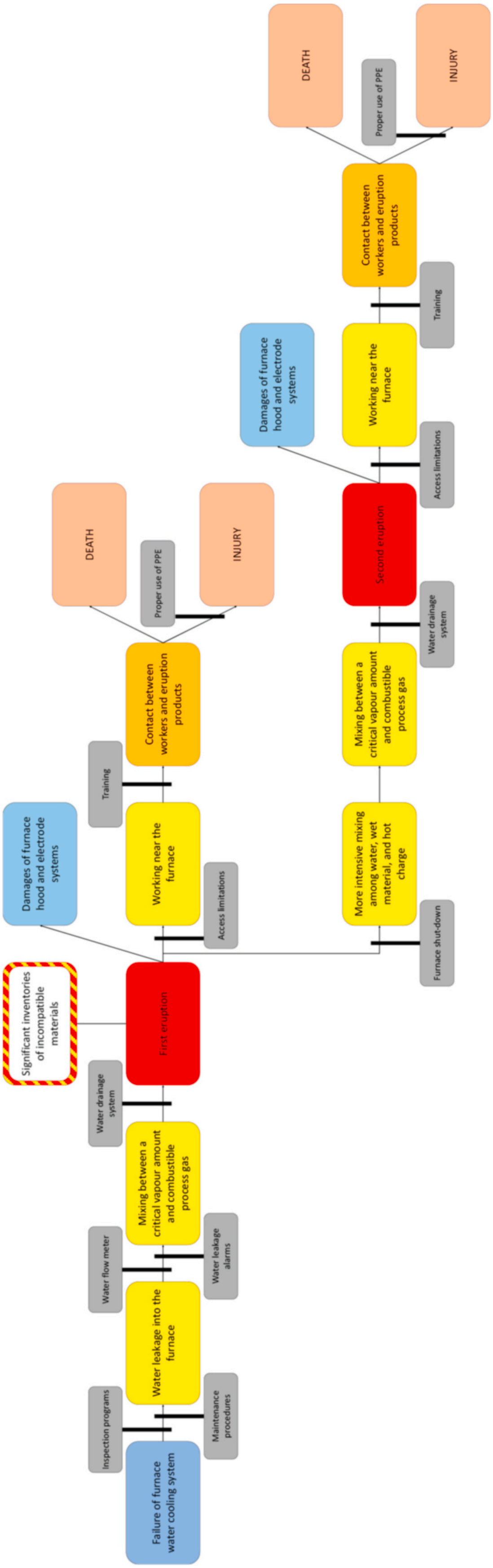

Fig. 6. Bow-tie chaining for the event at Elkem Thamshavn in 2006. (Note: PPE = Personal Protective Equipment).

- the impact of the blast wave and the contact between workers and the high temperature pit content, where the content of the pit was the molten metal, sand mould, steam, and hot water shattered and thrown around by the explosion (event 2);
- the contact between workers and hydrochloric acid and the vapours from the acid solution, which causes the workers' exposure to the chemical (event 3).

5.3. Risk estimation

As reported in Section 4.3, risk estimation follows the hazard identification step and permits analysing all the dimensions of risk introduced in Section 4.1.1. In the risk estimation step related to the studied events, we select the following six scenarios:

- Scenario A: death of one worker in event 1;
- Scenario B: temporary and recoverable injury for two workers in event 1;
- Scenario C: death for thirteen workers in event 2;
- Scenario D: permanent partial disability for six workers in event 2;
- Scenario E: death of one worker in event 3;
- Scenario F: temporary and recoverable injury for one worker in event 3.

With regard to event 1, we focus on the consequences due to the second eruption since it was the most violent, in event 2 on the consequences due to the contact between workers and the molten metal, and both the occurred consequences in event 3. Fig. 9 shows the obtained radar chart for all the six scenarios of interest.

The estimation of the scenario probability requires quantitative data and pieces of information. The descriptions of the investigated events do not allow developing a precise determination of this risk dimension. However, based on the reported qualitative considerations, we perform a rough estimation of the probability. For instance, in the case of event 1, we consider a reasonable frequency value of a major water leakage linked to an electrode system failure and the related probability of death and of injuries in similar companies. Tveit et al. (2008) underline that such events do not occur very often in one plant, but have happened quite frequently in the metallurgical industry. We hypothesise that Scenario B is characterised by a higher value of occurrence probability. On the contrary, the probability of occurrence of Scenario C and Scenario D are lower values than the ones of Scenario A and Scenario B (Scenario C is characterised by the lowest value and equals to 2, in accordance with Table 3). A possible reference value about explosions in foundry companies in China can be found in Xu et al. (2018). Scenario E and Scenario F present the highest probability value (scale = 6 in Table 3): working in confined spaces represents one of the most common causes of injuries in iron and steel companies (Stefana et al., 2019).

Based on the scale of the consequence severity proposed in Section 4.3, Scenario A, Scenario C, and Scenario E lead to the most severe outcomes, i.e. death of the worker (scale = 6 in Table 3). The difference between these scenarios is related to the number of workers that experience this consequence: Scenario A and Scenario E caused the death of one worker, while Scenario C resulted in 13 deaths and thus represents the scenario with the highest value of the number of workers involved.

In all the scenarios, the temporal evolution from the cause to the consequence is not negligible. Although the duration of an eruption is typically on the order of seconds and of an explosion of milliseconds (Tveit et al., 2008), the entire development of Scenario A, Scenario C, and Scenario D lasts several weeks. In Scenario A the longest period of time was between the eruption and the death of the worker (i.e. 4 weeks), whereas in Scenario C and Scenario D the time between the cause and the RPT explosion (i.e. 28 days) was the most critical determinant for the entire scenario duration. In Scenario E and Scenario F, the time period between the development of the hazardous atmosphere and the consequences on workers was the key factor of the temporal

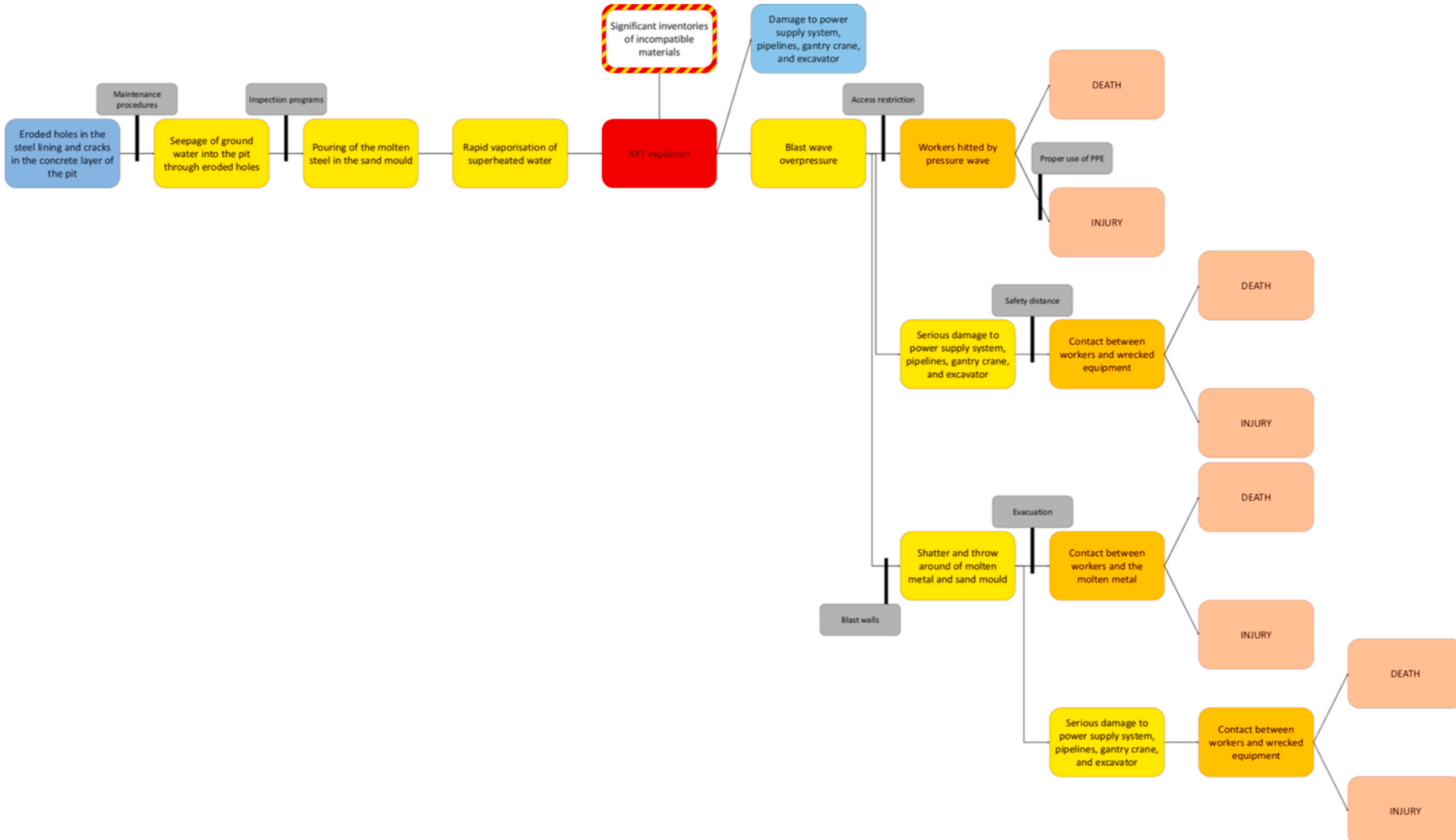

Fig. 7. Bow-tie chaining for the event at Steel Casting Plant in 2012. (Note: RPT = Rapid Phase Transition; PPE = Personal Protective Equipment).

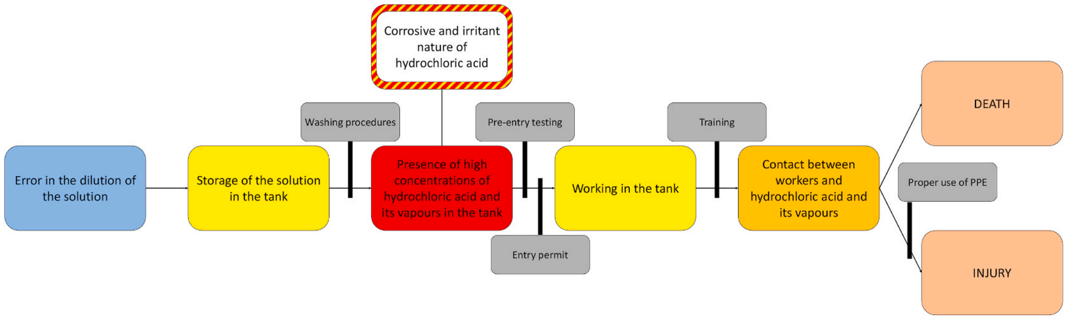

Fig. 8. Bow-tie chaining for the event in an Italian company in 2017. (Note: PPE = Personal Protective Equipment).

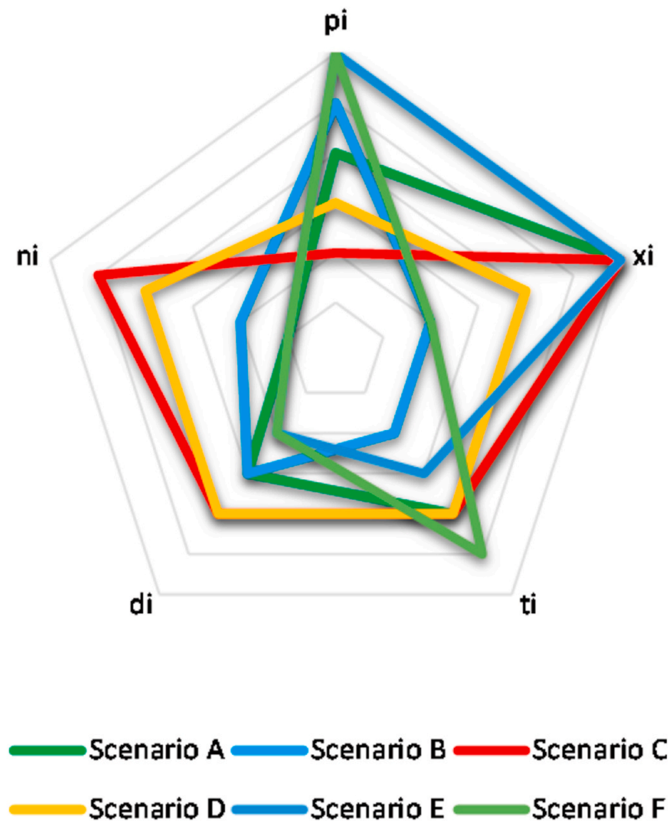

Fig. 9. Radar chart for risk estimation (Note: p_i = probability of that scenario; x_i = severity of the consequence of that scenario; t_i = temporal evolution of that scenario; d_i = spatial extension of that scenario; n_i = number of workers involved).

evolution (i.e. 3 days in Scenario E, and 56 days in Scenario F).

In terms of the spatial extension values in event 1 and event 2, we assume that the consequences happened in the proximity of the furnace, pit, or tank. Since the lack of quantitative data about the precise location of the cause, we hypothesise that the causes occurred at the middle of the equipment or space and the workers were a few metres away from the it.

The combination of the above dimensions permits calculating the polygon area of each scenario, which can be assumed as a proxy of the risk based on the dimensions taken into consideration. The area of Scenario B is equal to 17.12 and this is the lowest value of the risk among the six scenarios. On the contrary, Scenario C presents the highest value of risk (i.e. the polygon area is equal to 38.99). Scenario A, Scenario D, and Scenario E are characterised by similar risk values: the areas are equal to 31.86, 34.24, and 32.34, respectively. Finally, the area of Scenario F is equal to 19.02.

5.4. Risk evaluation

Thanks to the risk estimation by means of the multidimensional graph, radar chart, and scales for each dimension, we evaluated the risks thanks to the ranking of the dimensions (i.e. probability, severity, temporal evolution, spatial extension, number of workers) and of the risk values. The obtained dimension and risk-based rankings are summarised in Table 4: the first column reports the position in the ranking (where rank = 1 means the most critical dimension or risk), whereas the other columns propose the rankings for the different dimensions and for the overall value of the risk. Each cell of these columns contains a specific scenario and, in brackets, the scale for a particular risk dimension (Table 3) or the polygon area for the overall risk value (Fig. 9). If more than one scenario has the same scale for a specific risk dimension, the same rank is assigned to them (indicated by means of merged cells in Table 4).

Scenario B presents the lowest value of risk. On the contrary, Scenario C is ranked as the most risky scenario and requires particular attention because of higher values of consequence severity, spatial extension of the scenario, and number of workers involved (by using Table 3: scales equal to 6, 4, and 5, respectively). Scenario E is critical in terms of occurrence probability and severity of consequence (according to the scales proposed in Table 3, both p_i and x_i are equal to 6), while Scenario F is characterised by the highest values of occurrence probability and temporal evolution (in accordance to Table 3, p_i is equal to 6, and t_i to 5).

5.5. Risk treatment

Although an exhaustive risk treatment step for the three unwanted events is out of the scope of this paper, we propose some measures to prevent or mitigate the risks in order to complete the overall risk management process. Among the scenarios under investigation, priorities should be dedicated to Scenario C, mainly for reducing the severity of the consequence and the number of workers involved. Proper controls should be adopted for detecting the seepage as soon as possible and/or containment system to reduce the water in the pit, prevent the contact between the water and molten steel, and avoid the rapid vaporisation of

Table 4
Dimension and risk-based rankings (Note: p_i = probability of that scenario; x_i = severity of the consequence of that scenario; t_i = temporal evolution of that scenario; d_i = spatial extension of that scenario; n_i = number of workers involved; R_i = risk).

	p_i	x_i	t_i	d_i	n_i	R_i
Rank 1	E (6)	A (6)	F (5)	C (4)	C (5)	C (38.99)
Rank 2	F (6)	C (6)	A (4)	D (4)	D (4)	D (34.24)
Rank 3	B (5)	E (6)	C (4)	A (3)	B (2)	E (32.34)
Rank 4	A (4)	D (4)	D (4)	B (3)	A (1)	A (31.86)
Rank 5	D (3)	B (2)	E (3)	E (2)	E (1)	F (19.02)
Rank 6	C (2)	F (2)	B (2)	F (2)	F (1)	B (17.12)

superheated water. Adequate safety barriers should also be introduced in order to limit the transfer of energy to workers. This allows decreasing the overall risk level of this scenario. The detection of the seepage of the ground water into the pit eliminates the energy able to trigger the explosion. All these controls also help in the reduction of the risk level of Scenario D.

With regard to Scenario E and Scenario A, analysts should preliminarily focus on the severity of the consequence. In both the cases, the attention should be concentrated on the limitation of accesses in the dangerous zones (i.e. tank for Scenario E, furnace area for Scenario A) by workers. This could avoid the contact between the workers and the energy released (in other words, the exposure of the workers to the energy released). Scenario E is critical also for the probability of occurrence. In order to reduce the criticalities related to this scenario, valuable practices and procedures can be found in OSHA (2011). The adoption of these practices and procedures could also decrease the values of the risk dimensions of Scenario F.

In all the scenarios, the proper use of Personal Protective Equipment (PPE) may limit the possible consequences on the workers. Other safety barriers are depicted in Figs. 6, Figure 7, and Fig. 8.

6. Discussion

The analysed case study offers a preliminary application of IMPROSafety, the risk-based framework to integrate OSH and process safety proposed in this work, and focuses on some scenarios that occurred (and still occur) in the steel and iron industry. Two investigated events were related to the hazard of significant inventories of incompatible materials, which provoked sequential eruptions or an RPT explosion, while the third event regarded the presence of high concentrations of a corrosive and irritant chemical in a confined space where a worker performed manual tasks. The eruption, explosion, and high chemical concentrations represent loss events, in which a loss of control over the hazard leads to an irreversible release of energy and/or material. Different escalation possibilities, immediate damages to equipment and/or environment, and/or consequences on workers can follow this loss of control event. In particular, the consequences on workers occur because of a loss of control of human protection, which is the point in time when there is the transfer and interaction between the released energy and/or material and the human target. If not controlled and stopped by any safety measures, such loss of control of human protection provokes different and potential multiple consequences on workers. The eruptions in the Elkem Thamshavn plant produced the death of one worker and temporary and recoverable injuries of other two operators, the RPT explosion in the Steel Casting Plant of the Heavy Machinery Co. Ltd. triggered the death of thirteen workers, permanent partial disability for other six ones, and temporary and recoverable injuries for other eleven ones, and the high concentrations of hydrochloric acid and its vapours in a fiberglass tank of the purification system of an Italian company caused the death of one worker and temporary and recoverable injuries for another operator.

These cause-consequence pathways are depicted in our framework thanks to the bow-tie chaining method, i.e. an advanced but scarcely used evolution of the classical bow-tie approach. This particular structure is able to make explicit the chance of multiple events of loss of control and domino effects in a scenario. In the IMPROSafety framework, the strengths of the bow-tie chaining method are coupled with the perspective of the energy models, which can be defined as a cornerstone in the safety field. The adoption of energy point of view permits considering a large spectrum of hazards, which can be encountered in different organisations and traditionally classified as process safety or OSH related ones. As a consequence, the combination of the bow-tie chaining method and the energy perspective seems assuring a complete hazard identification step in our framework integrating OSH and process safety, regardless the variability level and the dynamic nature of the hazards (Abreu Saurin and Patriarca, 2020).

Among the possible scenarios in the unwanted events arising from the hazard identification phase, six chains were selected and examined in terms of the risk dimensions at the basis of our framework for estimating risks. In fact, in addition to the probability of occurrence of a scenario and the severity of consequences (i.e. the two classical parameters considered in the definition of risk provided by Kaplan and Garrick (1981)), we introduce further dimensions in order to make the main determinants of a risk more transparent. Such dimensions are defined thanks to the consideration of those factors that traditionally differentiate OSH and process safety, and the selection of the ones that allow providing a complete risk picture. For this purpose, we also analyse the temporal evolution and the spatial extension of a scenario, and the number of workers involved. The study of the spatial extension of a scenario and the number of workers involved separately allows avoiding assumptions related to the uniform distribution of the workers within a plant (e.g. Gnoni and Bragatto, 2013).

The five risk dimensions are estimated for all the investigated scenarios in order to complete the risk analysis. However, a proper estimation of the risk dimensions can be a not straightforward task. Indeed, the definition of reasonable assumptions and the employment of mathematical models represent prerequisites for obtaining good estimates of the dimensions. For instance, the calculation of the probability of the occurrence of a scenario depends on the probability of all the events composing the scenario itself, the success or failure of safety barriers, and the creation of specific conditions. The knowledge of such inputs is rarely available by analysts, and the collection of data and information could be a time-consuming operation. This also causes a certain level of uncertainty, which should be properly taken into account and characterised in the general risk assessment process. Moreover, the uncertainty increases with the complexity and the time duration of the scenario under investigation. Such difficulties are well demonstrated in the case study presented in this paper, where the probability estimation represents one of the main weaknesses. The probability estimation is based on qualitative pieces of information and assumptions inspired from the literature, but a complete quantification has not been carried out. A deep analysis of the contributing factors and the subsequent determination of the probability of occurrence of the investigated scenarios should be conducted in the future in order to refine the current calculation.

The procedure of the dimension estimation could be facilitated thanks to detailed descriptions and reports of incident and accident investigations, up-to-date and structured accident databases, and advanced methods made available through recent machine learning and meta-learning researches. Meta-learning, or learning about learning, regards the process of exploiting and learning from experience (Stefana and Paltrinieri, 2021). It could be particularly promising for learning from unwanted events and/or for performing predictions, also when data are scarce. This could further consolidate the possibility of applying our framework to both analysis of past events, and real-time risk assessments and proactive evaluation of future scenarios.

The translation of the risk dimension estimations into numerical values is performed by means of scales. Such scales permit assigning a value to the different dimensions through the identification of ranges, which can be customised according to the type of industry and organisation. Their definition should permit covering all the potential outputs obtainable in the dimension quantification, and simultaneously discriminating the most critical dimensions among the scenarios under investigation. In this paper, we propose and apply possible arbitrary scales that need to be improved thanks to further calibration and validation activities, also through the analysis of other case studies.

In addition to the estimation of the separate dimensions, the IMPROSafety framework allows determining a concise value about the risk, which is the area of the polygon created by the five dimensions characterising a specific scenario. In general, other methods could be employed for determining the risk level, e.g. the calculation of geometric mean of the dimensions or the quantification of arc lengths of the polygon.

The estimation of the risk and its dimensions and their evaluation via ranking provide an immediate and comprehensive overview of all scenarios, allow improving the dimensions separately, highlight the factors and their combinations requiring further attention by analysts, and assist in the design of risk reduction measures and strategies. Furthermore, the graphical visualisations and the rankings used in our framework facilitates the communication of the outcomes. This is fundamental to rapidly set priorities for preventing and/or mitigating undesired events and consequences on workers. The development of tools and dashboards based on these graphs and rankings could increase the applicability of IMPROSafety, also for comparisons over time of risks and scenarios of interest, and periodic risk assessments. In this sense, analysts could rely on dynamic tools feeding with updated data and sources of information.

In the risk evaluation step, the provision of outcomes in terms of both separate risk dimensions and an overall risk level permits capturing the fact that: (1) risk is a multifaceted concept that cannot be captured in a single metric, and (2) a single metric expresses only an aspect of risk, and should therefore not be used as the single basis for a decision (Johansen and Rausand, 2012). As a consequence, "a broad and balanced set of metrics is therefore necessary to ensure that the information fits the decision context", where a risk metric is a mathematical function of the probability of an event and the consequences of that event, relates to the occurrence of one or more hazardous events, and facilitates decision-making by providing a quantitative measure for risk evaluation (Johansen and Rausand, 2014). For instance, Fatal Accident Rate (FAR) (i.e. the expected number of fatalities within a specific population per 100 million hours of exposure) takes into account fatalities, but it does not cover other relevant consequences such as injuries, and fails to distinguish the risk related to some few extreme events with multiple fatalities from several minor accidents with single fatalities (Johansen and Rausand, 2014). Furthermore, other drawbacks of risk metrics (e.g. the aggregation of information and the inability to distinguish it, the combination of several hazardous events into a single value, hiding differences and relationships of the considered consequence dimensions (Edwin et al., 2016)) may be overcome by our framework that offers a possible solution for the visualisation of the risk assessed on a dynamic basis and thus for the support to the decision-making process.

The IMPROSafety framework and its application to the case study are lacking in a complete risk treatment step. Therefore, its future uses should provide further details in terms of safety barriers and measures, degradation factors and controls, from the preliminary phase of hazard identification. A degradation (or escalation) factor is "a situation, condition, defect, or error that compromises the function of a main pathway barrier, through either defeating it or reducing its effectiveness", while a degradation control represents a measure that helps prevent the degradation factor impairing the barrier (CCPS Energy Institute, 2018). Therefore, the inclusion of those elements in the bow-tie structure could give additional informative inputs to analysts for completing the risk management process.

The framework presented in this paper represents one of the potential options to integrate OSH and process safety. Several directions may be investigated that could offer effective leverages for improving the general safety level of an organisation. In fact, the study of OSH and process safety from an integrative perspective permits going beyond the different, often opposite, opinions on the differences and overlaps, and mainly on the factors characterising and differentiating each domain. The existence of multiple controversial points of view highlights the impossibility to map out unambiguous boundaries and well-defined ranges that define the "fields of application" and features of OSH and process safety. Moreover, they cannot be easily represented as single points in a probability-severity perspective (Fig. 1). As a matter of fact, fuzzy dividing lines divide them.

The real issue is not classifying incidents, accidents, or exposures as process safety or occupational safety ones. There is the need to focus on the risk prevention and workers' protection, i.e. the real and core objective of the safety science. OSH and process safety should be seen as two components of the same system, in which each one both assures and strengthens the functioning of the other. This also allows overcoming those ethical issues that sometimes are quoted in the comparison between OSH and process safety. Process safety-related accidents are typically events resulting in multiple major injuries and fatalities, and this feature partially justifies the need for a higher level of attention and efforts in the management of this domain. However, as stated by Jørgensen (2016), OSH incidents have killed or permanently injured more people in total than all the major accidents which have occurred, and the recognising that the consequences for each OSH event can be seen as minor compared to the major one is only valid from the society point of view, but not for the victims and their families.

7. Conclusions

This paper proposes IMPROSafety, a risk-based framework to integrate OSH and process safety. The focus on the risk concept permits going beyond the traditional classification of these safety domains, and prioritising the attention on several dimensions that analysts should investigate in depth. Besides the occurrence probability of scenarios and consequence severity, we analyse and evaluate the temporal evolution and spatial extension characterising each hazardous scenario, and the number of workers involved. All these dimensions assume paramount importance in every step of the risk assessment and management process.

A case study about three real unwanted events occurred in the steel and iron industry in the last decades was presented to offer a preliminary application of the framework. The eruptions happened at the Elkem Thamshavn plant furnace in 2006, the RPT explosion in an indoor moulding pit of the Steel Casting Plant of the Heavy Machinery Co. Ltd. in 2012, and the high concentrations of hydrochloric acid and its vapours in a tank of the purification system of an Italian company in 2017 were assessed by means of a stepwise process composed of hazard identification, risk estimation, risk evaluation, and risk treatment. Six scenarios of interest were selected based on the consequences of varying seriousness. In each scenario we estimated its occurrence probability of occurrence, consequence severity, temporal evolution, spatial extension, and number of workers involved. The combination of these dimensions also allowed calculating an overall level of risk. Such risk dimensions and overall level were ranked in order to address further risk prevention and mitigation activities.

Additional case studies about the application of the IMPROSafety framework should be explored. Possible future applications could be dedicated to the examination of real near misses and/or the risk assessment of an entire department or plant of various industries. A structured proposal in terms of safety measures and risk treatment could also complete our framework. The development of user-friendly applications and dashboards based on the main features of IMPROSafety is another aspect that deserves future investigation.

Author contributions

Elena Stefana: Conceptualisation, Data curation, Formal analysis, Investigation, Methodology, Visualisation, Writing - original draft. Federico Ustolin: Data curation, Formal analysis, Investigation, Methodology, Visualisation, Writing - original draft. Nicola Paltrinieri: Conceptualisation, Data curation, Investigation, Methodology, Supervision, Visualisation, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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