Techniques for investigating accidents

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Prepared by:

Dr Payam Pirzadeh,[1]

Professor Helen Lingard[1],

Dr Gregory Zelic[2],

Dr Salman Shooshtarian[1]

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[1] School of Property, Construction and Project Management, RMIT University

[2] Centre for WHS, NSW Government, Sydney 2000

Executive summary

Background and objectives

Accidents are often caused by a complex combination of different factors. A multitude of techniques for accident investigation exist, with their own theoretical underpinning and practical benefits and drawbacks.

This review considers the most widely used accident investigation techniques and identifies their characteristics and usage. It is not a comprehensive review but considers the application, strengths and limitations of the most frequently documented techniques. During the review, the following objectives were pursued:

1. To identify the most frequently used techniques for accident investigation in selected industries, including aviation, nuclear energy, transport, maritime, oil and gas and chemical processing,
2. To understand the characteristics of the techniques in terms of how they conceptualise and represent accident causation,
3. To identify the relevant leading agencies in the six areas and examine what safety accident investigation techniques are being used or recommended by these agencies, and
4. To provide examples of the application of safety accident investigation techniques from previous studies and credible published sources.

Method

The relevant literature was identified and screened in three stages as follows:

Stage I: a systematic desktop search of six major databases was conducted: Google Scholar, Scopus, PubMed, Wiley Online Library, Water Resource Abstracts (ProQuest) and Web of Science.

Stage II: the sources obtained in the first stage were analysed and those with highly relevant contents were shortlisted. The full text of selected sources was subsequently coded and archived for the third stage of examination.

Stage III: The third stage of examination involved checking the selected sources against three selection criteria: (1) application of one or more accident investigation techniques in at least one of the six target industries; (2) whether the source clearly described the application of the original version of investigation techniques; and (3) if it employed the widely accepted investigation techniques. Those sources that did not meet these criteria were excluded from further consideration.

The screened literature was then analysed and classified in four steps as follows:

1. The most widely used or suggested techniques for accident investigation in various high-risk industries were identified.
2. Various characteristics of the techniques identified in step 2 were examined and summarised.
3. Examples of the application of techniques in case studies were identified. In addition, the accident model(s) that underpins these techniques (e.g. sequential, epidemiological and systematic) were identified in this step.
4. Studies that conducted comparative evaluations between different investigation techniques in various high-risk industries were identified and the reasoning (if any) for recommending a preferred technique(s) over others was captured.

Results

The review resulted in the identification of 36 accident investigation techniques across various high-risk industries. The review and comparison of these techniques revealed a diversity of perspectives on accident causation and the benefits and limitations inherent in them. In particular, the academic literature highlights the benefits of a systemic approach to accident analysis, including a more comprehensive understanding of the complexities and dynamics involved in accident causation. Nevertheless, the application of systemic techniques, such as STAMP, FRAM, and AcciMap, has mostly been in the academic domain and practitioners are typically unaware of them or do not use them in their investigations. Some studies have suggested a number of difficulties with the application of systemic techniques in industrial environments, including their theoretical complexity, absence of domain-specific taxonomies to guide the investigation, generally high resource requirements (e.g. time, data collection), high sensitivity of the outcomes to the quality of data, and inconsistency of the results when applied to the same scenario by different users.

Compared to systemic techniques, sequential and linear techniques, such as Fault Tree Analysis and Causal Tree Method, are less resource intensive and easier to apply. Consequently, they have been widely used in practice. However, studies have suggested that these techniques do not effectively capture how human, management and organisational elements combine and contribute to accidents, and can lead to identification of easy-to-find causes and ignore less evident organisational (latent) factors that contribute to accidents.

Conclusion

The advantages and limitations of different accident models and investigation techniques suggest that there may be benefits in integrating or combining features of different techniques to capture different aspects of the accident problem and improve accident investigation outcomes.

A range of different strategies was identified that organisational decision-makers may consider when planning accident investigations. These are:

- Using different techniques during the investigation process can help the investigators to draw on the strengths of different techniques based on the requirements of their organisation and the accident situation.
- Applying multiple techniques can both improve the breadth of the investigation and address the bias that reliance on one perspective can entail.
- The selection of a technique to use, in part, depends on different factors including the aim of investigation, available resources, the investigators' knowledge and familiarity with different techniques, and an assessment of the complexity and/or severity of an accident. Therefore, organisations may choose to provide "scalable" investigation techniques; including some that are simple and flexible (e.g. Change Analysis, Barrier Analysis, Causal Tree Method), and others that are more in-depth (e.g. Swiss Cheese Model, ICAM, AcciMap).
- The techniques may also need to be adapted, combined and tailored to specific contexts and local needs in order to better meet the specific needs of practitioners in different domains. For example, domain specific knowledge and taxonomies can be integrated into generic systemic techniques such as AcciMap.
- Organisations may establish a process to review investigation quality to ensure that objectives are being met and information that is produced is of high quality, reflects the range of factors involved in an accident and can be used for prevention purposes and organisational learning.
- Organisations need to consider whether the accident investigation technique selected for use allows for the identification of latent factors including system design, management and organisational inadequacies and oversights. The resolution of these distal issues within an

organisational environment can help prevent a larger class of accidents than focusing attention on immediate (easily identifiable) causal factors.

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Introduction

The selection of an accident investigation technique is not a simple process. A multitude of techniques for accident investigation exist, each of which has its own theoretical and practical benefits and drawbacks. Furthermore, individuals engaged in accident investigation are constrained or influenced by factors, e.g. budgetary and time constraints, which can influence their selection and application of a technique.

This review considers the most widely used theoretical models of accident causation, before identifying the characteristics and usage of different accident investigation techniques. It is not a comprehensive review but considers the application, strengths and limitations of the most frequently documented accident investigation techniques.

Aim and objectives of the review

This review aims to identify the widely used accident investigation techniques and understand their characteristics and applications. During the review, the following objectives were pursued:

1. To identify the most frequently used techniques for accident investigation in selected industries, including aviation, nuclear energy, transport, maritime, oil and gas and chemical processing,
2. To understand the characteristics of the techniques in terms of how they conceptualise and represent accident causation,
3. To identify the relevant leading agencies in the six areas and examine what safety accident investigation techniques are being used or recommended by these agencies, and
4. To provide examples of the application of safety accident investigation techniques from previous studies and credible published sources.

Structure of the report

This report is structured as follows:

- The remainder of the 'Introduction' section provides an overview of accident investigation process as well as a general review of major accident causation theories and models.
- The 'Methods' section presents a description of how different investigation techniques were identified and reviewed.
- The 'Results' section describes techniques, their characteristics and applications.
- The 'Discussion' section provides an over-arching discussion of results from comparison of different techniques.
- The 'Conclusion' section summarises the findings and highlights some considerations for organisations when choosing what technique to apply in an accident investigation.

- The 'References' section presents a list of reference material used to inform this review.

The Accident Investigation Process

There are different reasons why an individual or an organisation chooses to initiate the investigation of an accident. The following reasons are identified by Novatsis and Wilkinson (2016) and UK's Health and Safety Executive (HSE, 2004):

- to understand contributing factors and causal mechanisms involved in accidents and prevent re-occurrence,
- in pursuit of regulatory, insurance, and organisational requirements,
- as part of monitoring an organisation's Safety Management System (SMS) to measure performance and evaluate risk management effectiveness,
- to identify deviations from what is specified in a SMS,
- to indicate a commitment to a positive safe culture and continuous improvement,
- to learn how work is actually being done, as opposed to what is presumed or specified by procedures and other formal SMS arrangements, and
- to enable wider organisational learning and learning transfer e.g. to other sites or other organisations.

Work Health and Safety Inspectors are given specific functions and powers under part 9 of the Model WHS Act 2011 (Cth), [legislated in NSW as the Work Health & Safety Act 2011 (NSW)] and include the function and power to investigate contraventions of the Act and assist in the prosecution of offences.

In NSW, statutory powers allow inspectors to enter and inspect a workplace, to provide information and advice, assist with issue resolution, issue or review WHS improvement notices, and investigate breaches of the WHS Act. Inspectors can prohibit unsafe work practices (by issuing a prohibition notice) and non-disturbance of an incident site to facilitate an investigation.

The selection and application of an accident investigation technique may depend upon the conditions relating to Inspectors' compliance powers and what they are permitted to do under WHS legislation, for example, powers to enter a workplace, to inspect, examine and make inquiries at the workplace, take measurements, samples, recordings etc.

Importantly, what is allowed during a workplace inspection varies between jurisdictions (Diamond, Redmond, & Robertson, 2020). Inspectors' powers and conditions specified by legislation may therefore be an important consideration in the selection of an investigation technique to use in the event of a workplace accident.

The key stages of an accident investigation are the detection and reporting of events, data gathering, the analysis of findings, writing recommendations, and sharing lessons learned (Novatsis and Wilkinson, 2016). These stages can be broken into the steps illustrated in Figure 1.

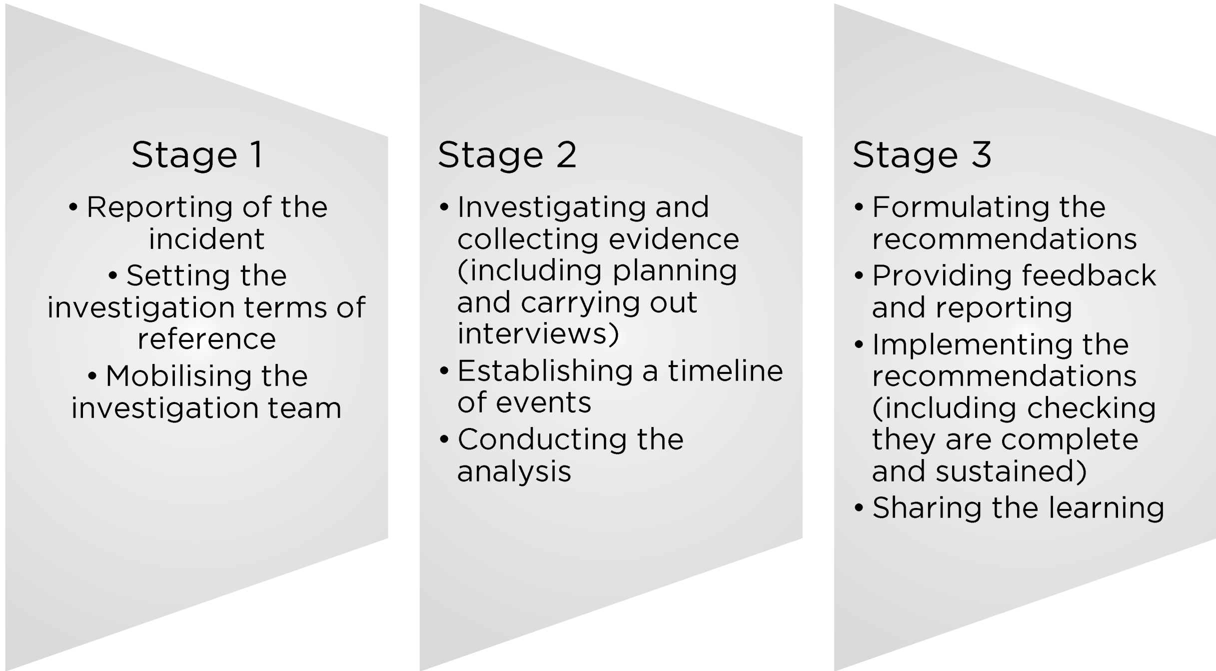

Figure 1: Detailed steps of an investigation process (adapted from Novatsis and Wilkinson (2016))

According to the Centre for Chemical Process Safety (CCPS) there are three main functions of techniques for accident investigation. The first function is to organise information about the accident once evidence has been collected. The second is to help in describing accident causation and developing hypotheses for further examination by experts, and the last is to help with the assessment of proposed corrective actions. In addition, the analytical techniques may also ensure that the results are transparent and verifiable (CCPS, 2010).

Accident investigation techniques are often classified based on the conceptual foundation that underpins them (see e.g. Kjellén, 2000; Hollnagel and Speziali, 2008; Qureshi, 2008; CCPS, 2010). These conceptual foundations reflect different positionings in relation to how and why accidents occur and will influence the selection and function of corresponding investigation techniques as well as investigation outcomes. It is therefore useful to understand the major theoretical perspectives on accident causation before reviewing accident investigation techniques.

Conceptualising accident causation

Single causes of accidents

The evolution of accident causation theories began with the identification of individual factors as direct causes of accidents. Early theories, in the 1920s, took a primitive and individual-related perspective on accident causation. These theories held an individual's unsafe behaviour and personal traits responsible for causing an accident. For example, Accident Proneness theory is an early theory suggesting that individuals with certain personality traits are more likely to be involved in accidents than the rest of workforce (Greenwood and Woods, 1919). The theory highlights the role of transient personal factors such as stress, socio-psychological make-up of an individual, safety culture, work environment, and previous involvement in accidents in explaining accident proneness (Khanzode et al., 2012). From this perspective, individuals are identified as direct and sole causes of accidents, blame is put on an individual rather than the broader work environment, and behavioural interventions are advocated for preventing accidents.

Sequences of causes to accidents

Sequential models recognised the involvement of multiple causal factors in accident causation and represented them in a sequential (linear) manner with a specific order. While earlier models tended to include a single sequence of events/causes, later models began to incorporate multiple sequences of events/causes in an accident path.

A single sequence of causes

A well-known sequential model was proposed by Heinrich in 1930s. Heinrich used the concept of dominos to propose one of the first sequential accident causation theories. In his "domino theory", Heinrich identified a chain of sequential events, represented as dominos, leading to an accident (Heinrich, 1932). Based on Henrich's perspective, accidents can be prevented by breaking the chain of events, that is, by removing any event from the sequence. Domino theory identifies five sequential pieces in accident causation:

- Social environment and ancestry which are natural and environmental flaws in an individual's life or family that can affect an individual's ability to acquire workplace related knowledge and skills
- Faults of a person which are negative personal traits (such as ignorance and recklessness) which can lead to an unsafe behaviour or situation
- Unsafe act or condition, including errors or conditions (such as a technical failure or a physical hazard) which can lead to accidents
- Accident, the undesired event which can lead to injury or damage, and
- Damage or injury, which is the consequence of accidents.

While identifying a sequence of multiple causal factors was an improvement over the single cause models, domino theory still focuses on the individual (human) as the main cause of accidents and proposes behavioural interventions aimed to prevent unsafe acts and conditions. Nevertheless, domino theory has been the foundation of other subsequent theories and models which emphasise the role and responsibility of a management system. For example, Bird and Loftus (1976) replaced the first domino (ancestry and social environment) with management's lack of control. They also added basic causes (personal and job factors) and immediate causes (substandard practices, conditions or errors) to the sequence of dominos.

Although sequential models such as the domino model represent the process of accident development from an "initiating event", these theories have been criticised for being too deterministic by not taking into account multiple sequences of events or complex interactions between numerous causes that can lead to accidents and injuries (Hollnagel, 2001; Qureshi, 2008). Further, focusing on only five events narrows the focus of the domino model and leads to the identification of unsafe acts as the ''easiest-to-blame'' factor, leaving unsafe conditions generally unattended and overstating the role of behavioural interventions when unsafe conditions demand more attention by management (Khanzode et al., 2012).

Multiple sequences of causes

The next generation of models were more complex but still linear and represented accident causation as a linear combination of proximal factors and higher-level organisational or environmental conditions. These models are also referred to as "complex linear" models (Pryor and Capra, 2012).

<u>Multiple chains of events</u>: These models describe accidents in terms of multiple sequences of events which reflect components failure, human error or energy transfer (Qureshi, 2008). The sequences are often represented as trees (e.g. event trees, logic trees and cause trees) or as networks of events (e.g. Multilinear Event Sequencing) (Lehto and Salvendy, 1991). These models depict a clear view of how interrelated events lead to an accident in relatively simple systems; however, they do not effectively capture how human, management and organisational elements combine and contribute to accidents (Underwood and Waterson, 2013).

The Multilinear Event Sequencing (MES) model (Benner, 1975) is an example of this type of models. In MES, events reflect actions undertaken by actors. The model captures different chains of events and their associated conditions and places them on a timeline. The resulting network indicates how events combine chronologically and lead to accidents. However, the model (and similarly other event-based sequential models) only account for linear causality. Selecting the first event that initiates the chain of events is often "arbitrary" and may lead to the selection of events which are familiar to the investigator, can be corrected, or those events which do not raise difficulty or political disputes (Leveson, 2001). Further, Qureshi (2008) states that building and analysing these models can take time and require extensive expertise.

Energy-damage model: A famous complex linear accident model is the energy-damage model (Viner, 1991). Viner proposed that damage occurs when an unwanted and harmful energy source is transferred unexpectedly to a recipient and the intensity of impact (energy) exceeds the recipient's damage threshold (Viner, 1991). Based on this model, identifying and controlling the potentially harmful energy (e.g. by physical containment, barriers, or procedures) will eliminate or reduce the latent conditions of the unsafe recipient in an unsafe place; thus, preventing an injury or damage.

Epidemiological accident models: These models were derived from the study of disease epidemics and use a similar analogy to represent injury patterns. These models explain an accident instance as the consequence of interactions between three key factors: the host (victim), the agent (deliverer of injury), and the environment (setting) in which host and agent are situated (Gordon, 1949; Khanzode et al., 2012). The environment can include psychological, social and organisational factors. Thus, these models encourage the user to consider distal factors in accident causation and provide a more comprehensive conceptualisation of accidents when compared to the earlier sequential models; yet, they still indicate cause-effect principles in a linear fashion to describe accidents (Hollnagel, 2004; Underwood and Waterson, 2013).

Epidemiological analogy has been the basis for developing different accident causation models. For example, Reason (1987) suggested the presence of destructive causal factors which can lie dormant in a system for some time (similar to the pathogens in human body) before an accident sequence begins (Reason, 1987, p.197). These factors were subsequently termed "latent conditions" in Reason's famous Swiss Cheese model.

Swiss Cheese Model: One of the most popular accident models, which is widely adopted in practice, is the Swiss Cheese Model introduced by Reason (1997). Reason's model (Figure 2) highlights the multi-causality of accidents and represents them as a consequence of alignment between latent conditions and active failures. In his model, Reason recognises the contribution of higher-level organisational factors to accidents, but his model depicts a sequential trajectory from higher-level factors (latent conditions) to lower-level factors (i.e. active failures) and accidents. This is indicated by a path which starts from a hazard or danger, passes through gaps in different layers of defence and leads to an accident. The gaps in defences are created by latent conditions and active failures.

Active failures are the immediate observable causes in an accident which are easily identified, such as unsafe work practices and cutting corners. Latent conditions are hidden problems in organisation and workplace systems that may be present, yet unidentified, for many years. Some examples of latent conditions are poor management practices, gaps in supervision, lack of training, priorities and decisions that lead to unrealistic work schedules, poor maintenance, and under staffing to name a few. The presence of these conditions in the organisation represents the inadequacy/absence of defensive barriers, such as training and procedures, which aim to prevent accidents (Underwood and Waterson, 2014).

Accidents happen when the gaps in control defences align sequentially from organisational factors, to local workplace conditions, to individual (or team) unsafe acts, to failed defences and bad outcomes. According to Reason, to avoid accidents, the proactive involvement of top management is essential to improve the defences. However, keeping the model generic, Reason does not specify what the gaps and defences represent in his model and leaves it to the analysts to identify them in specific cases they deal with.

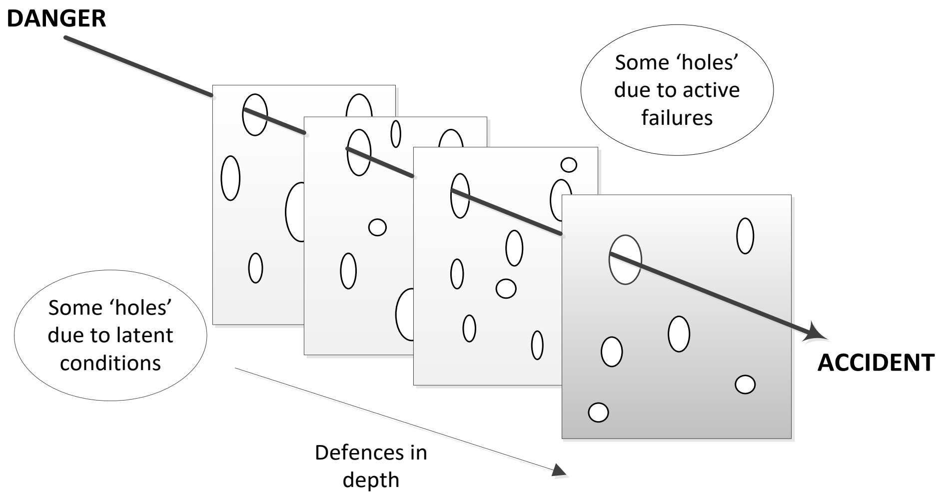

Figure 2: Swiss Cheese Model (after Reason, 1997)

Like most other models, the Swiss Cheese Model has been both commended and criticised. Critics of this model highlight its sequential, static, and therefore over-simplistic, view on accident causation (e.g. Hollnagel, 2012; Leveson, 2012). It has been stated that the model promotes a reductionist and linear perspective that fails to provide a holistic representation of systems as dynamic and adaptive entities, as proposed by systems theory (Grant et al., 2018; Leveson, 2011). In contrast, proponents of Reason's model suggest that the recognition of the influence of latent conditions on shaping accidents embodies (although implicitly) some basic elements of systems theory, which are found in contemporary systemic investigation techniques (Underwood and Waterson, 2014).

Linear causality in modern work systems

A number of researchers have argued that linear sequential models cannot represent the complex dynamics and interdependencies commonly observed in modern socio-technical systems (Herrera and Woltjer, 2010). Leveson (2011) states that sequential theories and models, oversimplify the accident process and exclude the systemic and non-linear aspects involved in accident development. This is because traditional theories of accident causation assume that accidents in complex systems are caused by sequences of causal events which are initiated by a "root cause" event, such as failure of equipment or unsafe human actions (Underwood et al., 2016). However, Leveson explains that sometimes accidents happen as a result of interactions between different factors or components which individually are fine, but do not fit well with each other; hence, the problem may lie in the interactions between a group of mismatched components or factors. These interactions and relational causes are not captured in sequential and chain-of-events models, which assume linear paths of failure leading to accidents (Leveson, 2011).

Systemic models of accident causation

In the 1980s, accident causation theories adopted concepts from systems theory to account for the complex interactions between contributing factors. The complexity of modern socio-technical systems and the environments in which they operate means that preventing accidents and maintaining safety do not involve a straightforward or linear process, but instead are driven by a complex web of interactions between human behaviour, technology and their environment (Underwood and Waterson, 2014). In these high-tech systems, accidents emerge as complex phenomena within the normal operational variability of perfectly functioning components (de Carvalho, 2011). Hence, accidents cannot be easily anticipated, and guarded against by monitoring and preventing the failure of individual components. In complex systems, system properties (including safety) emerge from the interactions between the components of the system, that is, how the parts fit together and cooperate (Ackoff, 1971). According to Leveson (2002), this type of component interaction accident is becoming more prevalent as the complexity of system designs increases.

Leveson further explains that work systems are not static and accidents within these systems tend to involve a migration to a state of high risk over time. If the high risk is not detected and reduced, the system will reach a point when an accident would be almost inevitable. Avoiding accidents therefore requires understanding and preventing system migration to a state of higher risk. This, in turn, requires models which look beyond just the events and conditions and capture the complex processes involved in shaping accidents (Leveson, 2011) and include factors residing at all levels of complex socio-technical systems and interactions across them (Salmon et al., 2012).

Putting forward the same reasoning, Rasmussen (1997) suggested a hierarchical framework to conceptualise a work system. The system comprises different organisational levels, including (from top to bottom) government, regulators, company, management, staff and work process. Each level is more complex than the level below and has emergent characteristics which do not relate to the lower levels. Safety is maintained by explicitly identifying the boundaries of safe operation, making them known to the individuals and allowing them to learn to cope with the boundaries. To achieve this, each upper level in the system imposes constraints on the lower levels by defining control processes and actions, and also receives feedback from the lower levels about the safety status and effectiveness of the control actions. Hence, Rasmussen views safety risk management as a control problem rather than a failure problem. While Rasmussen's framework has been the foundation for other socio-technical system models such as AcciMap, some researchers, for example Katsakiori et al. (2009), believe that the approach is most suited for complex and high-tech organisations because of its sophistication.

Using concepts of systems theory, it is possible to conceptualise a system holistically. In this approach, accidents are viewed as a system-level phenomenon resulting from unexpected, uncontrolled relationships between system components (Underwood et al., 2016). A systemic view is preferred because it reveals how the whole system dynamically transforms and adjusts its state to continue its safe operations; thus, emphasis can be put on proactive safety management (Hovden et al., 2010).

Traditionally, systems have been studied by deconstructing them into their constituting parts and each component is studied individually. This traditional scientific (reductionist) approach assumes that each component operates independently, the relationships between components are simple and straightforward, and that the behaviour of the system can be understood as a collection of characteristics and events across system components over time. However, these assumptions do not hold for complex socio-technical systems (Lindberg et al., 2010; Herrera and Woltjer, 2010).

Unlike the traditional approach, the systems approach focuses on a system as a whole and assumes that some system characteristics can only be understood sufficiently in their entirety, taking into account both the social and the technical aspects of the system and the relationships between them. This approach facilitates the examination of emergent system properties, such as safety (Leveson, 2011) and their results, e.g. accidents (Grant et al., 2018).

Using systems approach as the conceptual foundation, new types of conceptual models and investigation techniques have been developed. These models go beyond looking at failure events and unsafe actions. Instead, they attempt to look at a system as a whole entity and explain the processes and non-linear component interactions that shape system behaviour and push it towards high-risk states. This information can be used retrospectively to understand how accidents happen. It can also be used to prospectively detect and prevent the increasing risk, by devising suitable controls, making trade-offs between competing goals and control requirements, or refining the system design, before a loss happens (Leveson, 2011). Examples of widely-recognised systemic accident investigation techniques are: AcciMap (Rasmussen, 1997), Human Factors Analysis and Classification System (HFACS) (Wiegmann and Shappell, 2003), Systems Theoretic Accident Modelling and Processes model (STAMP) (Leveson, 2004), and the Functional Resonance Analysis Method (FRAM) (Hollnagel, 2004).

Method

The sources selected for this review study underwent three stages of examination as follows:

Stage I: a systematic desktop search of six major databases was conducted: Google Scholar, Scopus, PubMed, Wiley Online Library, Water Resource Abstracts (ProQuest) and Web of Science. The keywords used were: "accident investigation technique", "incident investigation techniques" and "accident causation and analysis". The names of study techniques and industries were also used for keyword searching. The desktop search resulted in 79 research outputs including journal articles, peer-reviewed conferences papers, industry reports and guidelines, and academic theses. To ensure that relevant sources were captured, the selected sources' references were also explored. At the end of this stage, 111 sources were obtained and their titles and links to their full-text versions were listed in a database to undergo the second stage of review.

Stage II: the sources obtained in the first stage were analysed and those with highly relevant contents were shortlisted and their full texts were downloaded. In particular, any source that had not fully described the application of an accident investigation technique was excluded from further investigation. The full text of selected sources was subsequently coded and archived for the third stage of examination.

Stage III: The third stage of examination involved checking the selected sources against three selection criteria: (1) application of one or more accident investigation techniques in at least one of the six target industries; (2) whether it clearly described the application of the original version of investigation techniques; and (3) if it employed the widely accepted investigation techniques. Those sources that did not meet these criteria were excluded from further consideration.

Data processing and analysis

The literature that was screened through stages I to III was analysed and classified in four steps as follows:

1. The most widely used or suggested techniques for accident investigation in various high-risk industries were identified.
2. Various characteristics of the techniques identified in step 1 were examined and summarised. These characteristics included: factors and aspects considered by the technique, accident modelling approach, examples of application areas, their underpinning conceptualisation, agencies that suggest or refer to each investigation technique, and references to practical applications or guidance material for users.
3. Examples of the application of techniques into case studies were identified and a link to the relevant source was provided. In addition, the accident models that navigate the functionalities of these techniques (i.e. sequential, epidemiological and systematic) were identified in this step.

4. Studies that conducted comparative evaluations between different investigation techniques in various high-risk industries were identified and the reasoning (if any) for recommending a preferred technique(s) over others was provided.

Results

Identified techniques of accident investigation

The desktop research resulted in the collection of 36 investigation techniques across various high-risk industries. A summary description of these techniques is provided in Table 1. A more comprehensive view of the techniques and their characteristics and applications is provided in Appendix 1 by combining Tables 1 and 2 in this section. Several of the techniques tabulated below were further extended to suit the requirements of various accident investigations and industries. For instance, a new technique was developed in the TRIPOD family (TRIPOD TRACK) by changing the framing of the question 'what happened?' to 'what made it happen?' (Verhoeve et al., 2004).

For the ease of evaluation and comparison between the investigation techniques, only fundamental and comparable information is provided. This information provides an understanding regarding the functionality and the purpose of the application of these techniques. Where possible, the steps involved in the application of the techniques are also presented. The description for each technique can tentatively guide the process of selecting suitable technique(s) for an accident investigation. Generally, technique selection takes place in accordance with the context of a particular accident and the purpose of the accident investigation.

Table 1: Various accident investigation techniques irrespective of their specific application

Acronym	Technique's extended name	Description	Reference
AcciMap	Accident Analysis Technique	The AcciMap approach is a systems-based technique for accident analysis, specifically for analysing the causes of accidents that occur in complex sociotechnical systems. The approach is not domain-specific and has been used to analyse accidents in a range of industries including aviation, defence, oil and gas, public health risk management, and rail transport. The AcciMap approach is useful for uncovering how factors in the various parts of the system contributed to an accident, and for arranging those factors into a logical causal diagram that illustrates how they combined to result in that event. The technique also promotes a systemic view of accident causation as the AcciMap diagram extends well beyond the most immediate causes of the event to reveal the full range of higher-level factors that contributed to the outcome. The AcciMap approach involves the construction of a multi-layered causal diagram in which the various causes of an accident are arranged according to their causal remoteness from the outcome (depicted at the bottom of the diagram). The precise format of the diagram varies depending on the purpose of analysis, but the lower levels typically represent the immediate precursors to the event, relating to the activities of workers and to physical events, processes and conditions that contributed to the outcome.	Rasmussen (1980)

Acronym	Technique's extended name	Description	Reference
AEB	Accident Evolution and Barrier Function model	The Accident Evolution and Barrier Function (AEB) model provides a technique for analysing accidents. It models the evolution towards an accident as a series of interactions between human and technical systems. The main principle is that it is possible to stop/interrupt the development of the sequence between any two successive errors (human or technical) through adequate barrier functions. Barrier function systems might consist of an operator, an instruction, an emergency control system, etc.	Svenson (2001)
ATSB	Australian Transport Safety Bureau Investigation Analysis Framework	ATSB provides a general framework, including an investigation analysis model, that can guide data collection and analysis activities during an investigation. It is a variation of Reason's Swiss Cheese Model. The model represents the operation of a system via five levels of "safety factors", where a safety factor is an event or condition that increases safety risk. The layers include "occurrence events", "individual actions", "local conditions", "risk controls" and "organisational influences".	Australian Transport Safety Bureau (2008)
BA	Barrier Analysis	Barrier analysis is used to identify hazards associated with an accident and the barriers (control) that should have been in place to prevent it. Barriers are put in place to prevent a hazard from reaching a target.	De Dianous and Fievez (2006)
CA	Change Analysis	Change analysis examines planned or unplanned changes that cause undesired outcomes. This technique is used to examine an accident scenario by comparing what occurred during the accident process with what has occurred before or what was expected to occur.	U.S. Department of Energy (1999)
CREAM	Cognitive Reliability and Error Analysis Method	CREAM is a technique used in Human Reliability Analysis to assess the probability of human error during a specific task. The result can inform measures to reduce the likelihood of errors and improve the overall levels of safety.	Hollnagel (1998)
CTM	Causal Tree Method	CTM, also called the INRS technique, is a Tree Technique. Using CTM, a causal tree is constructed by moving backwards from an accident and identifying factors and deviations from specified processes which have contributed to the accident. The tree indicates the causal relationships between these factors and the accident.	Leplat (1978)
ECF Chart	Events and Causal Factors Charting	ECFC is a charting technique to map the sequence of events involved in an accident. The technique is used to organise and display the events chronologically.	U.S. Department of Energy (1999)
ECFA	Events and Causal Factors Analysis	ECFA is an initial step in determining the root causes of an accident. It involves deductive reasoning to identify the events and conditions which have contributed to the accident. It is often used in conjunction with other tools, such as MORT, tree analysis, change analysis, and energy trace and barrier analysis, to achieve optimum results in from the investigation.	U.S. Department of Energy (1999)
FRAM	Functional Resonance Analysis Model	FRAM is based on a description of system functions and their possible variability. It describes how the variability of multiple functions may combine in unexpected ways and resonate, resulting in the variability of some functions to exceed normal limits and leading to accidents.	Hollnagel (2012)

Acronym	Technique's extended name	Description	Reference
FTA	Fault tree analysis	Using FTA, the possible failures that can contribute to an adverse event are identified and diagrammed as a tree. The adverse event is placed at the top of the tree; hence, it is called the top event. The tree shows logical connections and causes leading to the top event. Two logic gates (the AND and OR gate) are used to relate the combinations of preceding events and conditions to the top event.	Ferry (1988)
HERA	Human Error in Air Traffic Management	Human Error in Air Traffic Management focuses on the cognitive processes of air traffic control operators to identify and quantify the impact of the human factor in accident investigation and safety management. HERA is based on the view that human error is the primary contributor to accidents. The technique has two modes. A retrospective part for accident analysis and a prospective part for assessing human error probabilities.	Eurocontrol (2003) Issac et al. (2002)
HFACS	Human Factors Analysis and Classification System	HFACS was developed as a taxonomy-based aviation accident analysis approach. It identifies the human causes of an accident and provides a tool to not only assist in the investigation process, but to target training and prevention efforts. HFACS looks at four levels of human failure, referring to the Swiss Cheese Model. These levels include unsafe acts (operator error), preconditions for unsafe acts (such as fatigue and inadequate communication), unsafe supervision (such as pairing inexperienced aviators for a difficult mission), and organisational influences (such as insufficient flight time because of budget constraints).	Shappell and Wiegmann (2000)
HFIT	Human Factors Investigation Tool	HFIT is a theoretically based technique to assist with the investigation of the human factors causes of accidents in the UK offshore oil and gas industry. It classifies human factors information into four types: (a) the immediate action errors, (b) error recovery mechanisms, in the case of near misses, (c) the thought processes leading to the action error and (d) the underlying causes.	Gordon et al. (2005)
HINT – J-HPES	HINT – J-HPES	HINT is based on J-HPES, the Japanese version of INPO's Human Performance Evaluation System (HPES). The principle underlying this technique is to use a root cause analysis of small events to identify trends and use as a basis for proactive prevention of accidents. The steps involved are: Step 1: Understand the event Step 2: Collect and categorize causal factors Step 3: Root cause analysis Step 4: Proposal of countermeasures to prevent reoccurrence	Takano et al. (1994)
HPES	Human Performance Enhancement System	HPES was developed with sponsorship by the Institute of Nuclear Power Operations (INPO). The technique has a particular emphasis on human performance aspects. It incorporates different tools such as task analysis, change analysis, barrier analysis, cause and effect analysis, and event and causal factor charting. HPES has been the basis for other methodologies for other context-specific requirements. HPES has been adapted by other countries since its development in the United States. For example, K-HPES has been developed and used in Korea, and J-HPES in Japan.	INPO (1989)

Acronym	Technique's extended name	Description	Reference
HSG245	Health and Safety Executive (HSG245)	HSG245 is a workbook developed in 2004 by the HSE as a step-by-step guide for employers, unions, safety representatives and safety professionals to undertake health and safety investigations. The guide provides specific structured questions. The aim of the analysis is to find immediate, underlying and root causes. Immediate cause can be the agent of injury, underlying causes are unsafe acts and conditions, and a root cause is an initial failure or event from which all other failures arise. A checklist to assist with identifying underlying and root causes is also provided.	Health and Safety Executive (2004)
ICAM	Incident Cause Analysis Method	A fundamental concept of ICAM is acceptance of the inevitability of human error. ICAM is designed to ensure that the investigation is not restricted to the errors and violations of operational personnel. It identifies the local factors that contributed to the accident and the latent conditions within the system and the organisation. Through the analysis of this information, ICAM provides the ability to identify what really went wrong and to make recommendations on what needs to be done to prevent recurrence. It is directed towards building error-tolerant defences against future accidents. Therefore, ICAM provides a process to move beyond the idea of a single root cause and identify a range of immediate causes, contributing factors and underlying causes. ICAM is widely used in mining industry.	Reason (2016) De Landre et al. (2007) Patterson (2009)
ISIM	Integrated Safety Investigation Methodology	ISIM was developed in 1998 by the Transportation Safety Board (TSB) of Canada and it follows Reason's accident causation model. The technique starts with the collection of information regarding personnel, tasks, equipment and environmental conditions involved in the occurrence in order to determine the sequence of events and identify underlying factors and unsafe conditions. The next step is to assess the level of risk associated with such unsafe conditions or underlying factors and examines the status of barriers (physical or administrative) in order to identify those that are less than adequate. ISIM forces the investigator to look beyond the actions and decisions of front-line operators and into the latent unsafe conditions in the work system that provided the opportunity for the expression of those actions. Once the safety deficiencies have been identified, options for controlling risk have to be considered. The goal of ISIM is to ensure that both accident investigation and safety deficiency analysis are integrated. The risk control option analysis is a key step of ISIM aiming at generating recommendations and strategies for safety improvement.	TSB (1990)

Acronym	Technique's extended name	Description	Reference
MES	Multi-linear Events Sequencing	MES is a charting technique, which shows events chronologically ordered on a time-line basis. It is based on the view that an accident begins when a stable situation is disturbed. A series of events can then lead to an accident. The technique distinguishes between actors, actions and events. Actors can be people, equipment, substances while actions are anything carried out by an actor. Events are the unique combination of one actor plus one action. The technique helps the analyst to identify the main actors and their actions and map the relations between the events along a flexible timeline. The final product is thus an accident logic chart with the events, actors and actions sequentially placed	Benner (1975)
MORT	The Management Oversight and Risk Tree	MORT is an analytical procedure for determining contributing factors and causes to accidents. In MORT, the accident is defined as an unwanted energy transfer due to the inadequacy of energy barriers and/or controls. The technique follows the energy transfer and deviation concepts. It involves identifying hazardous forms of energy and deviations from the planned and normal production process. The MORT diagram is a logic tree (the accident being the top event) with three main branches: S-factors, the specific oversights and omissions associated with the accident being investigated, R factors or assumed risks, which are risks known but for some reason not controlled, and M-factors, which are general characteristics of the management system that contributed to the mishap. The various elements in the tree are numbered and these numbers refer to a list with specific questions that the analyst should pose. Analysis involves going through all elements in the tree and making an assessment of each, based on two assessment levels: "satisfactory" and "less than adequate" (LTA), in order to examine the adequacy of measures. The technique includes a large checklist to help investigate the facts and look for evidence, it permits a large number of problems to be identified and it prompts the investigator to look not only for direct causes, but also for causal contributions at the management and organisation levels.	Johnson (1973)

Acronym	Technique's extended name	Description	Reference
MTO-analysis	Man, Technology and Organisation	The basis for the MTO-analysis is that human, organisational, and technical factors should be considered equally in an accident investigation. MTO analysis was originally developed for accident investigation in the nuclear industry. The technique is based on HPES (Human Performance Enhancement System). An accident investigation technique often labelled MTO Analysis has been applied in different fields in the Scandinavian countries. One advantage of the technique is that it gives a graphical overview of the course of an accident and the influencing factors. The MTO-analysis is based on three techniques: • Structured analysis by use of an event- and cause-diagram • Change analysis by describing how events have deviated from earlier events or common practice • Barrier analysis by identifying technological and administrative barriers, which have failed or are missing	Rollenhagen (1995) Hollnagel and Speziali (2008)
NSB	Norske Statesbaner	NSB was developed by the Norwegian State Railways (Norske Statesbaner – NSB) for the analysis of accidents in the railway sector. The technique combines the approaches of both Reason and Hollnagel and focuses on human, technical and organisational interaction. Using NSB, a sequence of events is identified which lead to an accident. NSB uses a questionnaire which focuses on factors such as procedures, training, communication, human-systems interface, tools and equipment, work preparation and local management, organisational management, and work environment.	Skriver et al. (2003)
OARU	Occupational Accident Research Unit-Deviation Analysis	OARU was developed for the Occupational Accident Research Unit (OARU) of the Royal Institute of Technology in Stockholm – Sweden. The technique involves two levels of reasoning: describing the accident sequence and finding the determining factors. The accident sequence has three phases: the initial (deviations from the normal process), the concluding phase (loss of control and uncontrolled flow of energy), and the injury phase (energy meets the human body and causes physical harm).	Kjellen and Larsson (1981)
PEAT	Procedural Event Analysis Tool	PEAT was developed for the aviation industry. PEAT identifies key contributing factors to airline crew decisions. Remedial measures are then put in place to control the effects of contributing factors. The aim is to identify errors and to prevent the occurrence of similar errors in future. The tool includes database storage, analysis, and reporting capabilities.	Moodi and Kimball (2004)
RCA	Root Cause Analysis	Root cause analysis is a methodology. It includes a set of techniques based on the same approach to identify underlying deficiencies in a safety management system. A root cause is a deficiency or contributing factor that addressing it would prevent the same and similar accidents from occurring. Root cause analysis is a systematic approach based on core analytic techniques to determine the most important reasons for the accident.	IAEA (1999)

Acronym	Technique's extended name	Description	Reference
SAFER	Systematic Approach For Error Reduction	SAFER is a generic disaster analysis technique developed by the Tokyo Electric Power Company (TEPCO). This technique involves analysing causes of human error and identifying the mismatch between the surrounding environment and human characteristics. The technique involves eight procedures.	Yoshizawa (1999)
SCAT	Systematic Cause Analysis Technique	SCAT was developed by the International Loss Control Institute (ILCI). It originated from the Heinrich's domino theory and its updated version by Bird. It conceptualises an accident as a hierarchical sequence: loss (e.g. harm to people, properties, products or the environment), the accident event (the contact between the source of energy and the "victim"), the immediate causes and basic causes of an accident are the circumstances that precede the contact. They are called substandard acts/practices and substandard conditions.	Bird and Germain (1996)
SCM	Swiss Cheese Model	One of the most popular accident models, which is widely adopted in practice, is the Swiss Cheese Model introduced by Reason in 1990. It has been used in in healthcare, in the aviation safety industry, and in emergency service organizations. The model represents human systems as multiple slices of Swiss cheese arranged side by side. Absence or failure of risk controls are represented as holes in the slices. The model captures the multi-causality of accidents and represents it as an interaction between latent conditions and active failures. Latent conditions are hidden gaps in organisation and workplace systems that may be present, yet unidentified, for many years. Some examples of latent conditions are poor management practices, gaps in supervision and lack of training. Active failures are the immediate observable causes in an accident which are easily identified, such as unsafe work practices and cutting corners. Accidents happen when the gaps in control defences align sequentially from organisational factors, to local workplace conditions, to individual (or team) unsafe acts, to failed defences and bad outcomes.	Reason (2016) Reason (2000)
SHELL	Software, Hardware, Environment, Liveware	The SHELL was developed in the aviation context. The model focuses on human factors and the relationship between the aviation system environment and the human operator. It adopts a systems perspective and considers a range of contextual and task-related factors that affect operator performance.	Edwards (1988)

Acronym	Technique's extended name	Description	Reference
STAMP	Systems Theoretic Accident Model and Processes	This model was introduced by Leveson. STAMP takes a system perspective to represent accidents. It focuses on the interactions between system components as well as the control mechanisms used within the work system to limit these interactions. According to Leveson, safety is maintained by enforcing constraints on system behaviour. These constraints are sustained by loops of control actions and feedback information; thus, a state of dynamic equilibrium is maintained within the system. Based on STAMP, accidents result from inadequate enforcement of constraints in design, development and operations. That is, due to the inadequacy of controls structure, the system will not effectively handle any internal or external disturbance, such as a component failure or a disruption in interactions between system components.	Leveson (2004)
STEP	Sequentially Timed Events Plotting	STEP is a multi-linear approach that provides a systematic process for accident investigation. It takes on a process view of accident causation. An accident is viewed as a set of interacting events which happen in sequences or in parallel. An event is defined as an action performed by an actor. Normally, a flowchart is used to illustrate the accident process. The STEP process involves comparing the accident events with what was expected to happen.	Hendrick et al. (1986)
TRACEr	Technique for Retrospective Analysis of Cognitive Errors	TRACEr was initially developed for accident analysis in the air traffic control domain. Modified versions of TRACEr have also been used in other high-risk industries including railways and maritime. TRACEr is human error identification technique. It considers the human machine interface and external factors than might influence the operator's performance. Its taxonomy includes accident context, operator context and error recovery. Using TRACEr, the accident model is represented by a series of decision flow diagrams. Its application has been successful in analysing errors in Aircraft Proximity (AIRPROX) reports.	Shorrock and Kirwan (2002) Shorrock and Kirwan (1999)
TRIPOD Tripod-β	TRIPOD	TRIPOD was developed in for use in the oil and gas industry. It combines different theories of accident causation, including Reason's Swiss Cheese Model and human factor-oriented theories, to generate a single "TRIPOD tree" model. TRIPOD is based on the notion that unsafe acts are the direct causes of control/defence mechanisms in organisations, but active failures and unsafe acts are generated due to underlying organisational factors and mechanisms. The technique identified 11 categories of general failure types to classify deficiencies in a work system. The general failure types include human, organisational and technical factors. TRIPOD Beta is a computer-based tool that guides the investigator through the process of representing an accident as tree-like model.	Wagenaar and van der Schrier (1997)

Acronym	Technique's extended name	Description	Reference
WAIT	Work Accidents Investigation Technique	WAIT is a toolkit for the investigation of occupational accidents and near misses. It follows the theoretical concepts proposed by Reason and Hollnagel. WAIT comprises a technique and a classification scheme. The overall investigation process follows Reason's model by beginning from the active failures and progressing to the distal latent conditions. In addition, when analysing human failure, WAIT applies a classification scheme of human error modes which was adopted from CREAM. WAIT analysis is undertaken in two sequential stages starting with a simplified investigation followed by a second in-depth analysis. In the first stage, active failures, as well as their associated influencing factors in the working environment, are identified. The second stage involves an in-depth analysis of individual and job factors followed by the identification of organisational and management deficiencies. Overall, the two stages comprise nine sequential steps.	Jacinto and Aspinwall (2003)
WBA	Why Because Analysis	WBA is a generic accident analysis technique. It begins with describing an accident. An iterative process is then applied to identify the causes and establishing cause-effect links between them. Different formal tests are used to identify the causal links, e.g. the counterfactual test and the causal sufficiently test. The outcome is a graph representing the causal factors to an accident and the cause-effect links between them.	Ladkin and Loer (1998)

Further information on study accident investigation techniques

The second layer of information on the techniques identified in the previous section is presented in Table 2. This table summarises the characteristics of these techniques with a focus on the consideration of different investigation elements (i.e. human, organisation, environment, technologies and task), the modelling approach, the underpinning concept, and their application.

As highlighted in Table 2, each of these techniques places emphasis on a particular set of investigation elements. For instance, Accident Evaluation and Barrier Analysis (AEB) focuses on the interaction between humans (operator) and technologies (equipment). Accordingly, the information provided here can help the investigator to match the desired technique with the requirements of the investigation. The review showed that, in the majority of cases, these techniques consider human, organisation and technological factors that may have contributed to the occurrence of an accident.

The third column of Table 2 discusses the modelling approach, in terms of how causal information is collated and presented and what factors are emphasised in the collation and presentation of causal information. The techniques provide a wide range of outputs that need to be considered and matched to the purpose of an investigation when making a choice as to whether to use a particular technique.

The fourth column in Table 2 indicates instances of application of these techniques according to the evidence reviewed during this study. The techniques vary in terms of the extent to which they are generally applicable or focused on a particular context. For example, AcciMap was found to be applicable in a wide range of industries, whereas HPES is specifically designed to be used to investigate safety accidents in the nuclear energy industry. However, it is also noteworthy that even if a technique was developed for use in a particular context, it is possible that it may be effectively adapted for use in other contexts and industries.

The fifth column in Table 2 displays the theoretical concept underpinning each technique. Some of the techniques are based on a particular accident causation model while others draw on and combine ideas from more than one theoretical causation model (e.g. ATSB). The two last columns of the table provide more information on agencies that refer to each technique and, where possible, links are provided to guidance documents.

Table 2: Summary of characteristics of the accident investigation techniques

Technique	Aspects considered	Accident modelling approach	Application instances	Underpinning concept /model	Agencies referring to the technique	Links / references
AcciMap	It focuses on failures across the following six organisational levels: government, regulators, company, management, staff, and work process and surroundings.	AcciMap combines the classic cause-consequence chart and a multilevel organisational risk management framework. Using AcciMap involves the construction of a multi-layered causal diagram in which the various contributing factors to an accident are arranged according to their causal remoteness from the outcome (depicted at the bottom of the diagram).	Public health, Oil and gas, Construction, Aviation, Chemical industry, Electricity industry, Emergency services, Medical, Military, Maritime, Railway, road traffic, Space flight	Systemic models		Wienen et al. (2017) Waterson et al. (2017)
AEB	It models the evolution towards an accident as a series of interactions between human and technical factors. It considers the barrier function, and its structure, to control the development of accident.	AEB models an accident as a combination of interactions between human and technical systems. It describes the accident evolution in a flow diagram, indicating a sequence of steps belonging to either the human factors, organisational system or the technical system. Each step represents either the failure/ malfunction of a component or an incorrectly performed function within each system. The barrier function indicates how the development of the accident could be controlled.	Aviation, Chemical industry, Maritime, Railway, Nuclear industry	Linear causality	UK's Health & Safety Executive (HSE) American Institute of Chemical Engineers' Review Swedish Nuclear Power Inspectorate	Svenson (2000) Hollnagel (1999) Wienen et al. (2017)

Technique	Aspects considered	Accident modelling approach	Application instances	Underpinning concept /model	Agencies referring to the technique	Links / references
ATSB	It represents the operation of a system via five levels of “safety factors”.	It investigates the risk of an accident through five layers namely “occurrence events”, “individual actions”, “local conditions”, “risk controls” and “organisational influences”. The final output is presented as a chart that is based on AcciMap.	Railway industry	Reason’s accident causation model (SCM) AcciMap	Australian Transport Safety Bureau	Wienen et al. (2017)
BA	It considers hazards and the barriers (controls) that were missing, were defeated, or did not function as expected to prevent an accident.	The user classifies barriers that separate a hazard and a target (e.g. worker). The user identifies if each barrier prevents an accident, mitigates its harm, and if it can be defeated. The user also identifies the latent organisational conditions that can influence the barrier.	Energy industry, Nuclear industry		US’s Department of Energy International Atomic Energy Agency	U.S. Department of Energy (2012)
CA	It considers planned or unplanned changes that caused undesired outcomes.	It depicts a comparative model to identify differences between an accident sequence and the accident-free sequence (i.e. what has happened before or what was expected). Through the comparison, the causes of accident are identified. The results from a change analysis can stand-alone, but the results are most useful when they are combined with results from other techniques.	Energy industry, Nuclear industry		US’s Department of Energy International Atomic Energy Agency	U.S. Department of Energy (2012)
CREAM	It investigates three categories of individuals, technologies and organisations. These are the contributors to what ideally must be inferred in the case of an accident as opposed to what is observed.	Involves developing a graph of antecedent actions (functions) and conditions leading to an accident. There is a clear distinction between causes of human error and its manifestation.	Emergency Services, Medical, Nuclear industry, Railway industry, Road traffic	Cognitive systems engineering	Norwegian Public Roads Administration	Hollnagel (1998) Wienen et al. (2017)

Technique	Aspects considered	Accident modelling approach	Application instances	Underpinning concept /model	Agencies referring to the technique	Links / references
CTM	CTM is based on the assumption that accidents arise from variations in the normal process. These variations are caused by the individual, the task, the equipment and the environment.	It identifies the variations in processes and displays them in the analytic tree, showing causal relations in an event chain. The development of a tree starts with the accident in question.	Many types of accidents including Nuclear, Healthcare, Chemical	Sequential models	American Institute of Chemical Engineers' Review Institut National de Recherche et de Sécurité	Vasconcelos et al. (2013) Wienen et al. (2017)
ECF Chart	ECFC is used for any event investigation in which a timeline or sequence of events might apply. The initiating event can be equipment failure or related to human performance.	It involves producing a chronological display of events to portray an accident sequence.	Energy industry	Sequential models	US's Department of Energy	Buys and Clark (1995) U.S. Department of Energy (2012) Wienen et al. (2017)
ECFA	This technique is used for any investigation of a timeline or sequence of events and conditions leading to an accident	The output may vary depending on the requirements of the investigation. However, it is usual to include the event that compromises control and the event that makes the situation safe again.	Energy industry	Sequential models	UK's Institution of Occupational Safety and Health (IOSH)	Buys and Clark (1995) Kingston et al. (2004) Wienen et al. (2017)
FRAM	FRAM concerns with a description of system functions rather than its structure. It helps reveal how variability in human and technical functions can resonate to produce different and unexpected operating scenarios.	It displays non-linear propagation of variability in functions. Functions are described and linked to each other in terms of their input (I), output (O), preconditions (P), resources (R), time (T), and control (C).	Aviation, Medical, Air traffic management	Theory of functional resonance, systemic models		Hollnagel et al. (2014) Wienen et al. (2017)

Technique	Aspects considered	Accident modelling approach	Application instances	Underpinning concept /model	Agencies referring to the technique	Links / references
FTA	FTA represents the logical combination of technical factors and human actions which can lead to an undesirable top event.	The contributing factors to an accident are captured using a logic-tree in order to show the logical combinations of causes leading to an accident or failure.	Electricity industry, Emergency Services, Maritime, Nuclear industry	Sequential models Logic-tree	American Institute of Chemical Engineers' Review International Atomic Energy Agency The Dept. of Defence, USA.	Vesely et al. (1981) Wienen et al. (2017)
HERA	It considers the human factor in accident investigation, safety management and prediction of errors arising from new technology. It assumes that human error is the primary contributor to accidents.	HERA serves as a framework for capturing human error. It involves defining and classifying the error, developing a flowchart of error mechanism and its contextual conditions and capturing the detailed information in tables.	European Air traffic Services	Linear causality Human information processing models	European Air traffic Service organisations Eurocontrol	Pounds and Isaac (2002) Hallbert et al. (2006)
HSG245	Unsafe human act and conditions are regarded as the underlying cause. Root causes are generally management, planning or organisational failings.	The investigation starts with an adverse event and progresses through immediate causes (the agent of injury), underlying causes (unsafe acts and conditions) to reach a root cause.	Generic	Systemic models Swiss cheese model	UK's Health & Safety Executive	Health and Safety Executive (2004)

Technique	Aspects considered	Accident modelling approach	Application instances	Underpinning concept /model	Agencies referring to the technique	Links / references
HFACS	It investigates human factor in four levels: unsafe acts, preconditions for unsafe acts, unsafe supervision and organisational influences.	It produces a hierarchical chart starting from organisational influences (at top) and ending with unsafe acts.	Aviation Modified versions in: Railway, Maintenance, Maritime, Air traffic control, Military, mining	Swiss cheese model	US's Federal Railroad administration	Shappell and Wiegmann (2000)
HFIT	Investigates human influence on an accident in four levels: action error, error recovery mechanisms, thought processes, and underlying causes.	The four investigation levels (human factor types) are further broken down to 28 elements. Analysis starts with investigating elements related to action errors, followed by error recovery, situation awareness and threat.		Rasmussen's model of human malfunction	UK's Health & Safety Executive	Gordon et al. (2005)
HINT – J-HPES	The methodology is concerned with enhancing the identification of human performance issues.	The overall principle is to use a root cause analysis of small events to identify trends as a basis for proactive prevention of accidents. The technique comprises a number of steps. These are: Step 1: Understand the event. Step 2: Collect and classify causal factor data. Step 3: Causal analysis, using root cause analysis. Step 4: Proposal of countermeasures.	Electricity industry, Nuclear power	A variant of root cause analysis	Central Institute for Electric Power Industry (CRIEPI) in Japan US's Institute of Nuclear Power Operations	Hollnagel (2009)

Technique	Aspects considered	Accident modelling approach	Application instances	Underpinning concept /model	Agencies referring to the technique	Links / references
HPES	Although valid for all types of issues (technical, procedural, etc), the methodology is oriented to enhancing the identification of human performance issues.	It utilises event and causal factor charting. Barrier analysis, change analysis, and cause and effect analysis are graphically incorporated into the same chart. The integrated chart shows the direct causes, the root causes, the contributing causes, and the failed barriers, with their interconnections and dependencies.	Nuclear power		Institute of Nuclear Power Operations (INPO) American Institute of Chemical Engineers' Review	Wienen et al. (2017)
ICAM	It accepts the inevitability of human error to ensure that investigation is not restricted to human errors.	It proposes error-tolerant defences against future accidents by investigating local factors and latent hazards within the system and the organisation.	Aviation, Transport, Railway	Swiss cheese model	UK's Health & Safety Executive The Australian Transport Safety Bureau	De Landre et al. (2007) Patterson (2009)
ISIM	The technique starts with the collection of information regarding personnel, tasks, equipment and environmental conditions involved in the accident. It also looks into the latent unsafe conditions in the work system.	Creates a framework to ensure that both accident investigation and safety deficiency analysis are integrated to generate recommendations for safety improvement.	Aviation, Railway, Maritime, Energy	Swiss cheese model	Transportation Safety Board of Canada UK's Health & Safety Executive The Canadian Aviation Safety Board	Ayeko (2002) Wienen et al. (2017)
MES	It assumes that events result from the combination between one actor (human, equipment, substance) and one action.	It shows events in chronological order on a timeline basis where the relationships between them are identified. The final product is an accident logic chart with the events, actors and actions sequentially positioned.	Aviation, Transport	Sequential models Logic tree	US National Transportation Safety Board	Benner (1975) Wienen et al. (2017)

Technique	Aspects considered	Accident modelling approach	Application instances	Underpinning concept /model	Agencies referring to the technique	Links / references
MTO	Human, organisational, and technical factors should be focused on equally in an accident investigation.	The output includes details of factors contributing to an accident. The investigation procedure can be summarised in five steps: 1) Describe the chain of events 2) Search for causes and conditions 3) Identify barriers 4) Analyse consequences 5) Develop recommendations	Aviation, Chemical industry, Electrical industry, Emergency services, Medical, Maritime, Railway, Road traffic, Space flights	Complex linear causality Process models INPO's Human Performance Evaluation System	Swedish Nuclear Power Inspectorate	Wienen et al. (2017)
MORT	It prompts the investigator to look not only for direct causes but also for causal contributions at the management and organisation levels.	It forms a logic tree (with the accident being the top event). The tree has three main branches: S-factors (the specific oversights and omissions associated with the accident), R factors (i.e. assumed risks that are not controlled), and M-factors (inadequate characteristics of the management system). The model particularly displays an unwanted energy transfer due to inadequate energy barriers (controls).	Nuclear industry	Logic tree models Systemic models	UK's Health & Safety Executive American Institute of Chemical Engineers' Review	Knox and Eicher (1992) Kingston et al. (2009)
NSB	NSB focuses on human, technical and organisational factors as well as work environment.	It outlines the sequence of events which occur due to broken or missing barriers.	Railway	Human information processing models Systemic models	Norwegian State Railways	

Technique	Aspects considered	Accident modelling approach	Application instances	Underpinning concept /model	Agencies referring to the technique	Links / references
OARU	The technique recognises technical, organisational and social properties of the system that affect the accident sequence.	It looks into accidents from two angles: describing the event sequence and finding contributing factors. The event sequence involves initial, concluding and injury phases. The final product includes lists of deviations and accident determining factors.		Sequential accident causation models	Sweden's Royal Institute of Technology	Kjellen and Larsson (1981)
PEAT	Its primary objective is to identify specific contributing factors to flight crew error. These factors are conditions under management control that lead to procedural non-compliance.	It identifies key contributing factors to people's decisions and produces a list of recommendations used to prevent similar errors in future. It applies a structure analytics process that consists of a sequence of steps to identify key contributing factors to procedural non-compliance. This contributes to the development of recommendations aimed at the elimination of similar errors in the future.			UK's Health & Safety Executive	Moodi and Kimball (2004)
RCA	It identifies both active errors (errors occurring at the point of interface between humans and a complex system) and latent errors (the hidden problems within systems that contribute to adverse events).	It is a systematic process that determines the most important reasons for accidents by identifying underlying deficiencies in a safety management system. It is based on facts and results obtained from the core analytic techniques. The RCA has four steps, of which one is an ECFC. It does not apply any specific accident model.	Energy industry, Nuclear industry	Single cause philosophy	US's Department of Energy US' Occupational Safety and Health Administration International Atomic Energy Agency	Rooney and Heuvel (2004) U.S. Department of Energy (2012)

Technique	Aspects considered	Accident modelling approach	Application instances	Underpinning concept /model	Agencies referring to the technique	Links / references
SAFER	It involves analysing causes of human error and identifying the mismatch between the surrounding environment and human characteristics.	Involves developing an event flowchart to understand, organise and communicate information. It also involves developing a diagram to represent the causal relationships among different factors contributing to an accident. Measures to cut the causality are then identified, prioritised and implemented.	Electricity industry	m-SHEL model	Tokyo Electric Power Company	Hassall et al. (2014)
SCAT	The analysis is based on predefined categories of loss events, their potential direct and basic causes and guidance towards a management system structure for actions for improvement	The SCAT is presented as a chart which contains five elements including accident description, most common categories of contact that could have led to an accident, the most common immediate causes of this contact, underlying causes and a list of safety recommendations.	Aviation. Chemical industry, Electrical industry, Medical, Maritime, Road traffic	Sequential accident causation models Human information processing models Systemic models	UK's Health & Safety Executive American Institute of Chemical Engineers' Review The International Loss Control Institute	Strömgren et al. (2015) Wienen et al. (2017)
SHELL	The underlying notion is that the human element is the most critical and flexible component in the system, interacting directly with other system components, namely software, hardware, environment and liveware.	System components are represented as blocks. The human element is at the centre interacting directly with other system components, i.e. software, hardware, environment and liveware. The central block (human) has varied edges. The varied edges represent human limitations and variations in performance and suggest that other system components need to be adapted to accommodate human limitations.	Aviation		International Civil Aviation Organisation	International Civil Aviation Organization (2012) Australian Government Civil Aviation Safety Authority (2012)

Technique	Aspects considered	Accident modelling approach	Application instances	Underpinning concept /model	Agencies referring to the technique	Links / references
STAMP	The technique takes a system perspective to consider interactions between human, technology and environment within an organisational hierarchy. It also considers control mechanisms used within the system to control the interactions between elements.	It uses a hierarchical structure to represent interactions between socio-technical system elements. The main focus is on constraints the violation of which cause an accident. By representing the hierarchical levels of controls, constraints and processes, the STAMP diagram illustrates why a control structure that involves certain constraints was ineffective in the case of an accident.	Mostly academic applications in: Aviation, Chemical industry, Energy, Medical, Maritime, Road traffic, Railway, Space flight	System theory Feedback control system	UK's Health & Safety Executive	Leveson (2011) Wienen et al. (2017)
STEP	The technique represents the multi-linear combinations of actions performed by actors (human or machine) leading to an accident. Each actor's actions are traced from the beginning of the accident trajectory to the finish.	Accident events are positioned relative to one another along a timeline. Links are established between the events (using arrows) to illustrate the process leading to an accident. Events are further broken down into sequences of single actions by different actors.	Aviation, Chemical industry, Road Transport, Railway industry, Maritime, Military, Electrical industry	Multi-linear and sequential models Process models	UK's Health & Safety Executive American Institute of Chemical Engineers' Review	Hendrick et al. (1986) Wienen et al. (2017)
SCM	This model recognises multi-causality of accidents including human factors and organisational conditions.	The model depicts an accident as a sequential arrangement of gaps in controls at different organisational levels. Different levels are indicated as slices of Swiss cheese. holes in the slices represent gaps in controls. The model also depicts the contribution of distal organisational conditions to an accident.	Healthcare, Aviation. Emergency services, Engineering	Complex linear causality	South African Civil Aviation Authority International Maritime Organization	

Technique	Aspects considered	Accident modelling approach	Application instances	Underpinning concept /model	Agencies referring to the technique	Links / references
TRACEr	It primarily focuses on human error identification. It considers human-machine interface and external factors that may influence human performance.	It comprises seven taxonomies describing accident context, operator context, the error and the error recovery, while adopting a series of decision flow diagrams and tables.	Aviation, Railway industry	Error models Wickens' model of information processing in air traffic control	NSW Independent Transport Safety Reliability Regulator (ITSRR), RailCorp and Public Transport Safety Victoria (PTSV) UK's Health & Safety Executive International Civil Aviation Organization	Baysari et al. (2011)
TRIPOD and Tripod-β	It assumes that organisational failures are the main factors in accident causation. It identifies 11 categories of underlying mechanisms that lead to unsafe actions that give rise to failures. These mechanisms are associated with human, organisational and technical problem.	TRIPOD produces a tree diagram in which the extent of presence of 11 categories of general failure types (underlying mechanisms that produce unsafe acts) in an organisation is shown.	TRIPOD: Oil and gas industry Tripod-β: Chemical industry	Reason's Swiss Cheese Model	UK's Health & Safety Executive The Energy Institute U.K.	

Technique	Aspects considered	Accident modelling approach	Application instances	Underpinning concept /model	Agencies referring to the technique	Links / references
WAIT	WAIT analysis begins with the identification of active failures and their associated influencing factors in the work environment. It then progresses by considering more distal factors associated with organisational and management deficiencies.	It provides specific guidance for gathering information. It comprises two sequential phases, starting with a simplified investigation followed by a second in-depth analysis. It also implicitly adopts the classic tree technique to organise the information, however, no visible diagram is produced.	Railway industry, Aviation, Chemical industry, Energy, Financial services, Medical, Maritime, Transport.	Reason's accident causation model (SCM) Hollnagel's Cognitive Reliability and Error Analysis Method	UK's Health and Safety Commission	Jacinto and Aspinwall (2003) Wienen et al. (2017)
WBA	It aims to analyse the failure of complex, open systems. It considers events, non-events, processes, states and other factors involved in an accident.	The investigator produces a why–because graph (WBG). The WBG depicts causal relations between factors of an accident. The nodes of the graph are factors, while, directed links denote cause–effect relationships between factors.	Aviation, Railway	Sequential models	UK's Health & Safety Executive Railway Systems Engineering and Traffic Safety Australian Civil Aviation Safety Authority	Wienen et al. (2017)

Previous applications of the accident investigation techniques

Table 3 lists a number of case studies wherein the accident investigation techniques previously discussed above were used to understand the causes of a particular accident. This list provides examples of the practical application of these techniques. While efforts have been made to cover the application of each technique to the identified high-risk industries documented, publicly available applications of only a few techniques could be found.

Table 3: Examples of the use of the accident investigation techniques

Technique	Examples of application	
	Industry/application area	**Reference**
AcciMap	Natural disaster	Salmon et al. (2014)
	Railway	Underwood and Waterson (2014)
	Aviation	Papetta (2009)
	Maritime	Murray et al. (2017)
	Healthcare	Vicente & Christoffersen (2006)
	Oil and gas	Hopkins (2000)
AEB	Railway	Harms-Ringdahl (2009)
ATSB	Railway	Underwood & Waterson (2014)
BA	Oil and Gas & Natural disaster	Chakraborty et al. (2018) U.S. Department of Energy (2001)
CA	Oil and gas & Natural disaster	Chakraborty et al. (2018) U.S. Department of Energy (2001)
	Nuclear	Barnes et al. (2002)
CREAM	Railway	Hollnagel (1999)
	Maritime	Yoshimura et al. (2015)
CTM	Nuclear	Vasconcelos et al. (2013)
	Healthcare	Nunes et al. (2015)
ECFC	Nuclear	Barnes et al. (2002)
ECFC &C	Chemical/Natural disaster	Chakraborty et al. (2018)
ECFCA	Oil and Gas	U.S. Department of Energy (2001)
	Nuclear	Barnes et al. (2002)
FRAM	Aviation	Herrera and Woltjer (2010)
FTA	Maritime	Haga et al. (2013)
	Nuclear	Dehlinger & Dugan (2008)
HFACS	Maritime	Murray et al. (2017) Chen & Chou (2012)
	Aviation	Wiegmann & Shappell (2001)
	Oil & Gas	Theophilus et al. (2017)
HFIT	Oil & Gas	Antonovsky et al (2014)
	Aviation	Flin et al. (2013)
HPES	Nuclear	Barnes et al. (2002)

Technique	Examples of application	
	Industry/application area	Reference
ICAM	Aviation	De Landre et al. (2006)
ISIM	Transportation Safety - Maritime	Ayeko, M. (1999)
MES	Aviation	Zotov (2011)
MORT	Aviation	Appicharla (2012)
MTO	Oil & Gas	Chakraborty et al. (2018)
PEAT	Aviation	Moodi and Kimball (2004)
RCA	Maritime	Mousavi and Jafari (2017)
	Chemical	Chakraborty et al. (2018)
SAfER	Energy	Hassall et al. (2014)
SCM	Healthcare	Nunes et al. (2015)
	Railway	Underwood and Waterson (2014)
SHELL	Maritime	Mousavi and Jafari (2017)
	Aviation	International Civil Aviation Organization (2012)
STAMP	Railway	Underwood and Waterson (2014)
	Oil & Gas	Alkazimi (2015)
STEP	Aviation:	Herrera and Woltjer (2010)
	Oil & Gas:	Chakraborty et al. (2018)
TRACEr	Railway:	Baysari et al. (2008) Baysari et al. (2011)
	Oil & Gas:	Theophilus et al. (2017)
TRIPOD and Tripod-β	Oil & Gas (TRIPOD):	Hudson et al. (1991)
	Nuclear (TRIPOD and Tripod-β):	Ziedelis & Noel (2011)
WAIT	Healthcare:	Nunes et al. (2015)
WBA	Aviation:	Ladkin & Loer (1999) Ladkin & Stuphorn (2003)
	Railway	Ladkin (2005)
	Multiple examples from aviation, nuclear industry, army, railway	Sanders (2012)

Comparison of major accident investigation techniques

To conduct a systematic comparison of different techniques, one set of criteria was used as the review framework to structure the evidence provided by different studies. Further, because different studies focus on different aspects of techniques, it was decided to use a generic set of criteria. In addition, it was decided to limit the comparison to major conceptual models and investigation techniques to ensure that detailed information could be found about their applications in the academic literature. Consequently, 13 techniques were compared using the criteria applied by Underwood et al. (2016). Furthermore, to avoid missing useful evidence, two more fields were added to the comparison framework to capture the comparison approaches/scenarios for each technique and other advantages and disadvantages that were mentioned in some studies but did not fit within the evaluation framework. Table 4 provides the comparison results.

Table 4: Comparison of major accident investigation techniques

		Data requirements			Usability				
Technique	Evaluation scenario	Data type	Data processing	Validity	Guidance material	Resource requirements	Graphical representation of accident	Other advantages and disadvantages	References
AcciMap	1. Researchers used the technique to analyse a railway accident. The researchers had previous experience in accident analysis (see Underwood & Waterson, 2014) 2.Experienced human factor analysts applied the technique to an outdoor activity accident scenario (see Salmon et al., 2012) 3. The technique was applied by researchers to an aviation accident. (Debrincat et al., 2013)	Analysis not restricted by data type and format. Various types of data about system components at all levels and the environment.	Involves transforming the available data to data needed by the technique. No taxonomy to guide the analysis process. This potentially makes AcciMap comprehensive in identifying factors contributing to an accident, however, the output also dependents on availability of sufficient data and skills of the analyst.	Based on a recognised accident causation theory. The theoretical basis and application across multiple domains suggest a degree of face and external validity. Application to outdoor activity accidents and comparison of the results with other techniques has indicated valid results. (See Salmon et al., 2012)	Guidance provided by (Svedung and Rasmussen, 2002) about conceptual basis and purpose of the technique, but limited details are provided about its application. Branford et al. (2009) proposed nine guidelines for the development of AcciMaps.	Learning is intensive. Significant resources are needed for data collection, because of the holistic approach of the technique.	The AcciMap diagram provides information about the sequence of events and relationships between decisions and actions involved in an accident scenario at different system levels. The diagram involved little jargon and is relatively easy to understand and effective to communicate. Linkage of factors across different levels gives a comprehensive view of system wide failures. The lack of colour coding is a disadvantage.	AcciMap provides a comprehensive view of failures and interactions between factors from government and regulator levels to line operator and equipment levels. Consequently, a wider range of issues can be identified. The qualitative nature of the technique, little guidance on application and the absence of a detailed taxonomy of contributory factors leads to subjectivity and a low reliability, but at the same time provides more freedom for the analyst. Lacking a taxonomy makes AcciMap more suitable for single case studies rather than comparative analysis of multiple accident cases. Comparative analysis involves taxonomic approaches to identify themes and trends in causal factors (Salmon et al., 2012)	Underwood & Waterson (2014) Salmon et al. (2012) Debrincat et al. (2013)

		Data requirements			Usability				
Technique	Evaluation scenario	Data type	Data processing	Validity	Guidance material	Resource requirements	Graphical representation of accident	Other advantages and disadvantages	References
ATSB (a variation of SCM)	Researchers used the technique to analyse a railway accident. The researchers had previous experience in accident analysis (see Underwood & Waterson, 2014)	Analysis not restricted by data type and format. Various types of data about all system levels and the environment.	Involves transforming the available data to data needed by the technique. Absence of a publicly available taxonomy makes the data processing and classification hard.	Based on a recognised accident causation theory. The theoretical basis and application across multiple domains suggest a degree of face and external validity.	Substantial guidance material available on data collection and the application of ATSB in live investigations ATSB (2008). Structured approaches are outlined for identifying potential safety factors. The guidance contains a substantial amount of jargon.	Learning is intensive. Significant resources are needed for data collection, because of the holistic approach of the technique.	Involved developing a diagram of the accident scenario, based on AcciMap technique. Colour coding is used to make a distinction between different types of factors (e.g. local conditions, risk controls, etc.). Including the sequence of occurrence events indicates accident development over time. The above features provide a relatively simple and effective means of conceptualising and communicating the findings.	The qualitative nature of the technique and the absence of a publicly available detailed taxonomy of contributory factors negatively impact the reliability of the technique, but at the same time provides more freedom for the analyst. Detailed descriptions about accident causes and usage guidance provided by (ATSB, 2008) has improved the reliability of the technique.	Underwood & Waterson (2014)
Drift into failure model	Subject matter experts in accident causation and analysis reviewed the model in a workshop. (Grant et al., 2018)		This model conceptualises accidents as the outcome of a gradual shift in system's performance and ultimately crossing the boundary of safe performance.		Model description provided by Dekker (2011). Dekker presents a set of philosophies and principles based on complexity theory that explain the nature of drift within a system, but does not specify specific methodologies, approaches, or practical steps.			Takes a cultural and philosophical view on accident causation. Dekker questions the reductionist approaches which reduce failure to a single root cause.	Grant et al. (2018)

		Data requirements			Usability				
Technique	Evaluation scenario	Data type	Data processing	Validity	Guidance material	Resource requirements	Graphical representation of accident	Other advantages and disadvantages	References
FRAM	1. Two researchers applied the technique to analyse an aviation accident (Herrera and Woltjer, 2010) 2.A researcher applied FRAM to analyse an aviation (mid-air collision) accident. (de Carvalho, 2011)	Requires detailed data about system functions (which are required to complete tasks) and their variability and interdependencies.	Involves identifying system functions and understand their characteristics. The process comprises 4 steps: identifying essential functions, characterising potential variability, capturing dependencies between functions and defining the functional resonance, and identifying barriers to variability and monitoring requirements. These inform recommendations for monitoring performance.		Technique description and guidelines provided by Hollnagel (2012) and Hollnagel et al. (2014)	A free software has been developed to support FRAM. See: functionalresonance.com	FRAM involves developing a diagram of system functions and their aspects (e.g. input, output, time, precondition, control, resource) and interdependencies.	FRAM considers both normal performance variability and adverse variability. Consequently, the analyst understands the "how" and "why" of accident development. FRAM provides a comprehensive view of work system by describing non-linear dependencies, performance conditions, variability, and their resonance across functions. FRAM is better suited to interactable and tightly coupled systems. FRAM analysis can be used to improve a system or to investigate accidents.	Herrera and Woltjer, (2010) de Carvalho (2011)
FTA		Does not provide specific instruction on information collection.	An analytical tool for establishing logical relationships between events and conditions leading to an undesired event. Can help to classify and link evidence, but developing a logic tree depends on the skills of the analyst.	Has not been formally validated.		Requires skills for the development of logic tree.	Involved developing logic tree diagrams. AND and OR gates are used to reflect the combination of events and conditions.	Mainly focuses on the immediate causes of an accident. Applies a technical perspective when identifying causes. Helps to identify issues contribution to an accident, but it does not help to suggest corrective actions. Low reliability, outcomes depend on the "taste" of the user.	Katsakiori et al. (2009)

		Data requirements			Usability				
Technique	Evaluation scenario	Data type	Data processing	Validity	Guidance material	Resource requirements	Graphical representation of accident	Other advantages and disadvantages	References
HFACS	1. Experienced human factor analysts applied the technique to an outdoor activity accident scenario (see Salmon et al., 2012) 2.125 safety professionals received training on HFACS. They classified 95 causal factors (see Ergai et al., 2016).	The analysis requires detailed data in relation to failures and conditions across four organisational levels.	Involves classifying accident data into causal categories. The original HFACS taxonomy was developed for aviation accidents; however, the generic failure types have been applied to other contexts such as mining (e.g. Lenné et al., 2012). Further, modified taxonomies have been developed to classify factors in other domains including railway, maritime, mining, etc.	Based on a recognised accident causation theory. Has been applied in multiple domains (with modified taxonomies).	Guidelines and training courses are available for this technique. Teaching users how to code accident causal factors is part of HFACS training.		HFACS offers a systematic framework for representing accidents. Failures and contributory factors can be linked across four organisational levels.	The taxonomic nature HFACS makes it suitable for comparative analysis of accident cases where themes and trends in causal factors are identified. The presence of a taxonomy and guidance enhances the reliability of this technique. A number of studies have reported acceptable to high levels of inter-rater reliability (e.g. Ergai et al. (2016); Also see Salmon et al. (2012) for a list). However, the taxonomic nature of HFACS also constrains the analysis to specific classes of failure, particularly when the technique is applied outside aviation. Using four organisational levels limits the capacity of HFACS to consider failures outside of an organisation, e.g. government policy, regulatory factors, although in some applications, 'outside factors' have been added to the model (See Salmon et al. (2012) for details).	Salmon et al. (2012) Ergai et al. (2016)
ICAM		The technique focuses on both local and wider systemic factors such as organisational factors, tasks, environmental conditions, individual or team actions as well as absent and failed defences.	ICAM provides a structured framework to sort and code the investigation findings. The framework identifies four categories to organise accident causal factors: absent or failed defences, individual or team actions, task/environmental conditions, and organisational factors. There are subcategories under each of these major categories.	Based on a recognised accident causation theory. It has been applied across multiple domains.	Guidance material and training courses are offered by different providers.			Building on the Swiss Cheese Model, ICAM helps to consider a wide range of organisational issues. ICAM helps to identify what went wrong (including failed/absent defences), so corrective measures can be recommended to prevent recurrence. The underlying concept of ICAM is accepting that human error is inevitable. Therefore, the analysis aims to build error-tolerant defences.	De Landre et al. (2007) Patterson (2009)

		Data requirements			Usability				
Technique	Evaluation scenario	Data type	Data processing	Validity	Guidance material	Resource requirements	Graphical representation of accident	Other advantages and disadvantages	References
Normal Accident Theory (NAT)	Subject matter experts in accident causation and analysis reviewed the model in a workshop. (Grant et al., 2018)	Involves understanding system characteristics and the degree of coupling between components. The interdependencies between components are captured in a NAT matrix.	Accidents are conceptualised as the outcome of interactions between multiple failures in the system. These failures are not in a sequential order.		Theory is described by Perrow (1981, 1999)			Takes into account the complexity and interrelationships on a system.	Grant et al. (2018)
Rasmussen's risk management framework	Subject matter experts in accident causation and analysis reviewed the model in a workshop. (Grant et al., 2018)	A System is described in terms of what functions, roles and responsibilities it involved. This requires data about workflows, tasks, objects and actors, and their relationships across organisational levels.	Using this framework, a hierarchical description of complex sociotechnical systems and their dynamic environment can be developed. Controls and information flows across organisational levels maintain vertical integration. Loss of control makes the system vulnerable to adverse events.		Description provided by Rasmussen's (1997).				Grant et al. (2018)

		Data requirements			Usability				
Technique	Evaluation scenario	Data type	Data processing	Validity	Guidance material	Resource requirements	Graphical representation of accident	Other advantages and disadvantages	References
STAMP	1. Six workshop participants applied STAMP to a railway accident scenario. The participants were aviation accident investigation trainees. They did not have previous experience in using STAMP. Before the study, they received training in accident investigation and using STAMP (see Underwood & Waterson, 2016) 2.Experienced human factor analysts applied the model to an outdoor activity accident scenario (see Salmon et al., 2012)	Theoretically not restricted by data type and format. Various types of data about system components, structure and its environment. Apart from accident-related data, the analyst requires additional data to develop the control structure diagram. The analyst needs to understand the broader context e.g. government policies, legislation, rules, company procedures, etc. May be easier to use if data collection is guided by the requirements of the technique.	Users faced difficulties when trying to classify and analyse the evidence User's experience had impact on analysing different sources of data.	Has not been formally tested. Underwood & Waterson (2016) report that users considered it to have a level of face validity. Underwood & Waterson (2016) suggest further improvements are needed to gain acceptance among practitioners.	Detailed guidance is provided by Leveson (2012) as Causal Analysis based on STAMP (CAST). Users expressed difficulties in understanding and applying STAMP. The guidance contains a substantial amount of jargon.	Users may need training and multiple attempts to gain sufficient understanding. Significant resources are needed for data collection, because of the holistic approach of the model.	STAMP analysis findings are presented over several outputs, some of which are mainly text based. But it also involves developing a control/feedback structure diagram. Users considered the diagram as a principal part of analysis output, however, they had contradictory opinions about the usability of the diagram. Lacking a timeline within the control structure diagram was identified by users as a disadvantage.	Underwood & Waterson (2016) found variations in the way users represent a system, i.e. identifying components, constraints and controls at different system levels. Users believed STAMP effectively analysed organisational (high-level) system issues, but it was unclear whether they believed STAMP was effective in analysing lower-level factors. The qualitative nature of the model and the generic taxonomy of contributory factors negatively impact the reliability of the technique, but at the same time provides more freedom for the analyst. Salmon et al. (2012) report that users faced difficulties in using STAMP taxonomy to classify some of the human and organisational factors. They suggest that STAMP might be more suitable for capturing technical control failures. Detailed descriptions about accident causes and usage guidance provided by (Leveson, 2012) has improved the reliability.	Underwood & Waterson (2016) Underwood & Waterson (2014) Salmon et al. (2012)

		Data requirements			Usability				
Technique	Evaluation scenario	Data type	Data processing	Validity	Guidance material	Resource requirements	Graphical representation of accident	Other advantages and disadvantages	References
STEP	Two researchers applied the technique to analyse an aviation accident (Herrera and Woltjer, 2010)	A simple matrix (STEP worksheet) is used for recording data. The rows are labelled with actors' names and the column labels indicate timelines. Events are represented as blocks on this matrix. The events are linked by arrows to show the accident process.	After developing the accident process diagram, its validity is tested by conducting 3 tests: 1) a row test to verify the completeness of each actor's events, 2) a column test to verify the relative positioning of the events on the timeline, 3) the necessary and sufficient test to ensure that for each event, the proceeding events were sufficient to produce that event. The accident process is also compared with the expected (accident free) process to help find deviations that contributed to an accident. Alternative, the normal work process is evaluated to identify potential future risks.		The technique has been described in Hendrick et al. (1986)		STEP involves constructing a flowchart to arrange evidence and illustrate the accident process. This helps to create a "mental motion picture" of accident development.	STEP is relatively simple to understand. It provides a comprehensive illustration of events involved in an accident including what happened, who was involved and when. It also helps developing recommendations. However, it only focuses on what events/failures happened and does not capture why they happened, i.e. it does not consider the context of the events. STEP is suitable to analyse tractable systems which are known and can be described entirely.	Herrera and Woltjer, (2010)
Swiss Cheese Model (SCM)	The model was applied by researchers to an aviation accident. (Debrincat et al., 2013)	Requires understanding an organisation and the layers of defences put in place to safeguard against hazards.		Wide application and acceptance across multiple domains suggest a degree of face validity.	The model has been explained by Reason (1995, 1997)		Predominantly uses narration to describe accident causes and mechanisms. Conceptually, system defences are represented as layers in a diagram. Holes in defences represent deficiencies/gaps in controls/defences. An accident trajectory becomes possible when these holes line up.	SCM can be applied to analyse a wide range of organisational accidents. An emphasis on defences helps to identify and rectify weaknesses in accident controls across the organisation. SCM also recognises the contribution of higher organisational conditions to accident development. Lack of a timeline or dynamic representation of accident development has been identified as a disadvantage. It has been stated that the model is constrained to one (linear) accident trajectory.	Debrincat et al. (2013)

		Data requirements			Usability				
Technique	Evaluation scenario	Data type	Data processing	Validity	Guidance material	Resource requirements	Graphical representation of accident	Other advantages and disadvantages	References
Tripod beta		Data is collected in relation to events, objects and agents involved in the accident trajectory, barriers that were (or should have been) in place. These include failed barriers, missing barriers, effective barriers, and inadequate barriers.	Involves investigating both control failures and latent failures. Based on the collected data about events and barriers, the investigator tries to understand the causes of events and ineffective or missing barriers.		Guidance has been provided by the Stichting Tripod Foundation	Based on Tripod beta, software has been developed for accident analysis and prevention.	The evidence is organised in a tripod tree, in 3 sections: what happened, how it happened, and why it happened.	Applied in accident analysis, investigation and training. It is useful for the analysis of single accidents.	Stichting Tripod Foundation (2017) Fu et al. (2020)

Discussion

The review and comparison of accident models and investigation techniques presented in this document reflect a diversity of perspectives on accident causation and the benefits and limitations inherent in them. It is often acknowledged that while sequential and linear techniques, such as Fault Tree Analysis and Causal Tree Method, are easier to use, they provide a constrained view of accident causation, leading to the identification of more evident and easier-to-find factors, and are more likely to over emphasize human error and blame individuals for accidents. Progressively, as accident causation theories have evolved, more complex causation models have been developed. This has largely occurred in response to the challenges inherent in maintaining safety in increasingly complex modern work systems (Khanzode et al., 2012). In particular, the incorporation of a systems view to accident conceptualisation has been a major advance. The academic literature highlights the benefits of a systemic approach to accident analysis, including a more comprehensive understanding of the complexities and dynamics involved in accident causation. However, the current body of research also indicates that systemic techniques, such as STAMP, FRAM and AcciMap, are not being widely applied in practice (Underwood and Waterson, 2013) with multiple studies identifying a number of difficulties with the application of complex systemic techniques in industrial environments.

The use of taxonomies, which is meant to guide the accident investigation process, has both pros and cons. On the one hand, using generic taxonomies in AcciMap and STAMP arguably assists investigators to identify a comprehensive range of contributing factors and enables the application of techniques in multiple domains. However, it can also create confusion. Studies about the application of AcciMap and STAMP (e.g. Salmon et al., 2012; Underwood et al., 2016) have indicated that participants face difficulty in understanding the language used by these techniques and were confused when classifying some of the contributing factors. On the other hand, in the case of HFACS, the use of a taxonomy, which is specific to the aviation domain, has been considered as a constraining feature (Salmon et al., 2012) because if any contributing factor falls outside of the HFACS taxonomy, the factor will be left out of the investigation. This is especially the case when the technique is applied in domains other than aviation. In addition, some researchers have raised concerns about the suitability of checklist taxonomies to be used by normal practitioners (e.g. front-line employees), as these taxonomies are more useful for expert technology developers (Kirwan, 1998; Olsen and Shorrock, 2010).

Another aspect often considered in relation to the application of different accident investigation techniques is the reliability of investigation results. With regard to systemic techniques, the consistency of investigation outcomes has been a subject of discussion by some researchers including Waterson and Jenkins (2011), O'Connor (2008) and Underwood and Waterson (2013). While a number of studies have reported an acceptable level of consistency between users (e.g.

Ergai et al. (2016) in relation to HFACS), others have reported a poor level of agreement between participants' analysis results (Salmon et al., 2012; Olsen and Shorrock, 2010; Underwood et al., 2016). The participants in these studies often have developed different sets of contributing factors or classified factors differently when given the same accident data. This is considered to be an important issue for the reliability of techniques because the systemic approaches generally require input from multiple users; thus, achieving social consensus is highly important for the consistency of identified contributory factors, as this informs decisions on safety improvement solutions (Wallace and Ross, 2006). In addition, as these techniques are normally meant to be used over time by different users (to map the dynamic changes in a work system), the consistency in identification and classification of contributory factors is an important aspect for the reliability of results (Olsen and Shorrock, 2010).

This lack of agreement among users when classifying factors, in turn, has been attributed to several issues. Firstly, participants face confusion in using generic taxonomies as they need to rely on their subjective judgement (Salmon et al., 2012). With reference to AcciMap and STAMP, Underwood and Waterson (2014) state that because none of these techniques provide a detailed taxonomy of contributory factors, their reliability is reduced.

Secondly, as systemic techniques have mostly been developed within the academic community and are based on theoretical constructs, practitioners can sometimes face difficulty in understanding the concepts and language used (Underwood et al., 2016). Some researchers have even proposed that there is a gap between academia and industry, stating that a different understanding of systemic analysis approaches seems to exist between these two communities (Underwood and Waterson, 2013).

Furthermore, systemic techniques have mostly been used in the investigation of past accidents (Grant et al., 2018). The retrospective nature of accident analyses makes the quality of the results highly sensitive to, and dependent on, the quality of the accident data on hand. Systematic techniques, due to their comprehensive nature, require exhaustive and detailed information about components' functions, accident circumstances, failures and events at different organisational levels and over time. However, comprehensive data (particularly in relation to factors at higher organisational levels) is not normally collected when accidents happen (due to resource limitations or lack of necessity at the time of the accident) and may therefore not be available for future analyses. These issues limit the reliability and validity of the results when used in retrospective analyses of accident causality. Also, the qualitative nature of accident data and the analysis approach makes it very challenging to objectively test the reliability of accident investigation techniques in practice (Underwood and Waterson, 2013).

Finally, systemic accident investigation techniques are developed with consideration of highly complex systems and require a large amount of effort and resources to implement. Hollnagel and

Speziali (2008) suggest that systemic techniques are suitable for investigating accidents within highly complex and intractable systems, such as nuclear power plants. Similarly, Salmon et al. (2012) state that the systemic analysis of accidents is not a simple endeavour and needs significant effort, time and access to various domain experts. Both Leveson (2004) and Salmon et al. (2012) suggest that the data needed for STAMP and AcciMap analyses are only typically available in comprehensive reports for large-scale accidents. Consequently, the application of systemic approaches may only be justified for the investigation of major accidents where enough funding, time and trained and competent personnel are available to obtain the comprehensive information required to support the analysis of accident causality (Underwood and Waterson, 2013).

Nonetheless, in spite of these practical difficulties, systemic accident investigation approaches are preferred by many over traditional accident investigation approaches. This is because systemic approaches are theoretically capable of providing more comprehensive and useful insights into accidents that occur within modern socio-technical systems, particularly as these work systems have become increasingly complex and intractable (Hovden et al., 2010). However, notwithstanding this advantage, the application of systemic accident approaches in practice has been limited partly due to the above practical issues and because of low awareness and acceptance among practitioners.

To gain more recognition, systemic accident investigation techniques require considerable empirical validation within industrial settings (Underwood and Waterson, 2013). They also may need to be adapted and tailored to specific work contexts and local needs to better meet the specific needs of practitioners in different domains. For example, integrating domain knowledge to the generic systemic approaches, e.g. by developing specific taxonomies, has been suggested as a potential option, especially with regard to AcciMap (Salmon et al., 2012; Waterson et al., 2017). This is already being done for HFACS and a few modified versions of the technique exist, such as HFACS-RR, HFACS-ME, HFACS-CC, and HFACS-ADF.

In addition, the advantages and limitations of different systemic accident models and investigation techniques (revealed in the analysis presented in this report) suggest that there may be some benefits in integrating or combining features of different techniques to capture a wider range of causal factors and improve accident investigation outcomes. Different models of causation highlight different aspects of the accident problem (Kjellén, 2000). Lundberg et al (2009) describe this as the principle of 'what-you-look-for-is-what-you find.' The choice of investigation technique is therefore important because, depending on whether a technique focuses more heavily on human, technology, organisation or information-related factors will determine the outcomes of the investigation and ultimately shape the selection of solutions to be implemented in the aftermath of an accident. Lundberg et al. (2009) call this the principle of 'what-you-find-is-what-you-fix.' Therefore, integration of models (and the techniques built on them) can provide a more comprehensive and multi-perspective view of different contributing factors, events and functions and the complex interactions between them that shape accidents. It can also ensure that human factors, organisational aspects and technological issues are all considered in a meaningful way. This is particularly important to cope with the increasing complexity of modern socio-technical systems.

As such, another future direction proposed by some researchers (Hovden et al., 2010; Waterson et al., 2017) is to develop 'hybrid' accident models. AcciMap, due to its generic structure and format provides a good platform for developing new models by adding features and taxonomies from other models, as well as bringing in domain knowledge which plays an important role in hazard identification (Kanzode et al., 2012).

Conclusion

The selection and recommendation of a particular accident investigation technique as a standard investigation practice for an organisation or an industry is not straightforward. This report provided a review of 36 accident investigation techniques widely used in various industries, such as aviation, chemical processing, maritime, nuclear, oil and gas, and transport and railway.

While this review was not intended to provide a definitive recommendation as to what techniques are suitable for each industry, it provides insight into the performance and functionalities of techniques, which can assist organisations to make an informed selection of accident investigation techniques. There are a number of factors that organisational decision-makers may consider when deciding how to investigate an accident.

During the investigation process, it is recommended to use different techniques in order to analyse emerging problem areas (Sklet, 2004). Therefore, knowledge of different investigation techniques (such as their accident modelling approach, the accident causation aspects and factors they cover, their benefits and limitations) is useful, since this knowledge helps investigators to draw on the strengths of different techniques based on the requirements of their organisation and the accident situation they are dealing with. Further, the application of multiple techniques can both improve the breadth of the investigation and address the bias that reliance on one perspective can entail.

The selection of a technique to use, in part, depends on an assessment of the complexity and/or severity of an accident (Novatsis and Wilkinson, 2016). Some minor accidents may not need to be investigated in the same depth as those that have led to serious injuries (Lappalainen and Perttula, 2019). Therefore, organisations may choose to provide “scalable” investigation techniques; including some that are simple and flexible (e.g. Change Analysis, Barrier Analysis, Causal Tree Method), and others that are more in-depth (e.g. Swiss Cheese Model, ICAM, AcciMap).

The techniques may also need to be adapted, combined and tailored to specific contexts and local needs. Consequently, the techniques can better meet the specific needs of practitioners in different domains, for example by adopting domain specific knowledge and taxonomies. In addition, using different techniques, in combination, can provide multiple perspectives of accident causation and lead to a more comprehensive investigation.

It is also recommended that organisations establish a process to review investigation quality to ensure that objectives are being met and information that is produced is of high quality, reflects the range of factors involved in an accident and can be used for prevention purposes and organisational learning. The review needs to also consider the quality of evidence collected, as the investigation output will be significantly affected by the amount and quality of the evidence collected following an accident (Underwood et al., 2016)

Organisations should consider whether the accident investigation technique selected for use allows for the identification of latent factors including system design, management and organisational inadequacies and oversights. The resolution of these distal issues within an organisational environment can help prevent a larger class of accidents than focusing attention on immediate (easily identifiable) causal factors.

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Appendix 1

Overview of accident investigation techniques, their characteristics and applications

Acronym	Technique's extended name	Description	Aspects considered	Accident modelling approach	Application instances	Underpinning concept /model	Agencies referring to the technique	Reference
AcciMap	Accident Analysis Technique	The AcciMap approach is a systems-based technique for accident analysis, specifically for analysing the causes of accidents that occur in complex sociotechnical systems. The approach is not domain-specific and has been used to analyse accidents in a range of industries including aviation, defence, oil and gas public health risk management, policing and public health and rail transport. The AcciMap approach is useful for uncovering how factors in the various parts of the system contributed to an accident, and for arranging those factors into a logical causal diagram that illustrates how they combined to result in that event. The technique also promotes a systemic view of accident causation as the AcciMap diagram extends well beyond the most immediate causes of the event to reveal the full range of higher-level factors that contributed to the outcome. The AcciMap approach involves the construction of a multi-layered causal diagram in which the various causes of an accident are arranged according to their causal remoteness from the outcome (depicted at the bottom of the diagram). The precise format of the diagram varies depending on the purpose of analysis, but the lower levels typically represent the immediate precursors to the event, relating to the activities of workers and to physical events, processes and conditions that contributed to the outcome.	It focuses on failures across the following six organisational levels: government, regulators, company, management, staff, and work process and surroundings.	AcciMap combines the classic cause-consequence chart and a multilevel organisational risk management framework. Using AcciMap involves the construction of a multi-layered causal diagram in which the various contributing factors to an accident are arranged according to their causal remoteness from the outcome (depicted at the bottom of the diagram).	Public health, Oil and gas, Construction, Aviation, Chemical industry, Electrical industry/Electricity, Emergency services, Medical, Military, Maritime, Railway, road traffic, Space flight	Systemic models		Rasmussen (1980) Wienen et al. (2017) Waterson et al. (2017)
AEB	Accident Evolution and Barrier Function model	The Accident Evolution and Barrier Function (AEB) model provides a technique for analysing accidents. It models the evolution towards an accident as a series of interactions between human and technical systems. The main principle is that it is possible to stop/interrupt the development of the sequence between any two successive errors (human or technical) through adequate barrier functions. Barrier function systems are systems performing the barrier functions and might consist of an operator, an instruction, an emergency control system.	It models the evolution towards an accident as a series of interactions between human and technical factors. It considers the barrier function, and its structure, to control the development of accident.	AEB models an accident as a combination of interactions between human and technical systems. It describes the accident evolution in a flow diagram, indicating a sequence of steps belonging to either the human factors, organisational system or the technical system. Each step represents either the failure/ malfunction of a component or an incorrectly performed function within each system. The barrier function indicates how the development of the accident could be controlled.	Aviation, Chemical industry, Maritime, Railway, Nuclear industry	Linear causality	UK's Health & Safety Executive (HSE) American Institute of Chemical Engineers' Review Swedish Nuclear Power Inspectorate	Svenson (2001) Hollnagel (1999) Wienen et al. (2017)

Acronym	Technique's extended name	Description	Aspects considered	Accident modelling approach	Application instances	Underpinning concept /model	Agencies referring to the technique	Reference
ATSB	Australian Transport Safety Bureau Investigation Analysis Framework	ATSB provides a general framework, including an investigation analysis model, that can guide data collection and analysis activities during an investigation. It is a variation of Reason's Swiss Cheese model. The model represents the operation of a system via five levels of "safety factors", where a safety factor is an event or condition that increases safety risk. The layers include "occurrence events", "individual actions", "local conditions", "risk controls" and "organisational influences".	It represents the operation of a system via five levels of "safety factors".	It investigates the risk of an accident through five layers namely "occurrence events", "individual actions", "local conditions", "risk controls" and "organisational influences". The final output is presented as a chart that is based on AcciMap.	Railway industry	Reason's accident causation model (SCM) AcciMap	Australian Transport Safety Bureau	Australian Transport Safety Bureau (2008) Wienen et al. (2017)
BA	Barrier Analysis	Barrier analysis is used to identify hazards associated with an accident and the barriers (control) that should have been in place to prevent it. Barriers are put in place to prevent a hazard from reaching a target.	It considers hazards and the barriers (controls) that were missing, were defeated, or did not function as expected to prevent an accident.	The user classifies barriers that separate a hazard and a target (e.g. worker). The user identifies if each barrier prevents an accident, mitigates its harm, and if it can be defeated. The user also identifies the latent organisational conditions that can influence the barrier.	Energy industry, Nuclear industry		US's Department of Energy International Atomic Energy Agency	De Dianous and Fievez (2006) U.S. Department of Energy (1999)
CA	Change Analysis	Change analysis examines planned or unplanned changes that caused undesired outcomes. This technique is used to examine an accident scenario by comparing what occurred during the accident process and what has occurred before or what was expected to occur.	It considers planned or unplanned changes that caused undesired outcomes.	It depicts a comparative model to identify differences between an accident sequence and the accident-free sequence (i.e. what has happened before or what was expected). Through the comparison, the causes of the accident are identified. The results from a change analysis can stand-alone, but the results are most useful when they are combined with results from other techniques.	Energy industry, Nuclear industry		US's Department of Energy International Atomic Energy Agency	U.S. Department of Energy (1999)
CREAM	Cognitive Reliability and Error Analysis Method	CREAM is a technique used in Human Reliability Analysis to assess the probability of human error during a specific task. The result can inform measures to reduce the likelihood of errors and improve the overall levels of safety.	It investigates three categories of individuals, technologies and organisations. These are the contributors to what ideally must be inferred in the case of an accident as opposed to what is observed.	Involves developing a graph of antecedent actions (functions) and conditions leading to an accident. There is a clear distinction between causes of human error and its manifestation.	Emergency Services, Medical, Nuclear industry, Railway industry, Road traffic	Cognitive systems engineering	Norwegian Public Roads Administration	Hollnagel (1998) Wienen et al. (2017)
CTM	Causal Tree Method	CTM, also called the INRS technique, is a Tree Technique. Using CTM, a causal tree is constructed by moving backwards from an accident and identifying factors and deviations from specified processes which have contributed to the accident. The tree indicates the causal relationships between these factors and the accident.	CTM is based on the assumption that accidents arise from variations in the normal process. These variations are caused by the individual, the task, the equipment and the environment.	It identifies the variations in processes and displays them in the analytic tree, showing causal relations in an event chain. The development of a tree starts with the accident in question.	Many types of accidents including Nuclear, Healthcare, Chemical	Sequential models	American Institute of Chemical Engineers' Review Institut National de Recherche et de Sécurité	Leplat (1978) Vasconcelos et al. (2013) Wienen et al. (2017)

Acronym	Technique's extended name	Description	Aspects considered	Accident modelling approach	Application instances	Underpinning concept /model	Agencies referring to the technique	Reference
ECF Chart	Events and Causal Factors Charting	ECFC is a charting technique to map the sequence of events involved in an accident. The technique is used to organise and display the events chronologically.	ECFC is used for any event investigation in which a timeline or sequence of events might apply. The initiating event can be equipment failure or related to human performance.	It involves producing a chronological display of events to portray an accident sequence.	Energy industry	Sequential models	US's Department of Energy	U.S. Department of Energy (1999) Buys and Clark (1995) Wienen et al. (2017)
ECFA	Events and Causal Factors Analysis	ECFA is an initial step in determining the root causes of an accident. It involves deductive reasoning to identify the events and conditions which have contributed to the accident. It is often used in conjunction with other tools, such as MORT, tree analysis, change analysis, and energy trace and barrier analysis, to achieve optimum results from the investigation.	This technique is used for any investigation of a timeline or sequence of events and conditions leading to an accident	The output may vary depending on the requirements of the investigation. However, it is usual to include the event that compromises control and the event that makes the situation safe again.	Energy industry	Sequential models	UK's Institution of Occupational Safety and Health (IOSH)	U.S. Department of Energy (1999) Buys and Clark (1995) Kingston et al. (2004) Wienen et al. (2017)
FRAM	Functional Resonance Analysis Model	FRAM is based on a description of system functions and their possible variability. It describes how the variability of multiple functions may combine in unexpected ways and resonate, resulting in the variability of some functions to exceed normal limits and leading to accidents.	FRAM concerns with a description of system functions rather than its structure. It helps reveal how variability in human and technical functions can resonate to produce different and unexpected operating scenarios.	It displays non-linear propagation of variability in functions. Functions are described and linked to each other in terms of their input (I), output (O), preconditions (P), resources (R), time (T), and control (C).	Aviation, Medical, Air traffic management	Theory of functional resonance, systemic models		Hollnagel (2012) Wienen et al. (2017)
FTA	Fault tree analysis	Using FTA, the possible failures that can contribute to an adverse event are identified and diagrammed as a tree. The adverse event is placed at the top of the tree; hence it is called the top event. The tree shows logical connections and causes leading to the top event. Two logic gates (the AND and OR gate) are used to relate the combinations of preceding events and conditions to the top event.	FTA represents the logical combination of technical factors and human actions which can lead to an undesirable top event.	The contributing factors to an accident are captured using a logic-tree in order to show the logical combinations of causes leading to an accident or failure.	Electricity industry, Emergency Services, Maritime, Nuclear industry	Sequential models Logic-tree	American Institute of Chemical Engineers' Review International Atomic Energy Agency The Dept. of Defence, USA.	Ferry (1988) Vesely et al. (1981) Wienen et al. (2017)
HERA	Human Error in Air Traffic Management	Human Error in Air Traffic Management focuses on the cognitive processes of air traffic control operators to identify and quantify the impact of the human factor in accident investigation and safety management. HERA is based on the view that human error is the primary contributor to accidents. The technique has two modes. A retrospective part for accident analysis and a prospective part for assessing human error probabilities.	It considers the human factor in accident investigation, safety management and prediction of errors arising from new technology. It assumes that human error is the primary contributor to accidents.	HERA serves as a framework for capturing human error. It involves defining and classifying the error, developing a flowchart of error mechanism and its contextual conditions and capturing the detailed information in tables.	European Air traffic Services	Linear causality Human information processing models	European Air traffic Service organisations Eurocontrol	Eurocontrol (2003) Issac et al. (2002) Pounds and Isaac (2002) Hallbert et al. (2006)

Acronym	Technique's extended name	Description	Aspects considered	Accident modelling approach	Application instances	Underpinning concept /model	Agencies referring to the technique	Reference
HSG245	Health and Safety Executive (HSG245)	HSG245 is a workbook developed in 2004 by the HSE as a step-by-step guide for employers, unions, safety representatives and safety professionals to undertake health and safety investigations. The guide provides specific structured questions. The aim of the analysis is to find immediate, underlying and root causes. Immediate cause can be the agent of injury, underlying causes are unsafe acts and conditions, and a root cause is an initial failure or event from which all other failures arise. Checklists to assist with identifying underlying and root causes are also provided.	Unsafe human act and conditions are regarded as underlying cause. Root causes are generally management, planning or organisational failings.	The investigation starts with an adverse event and progresses through immediate causes (the agent of injury), underlying causes (unsafe acts and conditions) to reach a root cause.	Generic	Systemic models Swiss cheese model	UK's Health & Safety Executive	Health and Safety Executive (2004)
HFACS	Human Factors Analysis and Classification System	HFACS was developed as a taxonomy-based aviation accident analysis approach. It identifies the human causes of an accident and provides a tool to not only assist in the investigation process but to target training and prevention efforts. HFACS looks at four levels of human failure, referring to the Swiss Cheese Model. These levels include unsafe acts (operator error), preconditions for unsafe acts (such as fatigue and inadequate communication), unsafe supervision (such as pairing inexperienced aviators for a difficult mission), and organizational influences (such as lack of flight time because of budget constraints).	It investigates human factors in four levels: unsafe acts, preconditions for unsafe acts, unsafe supervision and organisational influences.	It produces a hierarchical chart starting from organisational influences (at top) and ending with unsafe acts.	Aviation Modified versions in: Railway, Maintenance, Maritime, Air traffic control, Military, mining	Swiss cheese model	US's Federal Railroad administration	Shappell and Wiegmann (2000)
HFIT	Human Factors Investigation Tool	HFIT is a theoretically based technique to assist with the investigation of the human factors causes of accidents in the UK offshore oil and gas industry. It classifies human factors information into four types: (a) the immediate action errors, (b) error recovery mechanisms, in the case of near misses, (c) the thought processes leading to the action error and (d) the underlying causes.	Investigates human influence on an accident in four levels: action error, error recovery mechanisms, thought processes, and underlying causes.	The four investigation levels (human factor types) are further broken down to 28 elements. Analysis starts with investigating elements related to action errors, followed by error recovery, situation awareness and threat.		Rasmussen's model of human malfunction	UK's Health & Safety Executive	Gordon et al. (2005)
HINT – J-HPES	HINT – J-HPES	HINT is based on J-HPES, the Japanese version of INPO's Human Performance Evaluation System (HPES). The principle underlying this technique is to use a root cause analysis of small events to identify trends and use as a basis for proactive prevention of accidents. The steps involved are: Step 1: Understand the event. Step 2: Collect and categorize causal factors. Step 3: Root cause analysis. Step 4: Proposal of countermeasures to prevent reoccurrence.	The methodology is concerned with enhancing the identification of human performance issues.	The overall principle is to use a root cause analysis of small events to identify trends as a basis for proactive prevention of accidents. The technique comprises a number of steps. These are: Step 1: Understand the event. Step 2: Collect and classify causal factor data. Step 3: Causal analysis, using root cause analysis. Step 4: Proposal of countermeasures.	Electricity industry, Nuclear power	A variant of root cause analysis	Central Institute for Electric Power Industry (CRIEPI) in Japan US's Institute of Nuclear Power Operations	Takano et al. (1994) Hollnagel (2009)

Acronym	Technique's extended name	Description	Aspects considered	Accident modelling approach	Application instances	Underpinning concept /model	Agencies referring to the technique	Reference
HPES	Human Performance Enhancement System	HPES was developed with sponsorship by the Institute of Nuclear Power Operations (INPO). The technique has a particular emphasis on human performance aspects. It incorporates different tools such as task analysis, change analysis, barrier analysis, cause and effect analysis, and event and causal factor charting. HPES has been the basis for other methodologies for other context-specific requirements. HPES has been adapted by other countries since its development in the United States. For example, K-HPES has been developed and used in Korea, and J-HPES in Japan.	Although valid for all types of issues (technical, procedural, etc), the methodology is oriented to enhancing the identification of human performance issues.	It utilises event and causal factor charting. Barrier analysis, change analysis and cause and effect analysis are graphically incorporated into the same chart. The integrated chart shows the direct causes, the root causes, the contributing causes, and the failed barriers, with their interconnections and dependencies.	Nuclear power		Institute of Nuclear Power Operations (INPO) American Institute of Chemical Engineers' Review	INPO (1989) Wienen et al. (2017)
ICAM	Incident Cause Analysis Method	A fundamental concept of ICAM is acceptance of the inevitability of human error. ICAM is designed to ensure that the investigation is not restricted to the errors and violations of operational personnel. It identifies the local factors that contributed to the accident and the latent conditions within the system and the organisation. Through the analysis of this information, ICAM provides the ability to identify what really went wrong and to make recommendations on what needs to be done to prevent recurrence. It is directed towards building error-tolerant defences against future accidents. Therefore, ICAM provides a process to move beyond the idea of a single root cause and identify a range of immediate causes, contributing factors and underlying causes. ICAM is widely used in mining industry.	It accepts the inevitability of human error to ensure that investigation is not restricted to human errors.	It proposes error-tolerant defences against future accidents by investigating local factors and latent hazards within the system and the organisation.	Aviation, Transport, Railway	Swiss cheese model	UK's Health & Safety Executive The Australian Transport Safety Bureau	Reason (2016) De Landre et al. (2007) Patterson (2009)

Acronym	Technique's extended name	Description	Aspects considered	Accident modelling approach	Application instances	Underpinning concept /model	Agencies referring to the technique	Reference
ISIM	Integrated Safety Investigation Methodology	ISIM was developed in 1998 by the Transportation Safety Board (TSB) of Canada and it follows Reason's accident causation model. The technique starts with the collection of information regarding personnel, tasks, equipment and environmental conditions involved in the occurrence in order to determine the sequence of events and identify underlying factors and unsafe conditions. The next step is to assess the level of risk associated with such unsafe conditions or underlying factors and examines the status of barriers (physical or administrative) in order to identify those that are less than adequate. ISIM forces the investigator to look beyond the actions and decisions of front-line operators and into the latent unsafe conditions in the work system that provided the opportunity for the expression of those actions. Once the safety deficiencies have been identified, options for controlling risk have to be considered. The goal of ISIM is to ensure that both accident investigation and safety deficiency analysis are integrated. The risk control option analysis is a key step of ISIM aiming at generating recommendations and strategies for safety improvement.	The technique starts with the collection of information regarding personnel, tasks, equipment and environmental conditions involved in the accident. It also looks into the latent unsafe conditions in the work system.	Creates a framework to ensure that both accident investigation and safety deficiency analysis are integrated to generate recommendations for safety improvement.	Aviation, Railway, Maritime, Energy	Swiss cheese model	Transportation Safety Board of Canada UK's Health & Safety Executive The Canadian Aviation Safety Board	TSB (1990) Ayeko (2002) Wienen et al. (2017)
MES	Multi-linear Events Sequencing	MES is a charting technique, which shows events chronologically ordered on a timeline basis. It is based on the view that an accident begins when a stable situation is disturbed. A series of events can then lead to an accident. The technique distinguishes between actors, actions and events. Actors can be people, equipment, substances while actions are anything carried out by an actor. Events are the unique combination of one actor plus one action. The technique helps the analyst to identify the main actors and their actions and map the relations between the events along a flexible timeline. The final product is thus an accident logic chart with the events, actors and actions sequentially placed	It assumes that events result from the combination between one actor (human, equipment, substance) and one action.	It shows events in chronological order on a timeline basis where the relationships between them are identified. The final product is an accident logic chart with the events, actors and actions sequentially positioned.	Aviation, Transport	Sequential models Logic tree	US National Transportation Safety Board American Institute of Chemical Engineers' Review	Benner (1975) Zotov (2011) Wienen et al. (2017)

Acronym	Technique's extended name	Description	Aspects considered	Accident modelling approach	Application instances	Underpinning concept /model	Agencies referring to the technique	Reference
MTO-analysis	Man, Technology and Organisation	The basis for the MTO-analysis is that human, organisational, and technical factors should be considered equally in an accident investigation. MTO analysis was originally developed for accident investigation in the nuclear industry. The technique is based on HPES (Human Performance Enhancement System). An accident investigation technique often labelled MTO Analysis has been applied in different fields in the Scandinavian countries. One advantage of the technique is that it gives a graphical overview of the course of an accident and the influencing factors. The MTO-analysis is based on three techniques: • Structured analysis by use of an event- and cause-diagram. • Change analysis by describing how events have deviated from earlier events or common practice. • Barrier analysis by identifying technological and administrative barriers, which have failed or are missing.	Human, organisational, and technical factors should be focused on equally in an accident investigation.	The output includes details of factors contributing to an accident. The investigation procedure can be summarised in five steps: 1) Describe the chain of events 2) Search for causes and conditions 3) Identify barriers 4) Analyse consequences 5) Develop recommendations	Aviation, Chemical industry, Electrical industry, Emergency services, Medical, Maritime, Railway, Road traffic, Space flights	Complex linear causality Process models INPO's Human Performance Evaluation System	Swedish Nuclear Power Inspectorate	Rollenhagen (1995) Hollnagel and Speziali (2008) Wienen et al. (2017)
MORT	The Management Oversight and Risk Tree	MORT is an analytical procedure for determining contributing factors and causes of accidents. In MORT, the accident is defined as an unwanted energy transfer due to the inadequacy of energy barriers and/or controls. The technique follows the energy transfer and deviation concepts. It involves identifying hazardous forms of energy and deviations from the planned and normal production process. The MORT diagram is a logic tree (the accident being the top event) with three main branches: S-factors, the specific oversights and omissions associated with the accident being investigated, R factors or assumed risks, which are risks known but for some reason not controlled, and M-factors, which are general characteristics of the management system that contributed to the mishap. The various elements in the tree are numbered and these numbers refer to a list with specific questions that the analyst should pose. Analysis involves going through all elements in the tree and making an assessment of each, based on two assessment levels: "satisfactory" and "less than adequate" (LTA), in order to examine the adequacy of measures. The technique includes a large checklist to help investigate the facts and look for evidence, it permits a large number of problems to be identified and it prompts the investigator to look not only for direct causes but also for causal contributions at the management and organisation levels.	It prompts the investigator to look not only for direct causes, but also for causal contributions at the management and organisation levels.	It forms a logic tree (with the accident being the top event). The tree has three main branches: S-factors (the specific oversights and omissions associated with the accident), R factors (i.e. assumed risks that are not controlled), and M-factors (inadequate characteristics of the management system). The model particularly displays an unwanted energy transfer due to inadequate energy barriers (controls).	Nuclear industry	Logic tree models Systemic models	UK's Health & Safety Executive American Institute of Chemical Engineers' Review	Johnson (1973) Knox and Eicher (1992) Kingston et al. (2009)

Acronym	Technique's extended name	Description	Aspects considered	Accident modelling approach	Application instances	Underpinning concept /model	Agencies referring to the technique	Reference
NSB	Norske Statesbaner	NSB was developed by the Norwegian State Railways (Norske Statesbaner – NSB) for the analysis of accidents in the railway sector. The technique combines the approaches of both Reason and Hollnagel and focuses on human, technical and organisational interaction. Using NSB, a sequence of events is identified which lead to an accident. NSB uses a questionnaire which focuses on factors such as procedures, training, communication, human-systems interface, tools and equipment, work preparation and local management, organisational management, and work environment.	NSB focuses on human, technical and organisational factors as well as work environment.	It outlines the sequence of events which occur due to broken or missing barriers.	Railway	Human information processing models Systemic models	Norwegian State Railways	Skriver et al. (2003)
OARU	Occupational Accident Research Unit-Deviation Analysis	OARU was developed for the Occupational Accident Research Unit (OARU) of the Royal Institute of Technology in Stockholm – Sweden. The technique involves two levels of reasoning: describing the accident sequence and finding the determining factors. The accident sequence has three phases: the initial (deviations from the normal process), the concluding phase (loss of control and uncontrolled flow of energy), and the injury phase (energy meets the human body and causes physical harm).	The technique recognises technical, organisational and social properties of the system that affect the accident sequence.	It looks into accidents from two angles: describing the event sequence and finding contributing factors. The event sequence involves initial, concluding and injury phases. The final product includes lists of deviations and accident determining factors.		Sequential accident causation models	Sweden's Royal Institute of Technology	Kjellen and Larsson (1981)
PEAT	Procedural Event Analysis Tool	PEAT was developed for the aviation industry. PEAT identifies key contributing factors to airline crew decisions. Remedial measures are then put in place to control the effects of contributing factors. The aim is to identify errors and to prevent the occurrence of similar errors in future. The tool includes database storage, analysis, and reporting capabilities.	Its primary objective is to identify specific contributing factors to flight crew error. These factors are conditions under management control that lead to procedural non-compliance.	It identifies key contributing factors to people's decisions and produces a list of recommendations used to prevent similar errors in future. It applies a structure analytics process that consists of a sequence of steps to identify key contributing factors to procedural non-compliance. This contributes to the development of recommendations aimed at the elimination of similar errors in the future.			UK's Health & Safety Executive	Moodi and Kimball (2004)
RCA	Root Cause Analysis	Root cause analysis is a methodology. It includes a set of techniques based on the same approach to identify underlying deficiencies in a safety management system. A root cause is a deficiency or contributing factor that addressing would prevent the same and similar accidents from occurring. Root cause analysis is a systematic approach based on core analytic techniques to determine the most important reasons for the accident.	It identifies both active errors (errors occurring at the point of interface between humans and a complex system) and latent errors (the hidden problems within systems that contribute to adverse events).	It is a systematic process that determines the most important reasons for accidents by identifying underlying deficiencies in a safety management system. It is based on facts and results obtained from the core analytic techniques. The RCA has four steps, of which one is an ECFC. It does not apply any specific accident model.	Energy industry, Nuclear industry	Single cause philosophy	US's Department of Energy US' Occupational Safety and Health Administration International Atomic Energy Agency	IAEA (1999) Rooney and Heuvel (2004) U.S. Department of Energy (2012)

Acronym	Technique's extended name	Description	Aspects considered	Accident modelling approach	Application instances	Underpinning concept /model	Agencies referring to the technique	Reference
SAFER	Systematic Approach For Error Reduction	SAFER is a generic disaster analysis technique developed by the Tokyo Electric Power Company (TEPCO). This technique involves analysing causes of human error and identifying the mismatch between the surrounding environment and human characteristics. The technique involves eight procedures.	It involves analysing causes of human error and identifying the mismatch between the surrounding environment and human characteristics.	Involves developing an event flowchart to understand, organise and communicate information. It also involves developing a diagram to represent the causal relationships among different factors contributing to an accident. Measures to cut the causality are then identified, prioritised and implemented.	Electricity industry	m-SHEL model	Tokyo Electric Power Company	Yoshizawa (1999) Hassall et al. (2014)
SCAT	Systematic Cause Analysis Technique	SCAT was developed by the International Loss Control Institute (ILCI). It originated from the Heinrich's domino theory and its updated version by Bird. It conceptualises an accident as a hierarchical sequence: loss (e.g. harm to people, properties, products or the environment), the accident event (the contact between the source of energy and the "victim"), the immediate causes and basic causes of an accident are the circumstances that precede the contact. They are called substandard acts/practices and substandard conditions.	The analysis is based on predefined categories of loss events, their potential direct and basic causes and guidance towards a management system structure for actions for improvement	The SCAT is presented as a chart which contains five elements including accident description, most common categories of contact that could have led to an accident, the most common immediate causes of this contact, underlying causes and a list of safety recommendations.	Aviation. Chemical industry, Electrical industry, Medical, Maritime, Road traffic	Sequential accident causation models Human information processing models Systemic models	UK's Health & Safety Executive American Institute of Chemical Engineers' Review The International Loss Control Institute	Bird and Germain (1996) Strömgren et al. (2015) Wienen et al. (2017)
SHELL	Software, Hardware, Environment, Liveware	The SHELL was developed in the aviation context. The model focuses on human factors and the relationship between aviation system environment and the human operator. It adopts a systems perspective and considers a range of contextual and task-related factors that affect operator performance.	The underlying notion is that the human element is the most critical and flexible component in the system, interacting directly with other system components, namely software, hardware, environment and liveware.	System components are represented as blocks. The human element is at the centre interacting directly with other system components, i.e. software, hardware, environment and liveware. The central block (human) has varied edges. The varied edges represent human limitations and variations in performance and suggest that other system components need to be adapted to accommodate human limitations.	Aviation		International Civil Aviation Organisation	Edwards (1988) International Civil Aviation Organization (2012) Australian Government Civil Aviation Safety Authority (2012)

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STAMP	Systems Theoretic Accident Model and Processes	This model was introduced by Leveson. STAMP takes a system perspective to represent accidents. It focuses on the interactions between system components as well as the control mechanisms used within the work system to limit these interactions. According to Leveson, safety is maintained by enforcing constraints on system behaviour. These constraints are sustained by loops of control actions and feedback information; thus, a state of dynamic equilibrium is maintained within the system. Based on STAMP, accidents result from inadequate enforcement of constraints in design, development and operations. That is, due to the inadequacy of controls structure, the system will not effectively handle any internal or external disturbance, such as a component failure or a disruption in interactions between system components.	The technique takes a system perspective to consider interactions between human, technology and environment within an organisational hierarchy. It also considers control mechanisms used within the system to control the interactions between elements.	It uses a hierarchical structure to represent interactions between socio-technical system elements. The main focus is on constraints the violation of which cause an accident. By representing the hierarchical levels of controls, constraints and processes, the STAMP diagram illustrates why a control structure that involves certain constraints was ineffective in the case of an accident.	Mostly academic applications in: Aviation, Chemical industry, Energy, Medical, Maritime, Road traffic, Railway, Space flight	System theory Feedback control system	UK's Health & Safety Executive	Leveson (2004) Wienen et al. (2017)
STEP	Sequentially Timed Events Plotting	STEP is a multi-linear approach that provides a systematic process for accident investigation. It takes on a process view of accident causation. An accident is viewed as a set of interacting events which happen in sequences or in parallel. An event is defined as an action performed by an actor. Normally, a flowchart is used to illustrate the accident process. The STEP process involves comparing the accident events with what was expected to happen.	The technique represents the multi-linear combinations of actions performed by actors (human or machine) leading to an accident. Each actor's actions are traced from the beginning of the accident trajectory to the finish.	Accident events are positioned relative to one another along a timeline. Links are established between the events (using arrows) to illustrate the process leading to an accident. Events are further broken down into sequences of single actions by different actors.	Aviation, Chemical industry, Road Transport, Railway industry, Maritime, Military, Electrical industry	Multi-linear and sequential models Process models	UK's Health & Safety Executive American Institute of Chemical Engineers' Review	Hendrick et al. (1986) Wienen et al. (2017)
SCM	Swiss Cheese Model	One of the most popular accident models, which is widely adopted in practice, is the Swiss Cheese Model introduced by Reason in 1990. It has been used in healthcare, in the aviation safety industry, and in emergency service organizations. The model represents human systems as multiple slices of Swiss cheese arranged side by side. Absence or failure of risk controls is represented as holes in the slices. The model captures the multi-causality of accidents and represents it as an interaction between latent conditions and active failures. Latent conditions are hidden gaps in organisation and workplace systems that may be present, yet unidentified, for many years. Some examples of latent conditions are poor management practices, gaps in supervision and lack of training. Active failures are the immediate observable causes in an accident which are easily identified, such as unsafe work practices and cutting corners. Accidents happen when the gaps in control defences align sequentially from organisational factors, to local workplace conditions, to individual (or team) unsafe acts, to failed defences and bad outcomes.	This model recognises multi-causality of accidents including human factors and organisational conditions.	The model depicts an accident as a sequential arrangement of gaps in controls at different organisational levels. Different levels are indicated as slices of Swiss cheese. holes in the slices represent gaps in controls. The model also depicts the contribution of distal organisational conditions to an accident.	Healthcare, Aviation. Emergency services, Engineering	Complex linear causality	South African Civil Aviation Authority International Maritime Organization	Reason (2016) Reason (2000)

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TRACEr	Technique for Retrospective Analysis of Cognitive Errors	TRACEr was initially developed for accident analysis in the air traffic control domain. Modified versions of TRACEr have also been used in other high-risk industries including railways and maritime. TRACEr is human error identification technique. It considers the human machine interface and external factors than might influence the operator's performance. Its taxonomy includes accident context, operator context and error recovery. Using TRACEr, the accident model is represented by a series of decision flow diagrams. Its application has been successful in analysing errors in Aircraft Proximity (AIRPROX) reports.	It primarily focuses on human error identification. It considers human-machine interface and external factors that may influence human performance.	It comprises seven taxonomies describing accident context, operator context, the error and the error recovery, while adopting a series of decision flow diagrams and tables.	Aviation, Railway industry	Error models Wickens' model of information processing in air traffic control	NSW Independent Transport Safety Reliability Regulator (ITSRR), RailCorp and Public Transport Safety Victoria (PTSV) UK's Health & Safety Executive International Civil Aviation Organization	Shorrock and Kirwan (2002) Shorrock and Kirwan (1999) Baysari et al. (2011)
TRIPOD Tripod-β	TRIPOD	TRIPOD was developed in for use in the oil and gas industry. It combines different theories of accident causation, including Reason's Swiss Cheese model and human factor-oriented theories, to generate a single 'TRIPOD tree' model. TRIPOD is based on the notion that unsafe acts are the direct causes of control/defence mechanisms in organisations, but active failures and unsafe acts are generated due to underlying organisational factors and mechanisms. The technique identified 11 categories of general failure types to classify deficiencies in a work system. The general failure types include human, organisational and technical factors. TRIPOD Beta is a computer-based tool that guides the investigator through the process of representing an accident as tree-like model.	It assumes that organisational failures are the main factors in accident causation. It identifies 11 categories of underlying mechanisms that lead to unsafe actions that give rise to failures. These mechanisms are associated with human, organisational and technical problem.	TRIPOD produces a tree diagram in which the extent of presence of 11 categories of general failure types (underlying mechanisms that produce unsafe acts) in an organisation is shown.	TRIPOD: Oil and gas industry Tripod-β: Chemical industry	Reason's Swiss Cheese Model	UK's Health & Safety Executive The Energy Institute U.K.	Wagenaar and van der Schrier (1997)
WAIT	Work Accidents Investigation Technique	WAIT is a toolkit for the investigation of occupational accidents and near misses. It follows the theoretical concepts proposed by Reason and Hollnagel. WAIT comprises a technique and a classification scheme. The overall investigation process follows Reason's model by beginning from the active failures and progressing to the distal latent conditions. In addition, when analysing human failure, WAIT applies a classification scheme of human error modes which was adopted from CREAM. WAIT analysis is undertaken in two sequential stages starting with a simplified investigation followed by a second in-depth analysis. In the first stage, active failures, as well as their associated influencing factors in the working environment, are identified. The second stage involves an in-depth analysis of individual and job factors followed by the identification of organisational and management deficiencies. Overall, the two stages comprise nine sequential steps.	WAIT analysis begins with the identification of active failures and their associated influencing factors in the work environment. It then progresses by considering more distal factors associated with organisational and management deficiencies.	It provides specific guidance for gathering information. It comprises two sequential phases, starting with a simplified investigation followed by a second in-depth analysis. It also implicitly adopts the classic tree technique to organise the information, however, no visible diagram is produced.	Railway industry, Aviation, Chemical industry, Energy, Financial services, Medical, Maritime, Transport.	Reason's accident causation model (SCM) Hollnagel's Cognitive Reliability and Error Analysis Method	UK's Health and Safety Commission	Jacinto and Aspinwall (2003) Wienen et al. (2017)

Acronym	Technique's extended name	Description	Aspects considered	Accident modelling approach	Application instances	Underpinning concept /model	Agencies referring to the technique	Reference
WBA	Why Because Analysis	WBA is a generic accident analysis technique. It begins with describing an accident. An iterative process is then applied to identify the causes and establishing cause-effect links between them. Different formal tests are used to identify the causal links, e.g. the counterfactual test and the causal sufficiently test. The outcome is a graph representing the causal factors to an accident and the cause-effect links between them.	It aims to analyse the failure of complex, open systems. It considers events, non-events, processes, states and other factors involved in an accident.	The investigator produces a why–because graph (WBG). The WBG depicts causal relations between factors of an accident. The nodes of the graph are factors, while, directed links denote cause–effect relationships between factors.	Aviation, Railway	Sequential models	UK's Health & Safety Executive Railway Systems Engineering and Traffic Safety Australian Civil Aviation Safety Authority	Ladkin and Loer (1998) Wienen et al. (2017)