OHS Body of Knowledge

Systems and Systems Thinking

Core Body of Knowledge for the Generalist OHS Professional

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Systems and Systems Thinking

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Core Body of Knowledge for the Generalist OHS Professional

Systems and Systems Thinking

Abstract

Occupational Health and Safety (OHS) is an emergent property of complex systems and cannot be adequately understood or managed without the adoption of a systems thinking approach that considers the overall work system, its many components, and the interactions occurring between them. Although the systems thinking approach is now prevalent in safety science research, a research-practice gap is hindering its application in OHS practice. This chapter provides an overview of the systems thinking approach to OHS, including its theoretical underpinnings and core safety models, and outlines a set of methods that can be applied to understand and manage OHS. The intention is for the reader to gain an understanding of key systems thinking principles and of state-of-the-art systems thinking-based risk assessment, accident analysis, and safety intervention development methods.

Keywords

systems theory, systems thinking, complexity, sociotechnical systems, risk assessment, accident analysis, incident reporting

Contextual reading

Readers should refer to 1.2 Contents for a full list of chapters and authors and 1.3 Synopsis of the OHS Body of Knowledge. Chapter 2, *Introduction* describes the background and development process while Chapter 3, *The OHS Professional: International and Australian Perspectives* provides a context by describing the role and professional environment.

Terminology

Depending on the jurisdiction and the organisation, Australian terminology refers to 'Occupational Health and Safety' (OHS), 'Occupational Safety and Health (OSH) or 'Work Health and Safety' (WHS). In line with international practice this publication uses OHS with the exception of specific reference to the Work Health and Safety (WHS) Act and related legislation.

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1 Introduction

Traditional strategies for managing occupational health and safety (OHS) are reaching the limits of their effectiveness (Carayon et al., 2015). In order to manage organisational health and safety, OHS professionals need to understand that OHS is an emergent property of complex work systems that cannot be conceptualised, measured or evaluated by looking only at component parts. Accidents tend to result from the interactions between component parts, rarely from malfunctioning of individual component parts. Systems thinking is a philosophy that enables OHS professionals to consider the broader work system and its interacting components to more effectively understand and manage safety.

The past three decades has seen a resurgence in the use of systems thinking-based models and methods to a point where they are now arguably dominant in safety science research (Hulme et al., 2019; Salmon et al., 2020; 2022). In addition to various established accident analysis methods, new systems thinking-based methods have been developed to support prospective risk assessment (e.g. Dallat et al., 2018; Hollnagel, 2012; Leveson, 2011), incident reporting and learning (e.g. Salmon et al., 2017), and the design of safety interventions (e.g. Goode et al., 2016; Read et al., 2018). These methods can be applied individually or in an integrated manner as part of safety management activities.

The aim of this chapter is to provide an overview of the systems thinking approach to OHS, outline a set of key systems thinking principles, and some of the methods that can be applied by both researchers and OHS professionals. The chapter begins by introducing systems thinking and discussing commonly applied systems thinking models that are relevant to OHS management. Following this, key principles are discussed and an overview of systems thinking-based methods for risk assessment, accident analysis, and safety intervention development is presented. The chapter closes by summarising the key points and outlining potential future applications arising from the changing nature of work.

2 An overview of systems thinking

Systems thinking represents “a way of seeing and talking about reality that helps us better understand and work with systems to influence the quality of our lives” (Kim, 1999). In this chapter the term ‘systems thinking’ is used to describe a philosophy within safety science that is applied to understand and respond to OHS issues.

The philosophy is underpinned by several models and analysis methods which assert that OHS and accidents are emergent properties arising from non-linear interactions between multiple components across complex sociotechnical systems (Leveson, 2004; Rasmussen, 1997). This creates a shared responsibility for OHS that spans all levels of work systems, up to and including regulatory bodies, government and international organisations. One of the core tenets of the philosophy is that the unit of analysis should be the overall work system, with any attempt to understand and manage safety looking beyond the so-called 'sharp-end' (e.g. individuals directly involved in incidents, the immediate circumstances, and the surrounding work environment) and considering factors within the broader organisational, social or political system. Accordingly, decisions and actions made at the government, regulatory and organisational levels of the work system also play a role in both OHS and adverse events. Systems thinking therefore offers an alternative approach to traditional individualistic and deterministic approaches that focus on human error and accident proneness (Read et al., 2021).

A system is "any group of interacting, interrelated, or interdependent parts that form a complex and unified whole that has a specific purpose" (Kim, 1999). According to Meadows (2008), a system must comprise three core components:

- Elements (or components)
- Interconnections, and
- A function or purpose.

For example, a university comprises components such as academic staff, administrators, students, lecture theatres, tutorial rooms, research laboratories, teaching and research materials, policies, and procedures to name only a few. The purpose of a university is, amongst other things, to create new knowledge, educate society, and generate wealth. Interconnections between University components are required to achieve these purposes. These include interactions between academic staff and administrators, between academic staff and students, between research staff and participants, between research staff and external partners, funding bodies, and collaborators, and between all staff and the materials required for their work. Whenever there are groups of interacting, interrelated and interdependent parts that work together toward a specific goal, they can be considered a system (Salmon et al., 2022).

Workplaces of all shapes and sizes can therefore be characterised as systems. *Work systems* comprise frontline or 'sharp-end' workers, the work environment, tools and equipment, policies and procedures, training programs, supervisors, managers, regulators, rules, and regulations and so on. Interactions between these work system 'components' creates 'emergent properties' which are essentially what we see as behaviour in work systems. Systems thinking therefore provides a way of thinking about work systems that can help OHS professionals to understand them in terms of what they comprise and why they behave as they do, in turn enabling them to optimise work performance and the health and wellbeing of those working within them.

To understand the systems thinking approach to OHS it is important to understand both its origins and its manifestations in OHS research and practice. Systems thinking is fundamentally interdisciplinary and has its roots in systems theory and complexity science. In the area of OHS specifically, systems thinking is central to:

- Sociotechnical Systems Theory (Trist & Bamforth, 1951)
- Rasmussen's Risk Management Framework (RMF; Rasmussen, 1997)
- Leveson's Systems Theoretic Accident Model and Processes (STAMP; Leveson, 2004); and
- Dekker's Drift into Failure (DIF) model (Dekker, 2011).

An overview of these theoretical perspectives is provided in sections 3 and 4.

3 Theoretical perspectives underpinning systems thinking

3.1 Systems theory

Systems theory first emerged within the biological and physical sciences. In his seminal work Von Bertalanffy (1969) outlined a set of principles of open systems as applied to living organisms. Skyttner (2001) subsequently outlined the properties of general systems theory for open systems, based on the work of Von Bertalanffy as well as numerous other systems theorists. According to Skyttner, open systems display the following characteristics:

- *Interrelationship and interdependence of components and their attributes:* the components of the system are interconnected rather than disparate.
- *Holism:* the system exhibits emergent properties that cannot be identified from analysing the components; the whole is more than the sum of its components.
- *Goal seeking:* the system has a goal or end state.
- *Transformation processes*: the system transforms inputs into outputs to attain its goal/s.
- *Inputs and outputs:* inputs are taken from the environment and transformed; outputs are returned to the environment.
- *Entropy:* systems tend toward disorder or randomness without intervention.
- *Regulation:* the interrelated components constituting the system must be regulated for goals to be obtained. Regulation can be achieved through control and feedback loops.
- *Hierarchy:* systems comprise sub-systems nested within one another in a hierarchical structure.
- *Differentiation:* specialised units performed specialised functions within a system.
- *Equifinality:* from the same initial conditions, systems have different alternative ways of achieving the same goal.

- *Multifinality:* from the same initial conditions, systems can obtain different goals and objectives.

These system properties provide the basis for *adaptive capacity*, which has been defined as "the *properties* of a system that enable it to *modify itself* in order to *maintain* or *achieve a desired state* in the face of perceived or actual stress" (Jakku & Lynam, 2010, p. 3). Because open systems are in a continual state of change as inputs are transformed to outputs, those most able to continue to achieve goals and avoid entropy are those that can adapt to external environmental conditions (i.e. changes to inputs and outputs) by using alternative means (via the property of equifinality). Matters such as how regulatory mechanisms within the system operate and the amount of differentiation available within the system can affect its capacity to adapt and to achieve its goals.

According to general systems theory, OHS is an emergent property of the interactions between system components. OHS therefore cannot be fully analysed or understood by examining components of the system without consideration of the whole (Ottino, 2003). For example, attempting to understand a worker's behaviour without considering the many interactions between other work system components and their influence on the worker's behaviour provides a limited perspective. Further, systems theory suggests that understanding OHS requires an understanding of the variability of behaviour and performance within regulatory structures. It also requires an understanding of how the system hierarchy affects system functioning, particularly the extent to which consistency and coherence is maintained across hierarchical levels. Finally, examining safety from a systems perspective requires acknowledgement that systems are dynamic, not static. Open systems are in a continual state of change as inputs are transformed to outputs, with the system tending towards a state of entropy over time. This means that even systems with exemplary OHS performance are continually being pushed toward their safety boundaries.

3.2 Complexity theory

Complexity science is the discipline concerned with attempting to understand and respond to problems that are dynamic and unpredictable, multi-dimensional, and comprise various interrelated components (Salmon et al., 2022). Whereas traditional reductionist approaches attempt to understand an entity by focusing on its smaller parts in isolation, complexity science also considers the interactions among elements, thus providing insights into dynamic processes and emergent behaviours, and a more holistic view (Turner & Baker, 2019). Analysing systems and interactions in this way involves the use of both quantitative and qualitative modelling techniques with the unit of analysis often representing the broader system in which the behaviours of interest occur.

Complexity has proven difficult to define (Cilliers, 1998); however, various authors have outlined core characteristics that can be found in complex systems (e.g. Cilliers 1998; Holland, 2014; Skyttner 2001; von Bertalanffy 1969). According to Luke and Stamatakis (2012), complex systems exhibit the following properties:

> …they are made up of a large number of heterogenous elements; these elements interact with each other; the interactions produce an emergent effect that is different from the effects of the individual elements alone; and, this effect persists over time and adapts to changing circumstances. (p.2).

Cilliers (1998) describes the following set of complex system characteristics:

- *Complex systems comprise multiple components*. According to Cilliers, complex systems comprise many components that interact dynamically with one another. Many components are necessary, but this is not sufficient – dynamic interactions between components are also required (Cilliers, 1998).
- *Interactions between components are multiple, rich, and non-linear*. Interactions between components are abundant and can be non-linear in nature, meaning that there is asymmetry between input and output (Cilliers, 1998), and small events can produce large outcomes and vice versa (Dekker, 2011). Emergent properties arising from interactions mean that "the action of the whole is more than the sum of its parts" (Holland, 2014, p. 2). Holland (2014) explains emergence by discussing the 'wetness' of water. Wetness is not something that can be assigned to individual water molecules, rather it is an emergent property arising from the interaction of water molecules. An action taken by a worker then, for example, is an emergent property of the interaction between components of the work system including other workers, equipment, supervisors and managers, policies and procedures, training programs and so on.
- *Interactions are short-range in nature*. Cilliers (1998) describes how information received by components mainly derives from proximal components and how long-range interactions are limited. However, as components often interact with many other components, it is possible to influence distal components through just a few interactions. For example, most workers are not likely to interact with the CEO of their employing organisation; however, they interact with their supervisors who in turn interact with managers and senior managers who in turn interact with the CEO (Salmon et al., 2022).
- *There are recurrent loops in the interactions*. The effect of an activity can feed back onto itself either directly or through other components. These feedback loops can be positive (reinforcing) or negative (balancing), and both are necessary for systems to function (Cilliers, 1998).
- *Complex systems are open systems*. Complex systems are open systems meaning that it is difficult to define their boundaries and that they interact with their environment. As a result of these interactions complex systems have an influence on their environment and are influenced by their environment in return (Cilliers, 1998). Therefore, Skyttner's (2001) properties of open systems, described above, apply to complex systems.
- *Components are ignorant of the system and its behaviour*. Components within the system are ignorant in that they respond only to local information and do not

fully comprehend the behaviour of the overall system or the effects of their actions on the behaviour of the overall system (Cilliers, 1998).

- *Complex systems are dynamic and do not operate in a state of equilibrium*. Constant inputs always need to be made by components to keep complex systems functioning. Without constant inputs, complex systems are unable to function (Cilliers, 1998).
- *Complex systems have a history and path dependence*. Within complex systems there is a dependence on initial conditions whereby past behaviour is co-responsible for present behaviour. This means that decisions and actions made previously (even many years previously) influence the here and now (Cilliers, 1998).

Complexity science is an extensive field. Castellani and Gerrits' (2021) Map of the Complexity Sciences (Figure 1) depicts the historical progression of five intellectual traditions – dynamical systems theory, systems science, complex systems theory, cybernetics and artificial intelligence. As noted by Hulme et al., (2021a), these traditions share several philosophical, theoretical and practical commonalities in their approaches to examining complex phenomena. Figure 1 indicates that when complexity is subjected to formal analysis there is no single, unified understanding of what it is from an operational standpoint. Rather, "researchers have a multitude of highly capable scientific approaches and modelling techniques at their disposal to understand complexity and complex problems so long as a suitable justification for their selection is offered" (Hulme et al., 2021a, p. 22). In the OHS context, this means there are various methods available to support the analysis of complex work (Salmon et al., 2022).

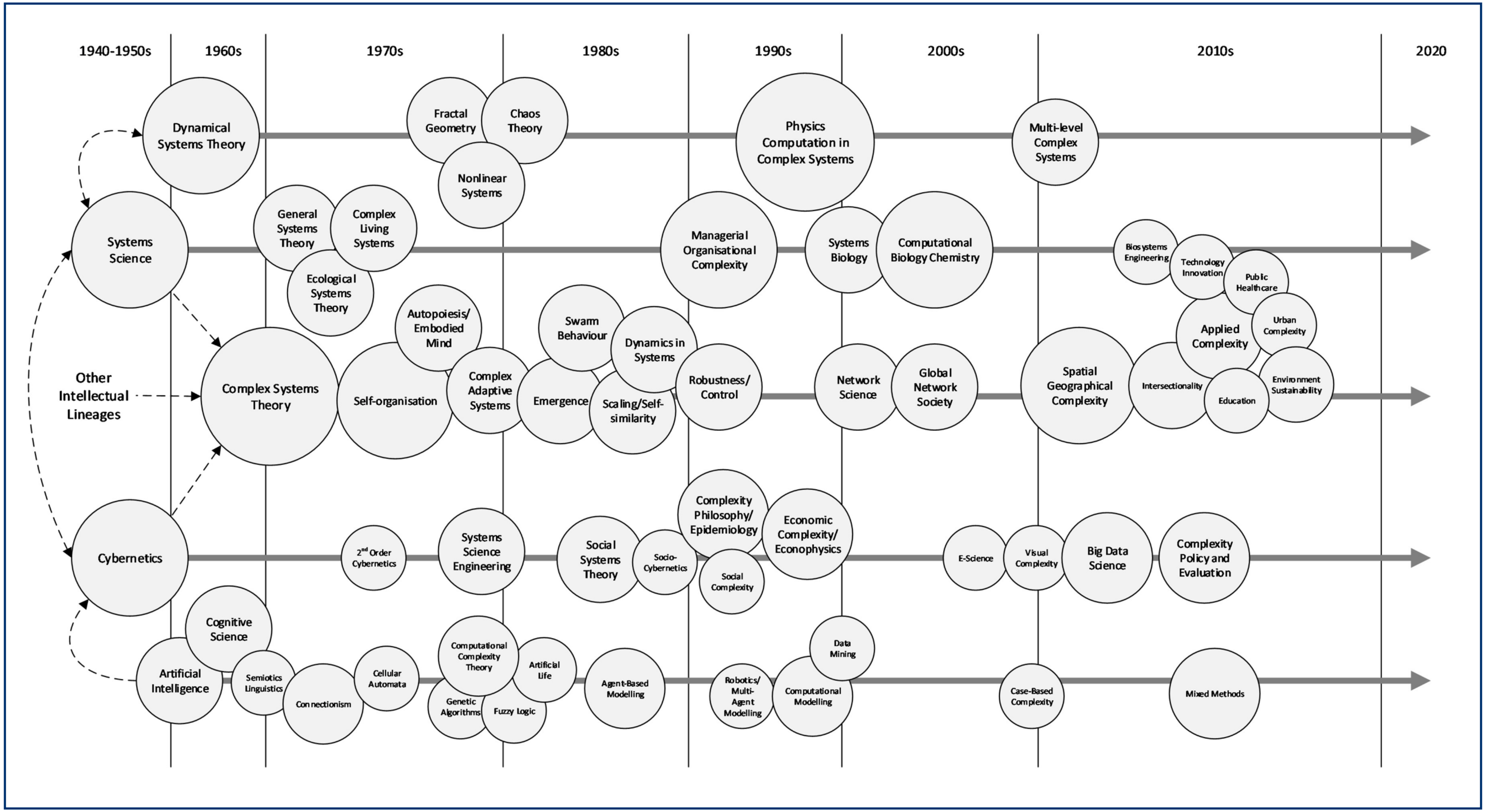

Figure 1: Historical evolution of complexity science (adapted from Castallini & Gerrits, 2021)

4 Systems thinking and OHS

This section introduces a series of systems thinking-based theories and models that can be useful for OHS applications.

4.1 Sociotechnical Systems Theory

The term 'sociotechnical system' was coined in the 1950s[1] to describe "a method of viewing organizations which emphasises the interrelatedness of the functioning of the social and technological subsystems of the organization and the relation of the organization as a whole to the environment in which it operates" (Pasmore et al., 1982, pp. 1181-1182). Sociotechnical Systems (STS) Theory was subsequently proposed in the 1950s based on a program of research undertaken at the Tavistock Institute exploring the disruptive impacts of new technologies on human work (Eason, 2008; Trist & Bamforth, 1951). STS theory is based on systems theory and contains principles related to participative democracy and humanistic values. This facilitates a focus on both the performance of the work system and the well-being and experiences of the people performing the work (Clegg, 2000). A key contribution of STS theory is the provision of various principles and values to support the design of sociotechnical systems that align with open systems principles (e.g. Cherns, 1976; Clegg, 2000; Davis, 1982; Walker et al., 2010). These are presented in Figure 2 which illustrates how the design process principles underpinned the values (shown by blue arrows), influence the content of the designed system, which can then promote systems with adaptive capacity.

Being underpinned by systems theory, STS theory shares the notion that sociotechnical systems are comprised of both social and technical elements co-engaged in the pursuit of shared goals. The interaction of these social and technical aspects creates emergent properties and the conditions for either successful or unsuccessful system performance (Walker et al., 2010). Accordingly, joint optimisation – as opposed to optimisation of solely the social or technical aspects – is required for safe and efficient system performance (Badham et al., 2006).

There is a significant body of work in which STS theory has been applied to the design of work and more recently societal systems. For example, Pasmore et al. (1982) conducted a meta-analysis of 134 studies undertaken between 1950 and 1980 that involved applications of STS theory; the results included evidence of improved productivity, attitudes, safety and quality control in most studies that reported on these variables. Until now the STS approach

[1] This was in the context of the classic studies undertaken at the UK Tavistock Institute that explored the disruptive impacts of technology (i.e. coal mining machinery) on coal miners. See, for example, Trist & Bamforth (1951).

has been applied overwhelmingly to the introduction of new technologies (such as IT systems) within organisations (Davis et al., 2014) given that such systems are traditionally designed to meet technical needs, without consideration of how they will affect the social system around the work (for example, impacts on informal communication and coordination within teams). However, the availability of OHS-applicable STS methods has seen the application of STS theory in many safety contexts (Waterson et al., 2015); for example, the re-design of transport systems to improve safety and the identification of incident prevention strategies in the led outdoor activity domain (Read et al., 2018).

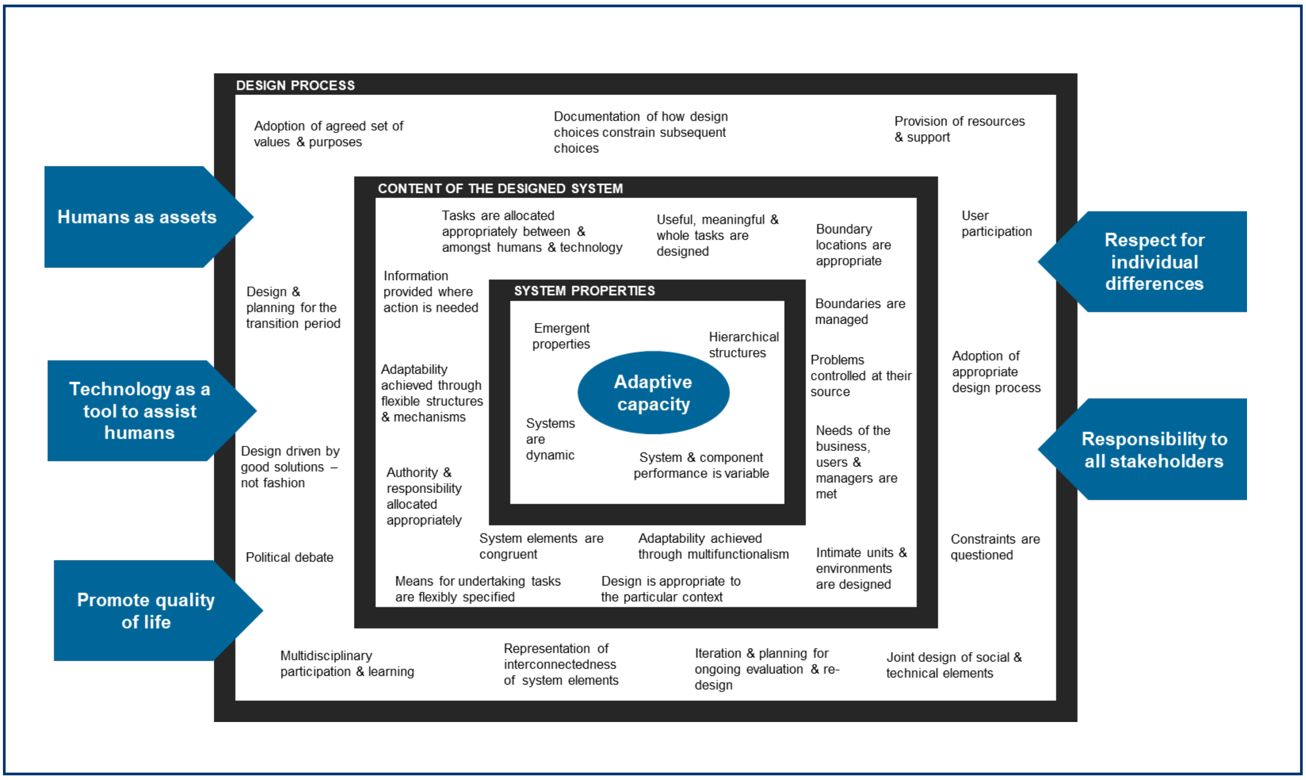

Figure 2: Sociotechnical systems theory, principles and values (adapted from Read et al., 2016, p. 356)

4.2 Rasmussen's Risk Management Framework

Rasmussen's Risk Management Framework (RMF) is currently the most popular systems thinking model in the area of OHS (Salmon et al., 2020). According to Rasmussen's RMF (Rasmussen, 1997; see Figure 3), systems comprise various hierarchical levels (e.g. government, regulators, company, company management, staff, and work), each of which contain actors (individuals, organisations or technologies) who are co-responsible for performance and safety. According to Rasmussen, decisions and actions at all levels of the hierarchy interact to shape performance, meaning both safety and accidents are influenced by all actors, not just frontline workers. Further, the RMF argues that accidents are caused by multiple contributing factors, not just one flawed decision or action. A key implication is that it is not possible to fully understand safety and accidents by decomposing the system and examining its components in isolation; rather, it is the interactions between all system components that are of interest.

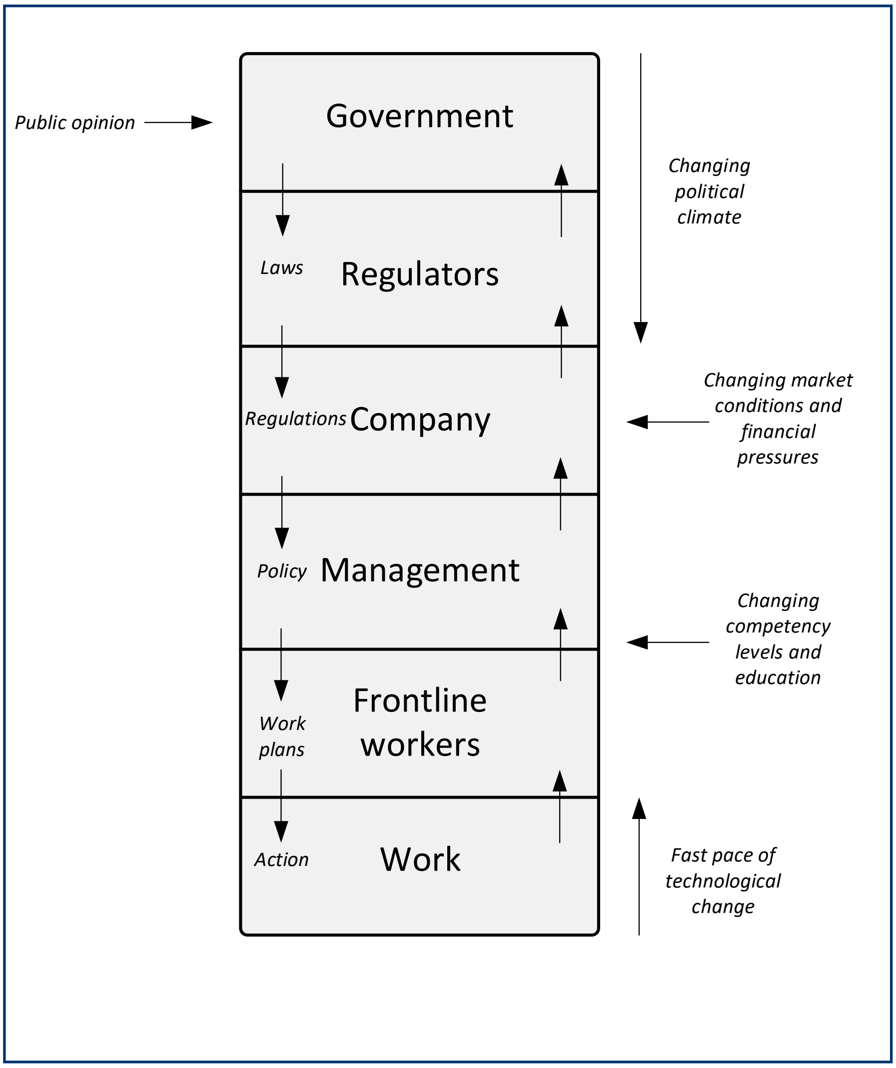

Figure 3: Rasmussen's risk management framework (adapted from Rasmussen, 1997).

Rasmussen's framework makes a series of assertions regarding safety and accident causation.

- Safety and accidents are emergent properties that are created by the decisions and actions of all system actors, not just frontline workers alone
- Accidents are caused by multiple contributing factors from across the work

system, not just by a single poor decision or action at the sharp-end

- Accidents can result from a lack of, or, poor communication and feedback (or 'vertical integration') across system levels, not just from deficiencies at one level alone
- Lack of vertical integration is caused, in part, by lack of feedback across levels of work and societal systems
- Behaviours within work and societal systems are not static, they migrate over time and under the influence of various pressures such as production, financial, and psychological pressures
- Migration occurs at multiple levels of work and societal systems
- Migration of practices (which occurs at multiple levels) causes work and societal system defences to degrade and erode gradually over time; accidents are caused by a combination of this migration and a triggering event(s). [2]

Rasmussen (1997) stressed the importance of identifying the boundaries of safe performance and the pressures (e.g. unacceptable workload, financial constraints) in the dynamic work context that can force *migration* towards or across these boundaries.[3] Migration is an important concept for OHS as it describes how work practices can gradually and unknowingly shift from safe to unsafe. The concept is based on the 'Brownian movements' of gas molecules and outlines how various pressures act to move work practices toward safety and performance boundaries. Financial constraints can influence organisations to shift their behaviour toward greater cost efficiencies which can often result in safety trade-offs. Production pressures can create unacceptable workloads as people working within the system try to meet difficult economic and financial objectives. The boundary of economic failure creates a pressure towards greater efficiency, which works in opposition to a similar pressure against excessive workload. These pressures create adaptations and variations in behaviour that are not designed or foreseen, can be hard to predict, and ultimately lead to increasingly emergent system behaviours, both good and bad (Clegg, 2000; Qureshi, 2008). If allowed to continue unchecked over time, migration in work practices can cause systems to cross safety boundaries resulting in adverse events (Qureshi, 2007; Rasmussen, 1997). The key, then, is to detect in advance where the boundaries are and how close the organisation is to them (Salmon et al., 2017).

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[2] In considering accident causation, Rasmussen (1997, p. 189) stated "court reports from several accidents such as Bhopal, Flixborough, Zeebrugge, and Chernobyl demonstrate that they have not been caused by a coincidence of independent failures and human errors, but by a systematic migration of organisational behaviour toward accident under the influence of pressure toward cost-effectiveness in an aggressive, competitive environment."

[3] In describing *migration*, Rasmussen (1997, p. 189) drew an analogy between behaviour moving towards the boundary of acceptable performance and "the 'Brownian movements' of the molecules of a gas."

4.3 The Systems Theoretic Accident Model and Process (STAMP)

The Systems Theoretic Accident Model and Process (STAMP) (Leveson, 2004) is a model of accident causation which provides useful tools for OHS including a proactive risk assessment method, the Systems Theoretic Process Analysis (STPA) (Leveson, 2011), and a retrospective incident analysis method, the Causal Analysis based on Systems Theory (CAST; Leveson, 2004). STAMP is based on control theory and Rasmussen's RMF and suggests that accidents occur when interactions between system components are not controlled through managerial, organisational, physical, operational and manufacturing-based controls. Leveson (2004) describes how safety risks are managed through a hierarchy of controls and feedback mechanisms and how failure to adequately control emergent properties results in accidents. STAMP therefore views OHS as an issue of control that should be managed through the enforcement of constraints on the behaviour and interactions of key agents across the system.

Central to STAMP, STPA and CAST is Leveson's notion of a system control structure that is used to manage safety during both system design and system operation (See Figure 4). The control structure is based on Rasmussen's risk management framework and incorporates a series of hierarchical system levels which are linked through control and feedback mechanisms designed to manage OHS. As shown in Figure 4, the control structure levels include congress and legislatures at the top (i.e. government and policy) and progress down through government and regulatory agencies and company management, to operations management and physical and technical work processes. Each level of the control structure includes a description of the relevant agents and organisations that play a role in system design or operation. Control and feedback mechanisms are included to show what controls are enacted down the hierarchy and what information about the status of the system is sent back up the hierarchy. Controls (or reference channels) are shown in Figure 4 via the arrows flowing down the hierarchy and feedback mechanisms (or measuring channels) are shown via the arrows flowing up the hierarchy. In other words, entities have control and authority over the entities immediately below them and are likewise subject to control and authority from the entities immediately above.

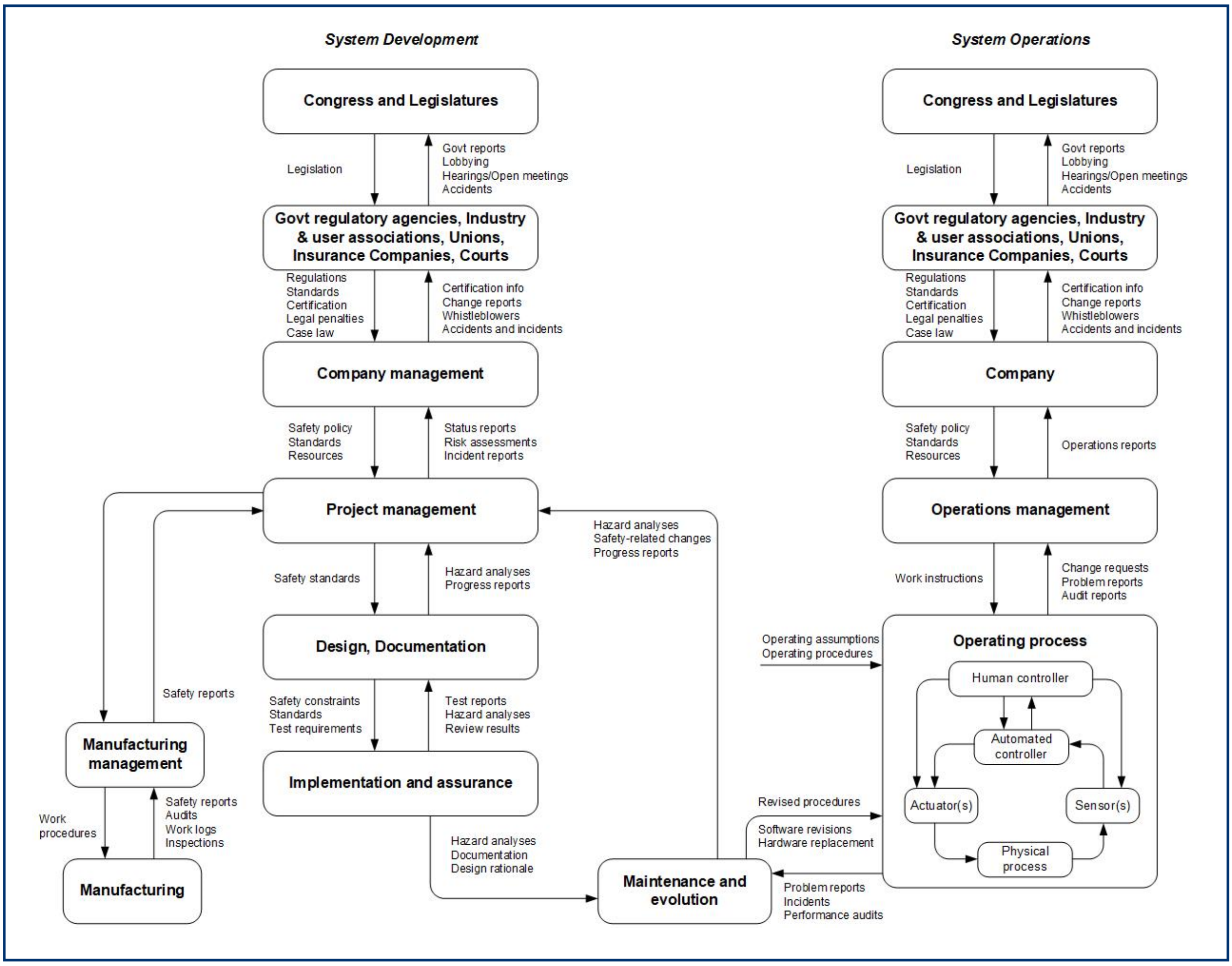

Figure 4: Generic STAMP control structure model (adapted from Leveson, 2004).

4.4 Drift into Failure (DIF) model

A more recent instantiation of systems thinking relevant for OHS management is Dekker's Drift Into Failure (DIF) model (Dekker, 2011). Inspired by systems and complexity theory, Snook's (2000) concept of practical drift, and building on Rasmussen's risk management framework, Dekker's DIF model describes how system behaviour gradually shifts, unchecked and often unrecognised, to a point at which safety is compromised. According to Dekker, accidents in complex systems result from the non-linear interactions between what often seem locally to be normal and acceptable behaviours. Multiple decisions and actions, occurring over time, in different contexts, under different constraints, and with only limited knowledge of effects, gradually lead the system beyond the safety boundary towards adverse events.

The DIF model outlines five key aspects of drift:

- Scarcity and competition
- Decrementalism
- Sensitive dependence on initial conditions
- Unruly technologies
- Contribution of the protective structure.

Scarcity and competition reflects the fact that, in most work and societal systems there is limited availability of resources and competition between organisations for these resources. According to Dekker, operations are influenced by various resource constraints (e.g. financial, personnel, organisational and regulatory constraints) and strong competition exists between organisations operating in similar contexts. As a result, multiple trade-offs are made in order to remove or balance resource limitations and production pressures, and this often leads to a steady adaptation of processes and technologies toward unsafe practices (Dekker, 2011).

Decrementalism refers to the gradual, step-by-step degradation of safe operational practices to the point at which they become unsafe. A key feature of decrementalism is that each change in practice often seems appropriate and safe and is accepted by system stakeholders. Each small change is accepted as it is only a minor departure from the previously accepted norm, and safe, successful performance following each step is taken as an indicator that the adaptation is safe (Dekker, 2011). In fact, when combined over time, each small modification to practice eventually creates a major shift in behaviour, often from safe toward unsafe. A simple example in the OHS context would be minor cost driven extensions to equipment maintenance schedules which, over time, would result in work equipment being used for far longer periods before receiving maintenance.

Sensitive dependence on initial conditions, also known as the butterfly effect (see Hilborn, 2004), describes how even minor differences in initial conditions can lead to dramatic changes in system behaviour (Hilborn, 2004). In the OHS context this means that the initial conditions of the work or societal system continue to influence OHS today. Decisions and actions made even years previously continue to interact with and influence system components and can often play a causal role in adverse events. For example, in relation to the Pike River disaster (see section 5.2.1), industry deregulation was a critical antecedent which occurred many years prior to the accident (Hulme et al., 2021b). Specifically, the 1992/93 repeal of the New Zealand Coal Mines Act of 1979 and liquidation of the mining inspectorate had an influence on both the initial mine design and construction, as well as the management strategies and more broadly regulation of mining practices.

Unruly technologies refer to the lack of control that stakeholders have over the technologies that are introduced into work and societal systems. Despite the best efforts of designers, certification bodies and regulators, new technologies often behave in unexpected ways when introduced into complex systems (Dekker, 2011). This is typically a result of failing to consider how the new technology might interact with other components in the system or emergent uses of the technology which arise due to system constraints. An example of unruly technology within road safety is drivers use of mobile phones whilst driving and the subsequent impact on driving performance and safety (Salmon et al., 2012).

Finally, *contribution of the protective structure* refers to the influence of the various structures that are in place to ensure that systems operate in a safe manner. Protective structures include regulatory arrangements, safety committees and teams, and quality review and certification boards to name only a few. According to Dekker (2011) in addition to often failing to intervene when it should, the protective structure can actively contribute to drift through poor knowledge, lack of access and information, conflicting goals, and decisions that make only local sense. For example, risk controls brought in to solve one problem may introduce new problems elsewhere in the system, pushing it toward the safety boundary. The Boeing Manoeuvring Characteristics Augmentation System (MCAS) provides an example of a risk control that brought unintended negative consequences, within a wider protective structure that failed to ensure the safe introduction of automation within aviation. The Federal Aviation Administration (FAA) were criticised for approving the MCAS system, for not adequately reviewing the new MCAS, and for delegating too much oversight to Boeing for managing the safety of new technologies (Leggett, 2019).

4.5 The systems thinking tenets

Although the systems thinking models such as those described above have commonalities based on systems and complexity theory, there are also key points of difference and no single model is universally accepted (Grant et al., 2018). For example, Leveson's STAMP bases its control structure upon Rasmussen's system hierarchy, but views accident causation as predominantly a problem of control and feedback (Leveson, 2011). Dekker's DIF model again builds upon Rasmussen's idea of migration and incorporates concepts from complexity science such as sensitive dependence on initial conditions and decrementalism.

Seeking some consensus, Grant et al. (2018) reviewed the five most frequently cited accident causation models – Rasmussen's (1997) RMF, Leveson's (2004) STAMP, Dekker's (2011) DIF model, and Perrow's (1984) Normal Accident Theory, and Hollnagel's (2012) Functional Resonance Analysis Model (FRAM) to identify a set of work system features which interact to create both safe and unsafe performance. Labelled the 'system thinking tenets', they represent features of complex systems that create either safe or unsafe behaviour. Early testing provided positive evidence for their presence in the lead up to major accidents. Grant et al., (2019) explored the extent to which the tenets played a contributory role in the Kimberly Ultramarathon fire incident that occurred in 2011 in Western Australia. They concluded that all tenets were present and that using the tenets to describe the incident's contributory factors provided a useful explanation of the incident and its causes. Hulme et al. (2021b) conducted a more comprehensive assessment to explore the presence of the tenets in 11 major incidents occurring in a range of safety critical domains. Hulme and colleagues (2021b) reported that all 15 tenets were found across the 11 accidents analysed. They also reported that some tenets appeared more often than others, with less frequently identified tenets including feedback loops, modularity, decrementalism, and unruly technologies.

Salmon et al. (2023) revised and updated the tenets via expert Delphi study to form a final set of 10 (Table 1). It is important to note that all ten are not required to create an adverse event and that different combinations of the tenets can co-occur to create adverse events (Hulme et al., 2021b). The ten tenets therefore represent aspects of system behaviour that, either together or in isolation, are thought to create adverse events in complex sociotechnical systems. An important contribution of this work is therefore to provide a set of agreed upon tenets that reflect the core philosophies of state-of-the-art accident causation theory, models and approaches (Dekker, 2011; Hollnagel, 2012; Perrow, 1984; Rasmussen, 1997; Leveson, 2004).

Table 1: Salmon et al.'s (2023) systems thinking tenets.

Tenet	Definition	Unsafe system description	
Vertical integration	Interactions between elements within and across levels of the system hierarchy.	*Decisions and actions do not filter through the system and impact behaviour. Information regarding the current status of the system across levels is not used when making decisions.*	
Constraints	System elements that impose limits on, or influence, other system elements.	A constraint that has failed to perform its function and/or restrict an appropriate response, behaviour or the desired variability in performance.	
Normal performance	Routine behaviours that are typically performed within a system, regardless of formal rules and procedures.	*Routine and expected behaviours that played a contributory role (i.e. were a 'normal' part of the aetiological mechanism).*	
Performance variability	System elements vary their behaviour in response to changing conditions in the system and its environment.	Behaviours are adjusted to cope with changing circumstances; however, the outcome of the adjustment is not desirable.	
Emergence	Outcomes that result from interactions between elements in the system that cannot be fully explained or reliably predicted in advance by examining the elements in isolation.	Emergent behaviours or outcomes that are unsafe or undermine the goals of the system.	
Tight and loose coupling	The degree of interdependence that exists between system elements.	Tight coupling: Cascading failures that propagate quickly and widely through the	Loose coupling: Loss of control regulating behaviours. Too much

Tenet	Definition	Unsafe system description	
		system when one element breaks down.	independence between elements.
Feedback loops	Self-reinforcing and self-correcting forms of feedback between system elements which influence the system's behavior.	Feedback mechanisms are not controlled and amplify through the system, increasing risk and accident potential.	
Sensitive dependence on initial conditions	Characteristics of the originally designed system that influence system behaviour at a later point in time.	*Initial conditions and their influence on the system create unsafe behaviours.*	
Decrementalism	Minor and accepted modifications to system elements that gradually create a significant change in system behavior.	Constant small changes eventually create unsafe behaviours and practice through migration and drift.	
Contribution of the protective structure	The contribution of the formal and organised structure that is intended to protect and optimise system safety.	*Protective structure competes for resources with negative effects on behaviour and safety.*	

To summarise, the key principles of systems thinking for OHS management are presented below.

Key principles of systems thinking for OHS management

- Both safety and accidents are caused by:
    - Interacting decisions and actions of people operating across all levels of work systems including supervisors, managers, regulators and government
    - Multiple interacting contributory factors, some of which reside outside of the workers, equipment, and work environment involved.
- Work practices adapt and change under the influence of various pressures. These 'migrations' or 'drifts' in practice bring organisations closer to safety boundaries.
- Communication and feedback across work systems is critical to maintaining safety and optimal performance.
- Efforts to understand behavior, safety and risk must focus on:
    - The whole (i.e. the overall work system) and not the parts (i.e. individual workers)
    - The interactions between work system components and not the behaviour of individual components.

5 Systems thinking and safety management methods

This section outlines an initial set of practical systems thinking-based methods which can be used to apply systems thinking principles in OHS risk assessment, accident analysis, and the development of safety interventions.[4]

5.1 Risk assessment

5.1.1 Application of systems thinking to risk assessment

Prospective risk assessment is a critical aspect of OHS management systems. Unlike accident analysis which takes a reactive approach to modelling and understanding the causes of adverse incidents, risk assessment aims to proactively identify hazards and risks that conceivably pose a threat to the health and well-being of workers.

Formal risk assessment involves the use of structured methods to proactively identify potential hazards that may create adverse outcomes during specific work tasks. Various forms of qualitative and quantitative methods exist, enabling the identification of hazards and associated risks and/or an estimation of their likelihood of occurrence (see Dallat et al., 2019 for a review).[5] The ability to forecast potential loss events prior to their occurrence is essential for developing new interventions that ensure that OHS practices are safe, productive and sustainable long-term. Despite the value and utility of an established OHS strategy and management program, most risk assessment activities have traditionally provided a component-level view, focusing on individual behaviours in an attempt to identify potential errors and faults resulting from poor decisions, lapses in judgement and flawed beliefs (Dallat et al., 2019; Salmon et al., 2011; Stanton et al., 2019). This approach is now widely accepted to be reductive and largely unhelpful when it comes to enhancing safety and optimising overall system and organisational performance (Leveson, 2011). Accordingly, the systems thinking risk assessment paradigm is gaining increasing attention and application in OHS research and practice.

Applying the systems thinking paradigm to risk assessment follows the same conceptual approach to that used in accident analysis and investigation. Like accidents, hazards and risks within safety-critical workplaces and organisations emerge from the complex interactions among a network of human and non-human factors (Dallat et al., 2019; Perrow,

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[4] Additional methods are available to support safety management activities (see Salmon et al., 2022).

[5] See also *OHS BoK* 31.1 Risk for a discussion on risk and risk assessment.

1984; Rasmussen, 1997). These factors reside and interact across all levels of a system, including the political and organisational levels at the 'blunt end', down to and including the environment and equipment at the 'sharp-end' (Dallat et al., 2018; Salmon et al., 2020; Stanton et al., 2019). Thus, the systems thinking risk assessment approach recognises that the 'whole workplace system' is greater than the sum of its 'individual parts', and that anticipating loss events requires appreciation for several principles including holism, complexity and multiscale factor interactions.

5.1.2 The risk assessment cycle

The management of risks and the enhancement of health and safety is an ongoing and recognised OHS process that helps organisations respond to change and facilitate continuous improvement in working practices. The effective systematic management of risks includes four main sequential steps that can be conceptualised in the form of a continuous cycle:

- Hazard identification (what can cause harm?)
- Risk assessment (what is the probability of that harm occurring?)
- Hazard and risk control (implementing interventions to control hazards and mitigate risk)
- Review and refine (are the interventions from step three working as planned?) (see for example SWA, 2018).

As with traditional methods, the systems thinking risk assessment approach follows this four-stage process.

5.1.3 Systems thinking-based risk assessment methods

The principles of the systems thinking risk assessment approach are grounded in systems theory and complexity science. Key principles and their OHS description can be viewed in Table 2. Systems thinking risk assessment methods and models should ideally be underpinned by these principles in order to effectively translate their theoretical basis and meaning through practical application.

There are currently three dedicated systems thinking risk assessment methods that are domain independent and publicly available:

- The System-Theoretic Process Analysis (STPA) method (Leveson, 2011)
- The Event Analysis of Systemic Teamwork Broken Links (EAST-BL) method (Stanton and Harvey, 2017)
- The Networked Hazard Analysis and Risk Management System (Net-HARMS) (Dallat et al., 2018).

Unlike STPA, which has been used in various safety-critical domains (e.g., Allison et al., 2017; Leveson, 2011; Mahajan et al., 2017; Revell et al., 2019; Rising & Leveson, 2018; Schmid & Stanton, 2018), EAST-BL and Net-HARMS are relatively new approaches that were designed to incorporate the systems thinking principles outlined earlier. As the most established method, a detailed overview of STPA is provided below.

Table 2: Characteristics of a systems thinking risk assessment approach applied to OHS[6]

Characteristics	Meeting applied to adjust practice
Multiple levels, scalable	Risks reside at multiple levels of the work system. While manual tasks and handling practices might pose the greatest physical risks to workers, there are other risks that manifest systemically under latent conditions. Decisions and actions at the political, legislative, and company management levels are highly influential, affecting behaviours and practices at the 'coal face'.
Diverse range of ages (i.e. people, organisations, living entities) and factors (e.g. equipment products, services, technologies, ideas)	Risks are created by fundamentally different agents and factors that reside at multiple work system levels. The multiscale and spatio-temporal interactions among agents and factors means that no single worker, member of staff or entity, if operating and working under loyal intent, should be held liable for their actions. Risks are invariably a symptom of a deeper underlying causes or set of courses within the organisation.
Open boundaries	Organisations exhibit permeable boundaries that delineate sectors, departments, and systems of operation but these systems are, however, open, to information exchange and slow on effects. Organisations continually reshape and reconfigure response to changes both internal (e.g. staff turnover, company growth, new directives and priorities) and external (e.g. fluctuations in the economy, service and product demand). Risks do not occur within a cultural, social, organisational vacuum and are shaped by both minor perturbations and major change.
Adaptive and self organising	Risks are created in a system shift towards and away from acceptable boundaries of safety and performance. Workers navigate to a set of personal and professional obligations; the internal and external competition within the company, and the pressure to keep pace from outside demand can force workplaces and organisations to adapt and self-organise without there being a single identifiable controller of events. The likelihood of a hazard occurring will, for better or for worse, change over time, necessitating ongoing monitoring with proactive risk assessment methods.
Complex behaviours and relationships	Workplaces and organisations exhibit non-linear behaviours and feedback among their various components. Small changes can lead to large catastrophic risks. Systems are becoming more technology-centric and problematically complex, exacerbated by more interdependencies and tight coupling of system elements. For example, the pressure to produce resources and boost capital due to global demand may expediate staff recruitment. Induction and training of new staff takes time, impacting productivity which in turn increases pressure to produce and meet company quotas resulting in new hazards and risks, emphasising the need for a dynamic and capable OHS management process.
Emergent properties	Risks interact in complex ways and can even produce entirely new and potentially more dangerous hazards that must be anticipated and controlled. In this sense 'emergent risks' are defined as difficult -to-predict, adverse outcomes that are created when the above characteristics are considered as a whole. To account for emergent risks, workplaces and organisations should incorporate a systems thinking risk assessment approach to the OHS practices to account for the so-called emergent risks

[6] This table is informed by characteristics of complex systems as adapted by Hulme et al. (2021) and is based on the work of various authors.

5.1.4 The System-Theoretic Process Analysis (STPA) method

The STAMP-STPA method (Leveson, 2011) is a proactive systems thinking-based risk assessment method that is used to identify credible hazards and risks associated with the failure of safety controls and feedback mechanisms. STPA uses an unsafe control/feedback actions taxonomy that is applied to a control structure model of the system in question to identify credible hazards and risks.

Applying STPA involves firstly developing a control structure model (see Figure 4) of the target system. The analyst then considers each of the control and feedback mechanisms described in the control structure along with an unsafe control/feedback actions taxonomy comprising the following four failure modes (Leveson 2011; Leveson & Thomas 2018):

1. Control or feedback action is not provided or followed
2. An unsafe (incorrect) control or feedback action is provided
3. Control or feedback action is provided too early or too late (wrong time or sequence)
4. Control or feedback action is stopped too soon or applied too long (for continuous control actions, not discrete ones).

The STPA output which includes a description of potential control and feedback failures and their consequences is used to support the identification, development and implementation of appropriate risk controls. Appendix 1 shows an example STPA control structure and output. The use of STPA helps analysts to gather information about how existing system constraints and feedback mechanisms could fail to ensure their appropriate and ongoing enforcement. Remedial measures are subsequently developed with an emphasis on either preventing the control and feedback failures or mitigating their consequences should they occur.[7]

5.2 Accident analysis

Systems thinking-based accident analysis methods adhere to the same principles that systems-based risk assessment approaches draw upon. The main difference, however, is that accident analysis methods are used when OHS professionals and managers are tasked with retrospectively understanding the conditions that created an accident. The evolution of accident analysis methods has a relatively long history, with ideas about the nature of causation dating back to the days of Heinrich and the Domino model (1931) and the advent of STS theory decades later (Trist & Bamforth, 1951). The arrival of sociotechnical systems approaches prompted an examination of accident causes beyond the individual and their

[7] For more information about STPA, see, for example, Leveson & Thomas (2018), Rising & Leveson (2018) and Revell et al., (2019).

immediate environment and subsequently informed the development of novel systems thinking accident analysis methods (Waterson et al., 2015). Whilst there are many existing accident analysis methods to choose from, all of which are underpinned by their respective theories and models, for example Reason's (1990) Swiss Cheese Model and HFACS (Wiegmann & Shappell, 2003), this chapter provides an overview of two popular contemporary systems thinking methods: AcciMap and STAMP-CAST.

5.2.1 Accident Mapping (AcciMap) method

AcciMap (Rasmussen, 1997; Svedung & Rasmussen, 2002) provides a means with which to describe accidents based on Rasmussen's risk management framework. Specifically, the method supports the development of a graphical representation of the system-wide failures, decisions, and actions that play a contributory role in accidents (Waterson et al., 2017). AcciMap was developed in response to limitations associated with analysis methods at the time which included the inability to model the systemic network of factors underpinning accidents (Svedung & Rasmussen, 1997). In line with Rasmussen's model, AcciMap is based on the idea that behaviour, safety and accidents are emergent properties created by the decisions and actions of all stakeholders within a system – politicians, chief executives, managers, safety officers and work planners – not just by frontline workers alone (Cassano-Piche et al., 2009). The method therefore supports analysts in identifying and representing the network of contributory factors across a system hierarchy. Six hierarchical levels are typically used (however these can be modified as required for the system in question):

- Government policy and budgeting
- Regulatory bodies and associations
- Local area government planning and budgeting
- Technical and operational management
- Physical processes and actor activities, and
- Equipment and surroundings.

Using AcciMap typically involves applying two analysis methods: the ActorMap and AcciMap. ActorMap forms the first step and is used to develop a representation of the stakeholders ('actors') who share the responsibility for safety and accidents within the system under analysis. Relevant actors are identified at each of the levels described above. The resulting ActorMap shows the actors who operate within the system and at which level of the system they reside. For example purposes, a generic ActorMap is presented in Figure 5.

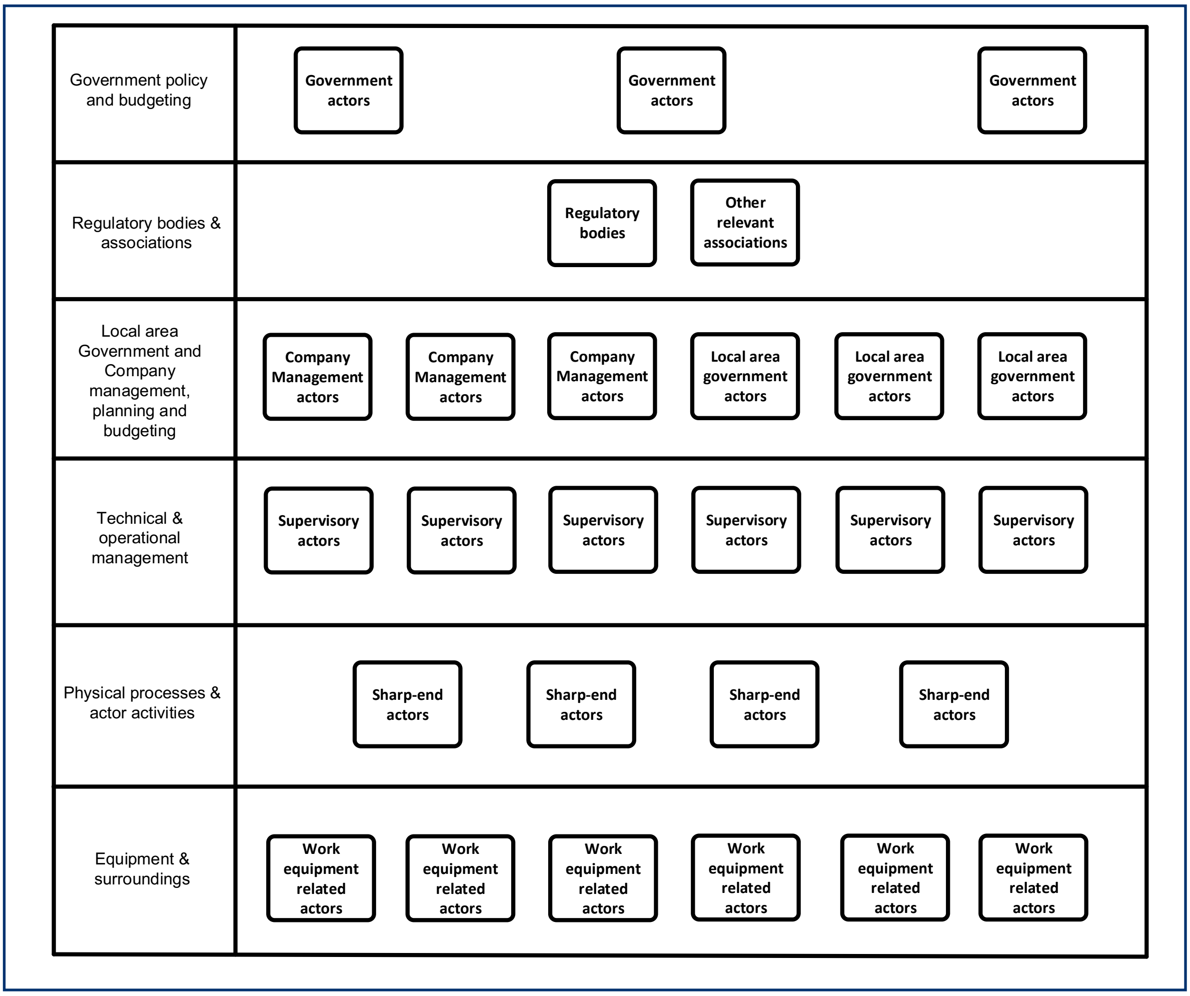

Figure 5: Generic ActorMap (Salmon et al., 2021, p. 7)

Once the ActorMap is developed the AcciMap method is used to identify and represent the network of contributory factors involved in the accident using the same hierarchical levels as the ActorMap. Contributory factors are identified, mapped to one of the six levels, and then linked between and across levels based on cause-effect relations. The AcciMap output thus provides a 'map' of contributory factors and their interrelationships across the work system. AcciMap has been applied to analyse and describe both minor and major OHS incidents in a diverse set of safety-critical domains (Hulme et al., 2019; Salmon et al., 2023).

On 19 November 2010, there was an underground explosion at the Pike River coal mine. Situated in the West Coast region of New Zealand's South Island, the Pike River coal mine was officially opened in 2008. Access to the mine workings was through a 2.3km stone 'drift', or tunnel, which ran on a slight uphill angle through complex geological faulting to intersect a major coal seam where a majority of the mining activities occurred. The immediate cause of the explosion was the ignition of a substantial volume of methane gas, however the source of the accumulated methane and the circumstance in which it was ignited are subject to several possible explanations. (Royal Commission on Pike River Coal Mine Tragedy, 2012) Methane gas, which is found naturally in coal seams, is highly explosive when it comprises 5%-15% volume of air. The monitoring and control of methane with the appropriate technologies and ventilation systems is a critical requirement in both the design and operational phases of coal mining. There were numerous warnings of a potential catastrophe at Pike River, including reports of high methane levels by underground workers and deputies. (Royal Commission of Pike River Coal Mine Tragedy, 2012) For a range of reasons, these warnings were not taken seriously, and the drive to produce coal before the mine was ready from a safety perspective resulted in an explosion that led to the death of 29 workers. (Hulme et al., 2021, p. 827)

The AcciMap in Figure 7 shows the complexity and interconnectedness of the factors that created the incident. A few notable contributory factors in the AcciMap are found at the government and parliament levels of the system. Specifically, the New Zealand government repealed the Coal Mines Act of 1979 which influenced health and safety regulations, and further impacted the mining inspectorate and the resources available to it. As a result, there was lack of inspectorate oversight and reduced auditing processes and industry deregulation affected many other factors. Also, there were multiple delays to underground infrastructure during the development of the Pike River Mine, indicated at the physical processes and actor activities level of the system. Consequently, mining operations fell behind schedule at the technical and operational management level which added further to financial pressure on company management.

The take-home message here is that these many latent antecedent factors are not always immediately apparent in relation to an accident, or many disasters for that matter. Rather, as in the case of Pike River, it may be tempting to simply consider the role of faulty gas monitoring equipment and worker risk taking behaviours at the physical processes level of the system.

Salmon et al., (2020) recently analysed previously published AcciMap analyses to examine the frequency and prominence of the contributory factors identified across a range of incidents and safety critical domains. This involved coding over 5,500 contributory factors and placing them on a generic AcciMap hierarchy. The resulting analysis showing the frequency and proportion of contributory factors identified in previous published AcciMap analyses is presented in Figure 7. The analysis also produced a generic AcciMap contributory factors classification scheme that organisations can help identify and classify contributory factors during accident analysis efforts (see Table 3).

As shown in Figure 7, contributory factors were found across all six levels, providing support for many of Rasmussen's risk management framework tenets (Rasmussen, 1997). For example, the findings demonstrate that, at least in the sample analysed, accidents are created by multiple contributory factors relating to the decisions and actions of multiple actors across all levels of work and societal systems (Salmon et al., 2020). It is important to note that the findings indicate that Rasmussen's tenets (section 4.2) apply regardless of domain or severity, with multiple interacting contributory factors being reported in all studies which were undertaken in multiple domains and covered both minor injury and major multi-fatality incidents (Salmon et al., 2020). It is recommended that Salmon et al.'s (2020) generic AcciMap contributory factors classification scheme be used by organisations wishing to apply AcciMap to analyse multi-incident datasets.

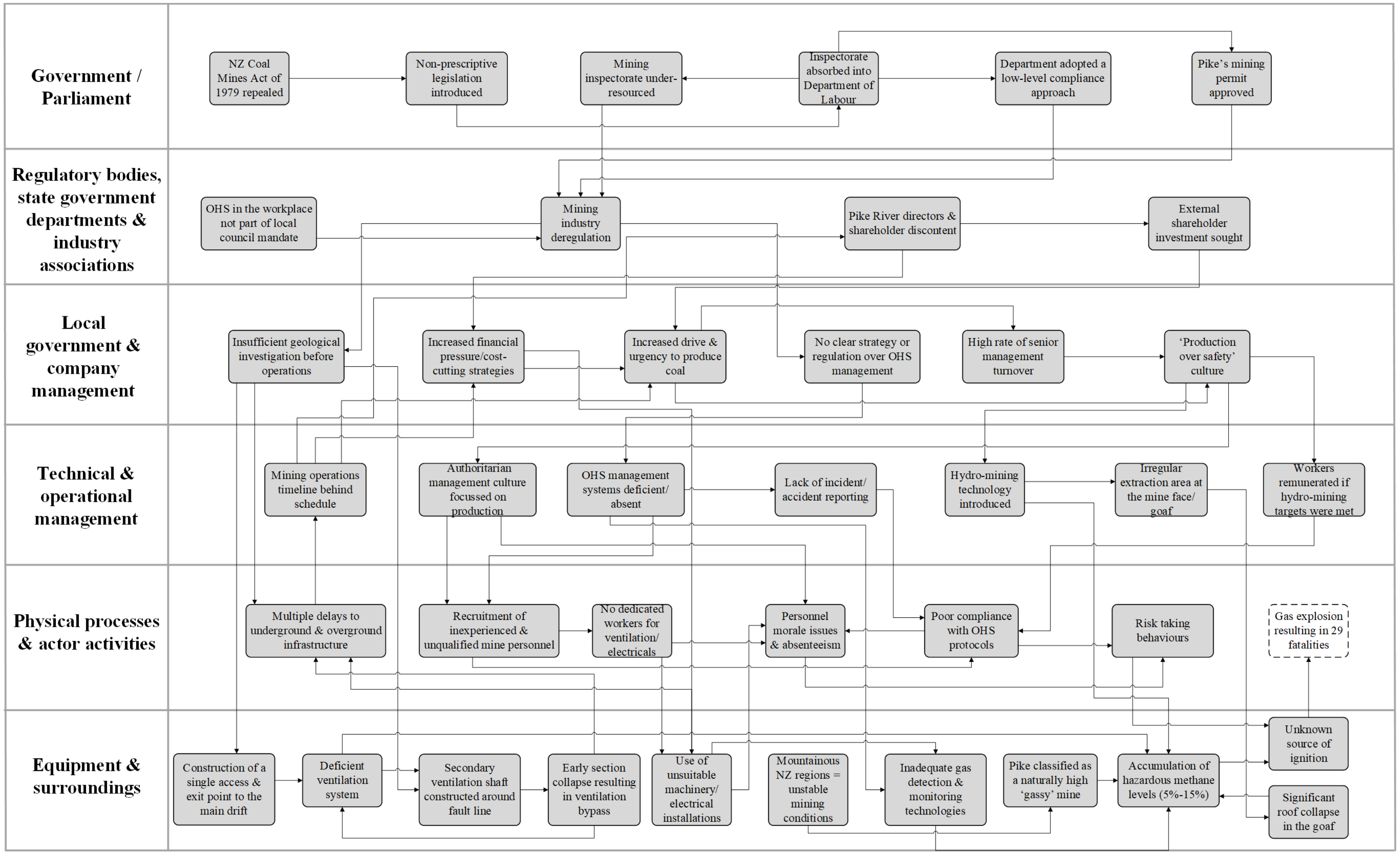

Figure 6: Pike River Mine tragedy AcciMap (Hulme et al., 2019)

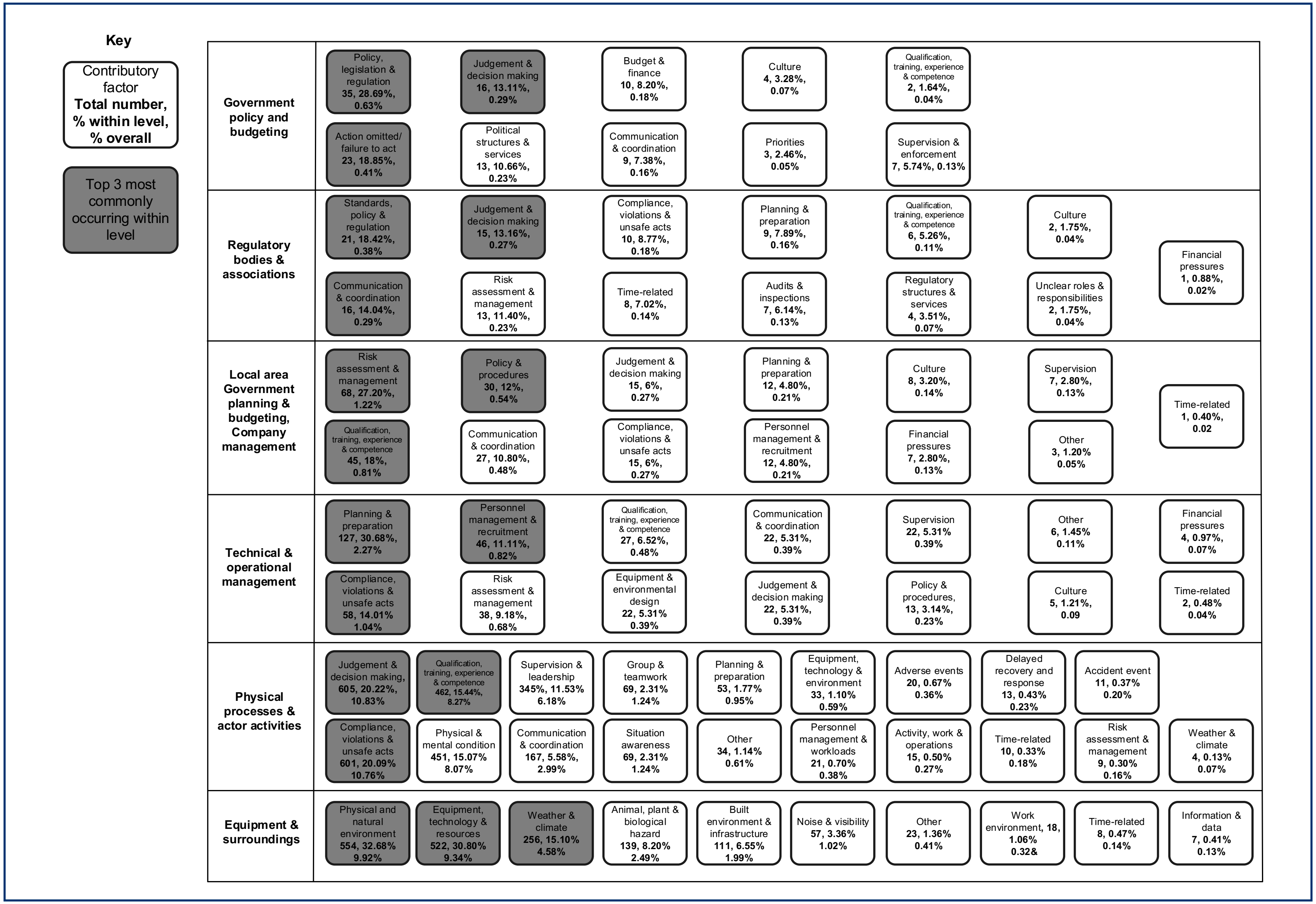

Figure 7: Frequency and proportion of contributory factors identified in published AcciMap analyses (Salmon et al., 2020, p. 6)

Table 3: Generic AcciMap contributory factors classification scheme (Salmon et al., 2020).

Equipment, environment and surroundings	Local area government, planning , budgeting & company management
1. Animal, plant & biological hazards	44. Communication & coordination
2. Built environment & infrastructure	45. Compliance with procedures, violations & unsafe acts
3. Equipment, technology & resources	46. Culture
4. Information & data	47. Financial pressures
5. Noise & visibility	48. Judgement & decision-making
6. Other	49. Other
7. Physical & natural environment	50. Personnel management & recruitment
8. Time-related	51. Planning & preparation
9. Weather & climate	52. Policy & procedures
10. Work environment	53. Qualification, training, experience & competence
Physical processes and actor activities	54. Risk assessment & management
11. Accident event	55. Supervision
12. Activity, work & operations	56. Time-related
13. Adverse events	**Regulatory bodies and associations**
14. Communication & coordination	57. Audits & inspections
15. Compliance with procedures, violations & unsafe acts	58. Communication & coordination
16. Delayed discovery & response	59. Compliance with procedures, violations & unsafe acts
17. Equipment, technology & environment	60. Culture
18. Group & teamwork	61. Financial pressures
19. Judgement & decision-making	62. Judgement & decision-making
20. Other	63. Planning & preparation
21. Personnel management & workloads	64. Qualification, training, experience & competence
22. Physical & mental condition	65. Regulatory structures & services
23. Planning & preparation	66. Risk assessment & management
24. Qualification, training, experience & competence	67. Standards, policy & regulations
25. Risk assessment & management	68. Time-related
26. Situation awareness	69. Unclear roles & responsibilities
27. Supervision & leadership	**Government policy and budgeting**
28. Time-related	70. Action omitted & failure to act
29. Weather, climate & natural processes	71. Budget & finance
Technical and operational management	72. Communication & coordination
30. Communication & coordination	73. Culture
31. Compliance with procedures, violations & unsafe acts	74. Judgement & decision-making
32. Culture	75. Policy, legislation & regulation
33. Equipment & environmental design	76. Political structures & services
34. Financial pressures	77. Priorities
35. Judgement & decision-making	78. Qualification, training, experience & competence
36. Other	79. Supervision & enforcement
37. Personnel management & recruitment	
38. Planning & preparation	
39. Policy & procedures	
40. Qualification, training, experience & competence	
41. Risk assessment & management	
42. Supervision	
43. Time-related	

5.2.2 Causal Analysis based on Systems Theory (CAST) method

The STAMP-CAST method (Leveson, 2004) uses the same control structure model as STPA – the risk assessment method described in section 5.1.4. However, STAMP-CAST is used post-accident to identify contributory control and feedback failures. When using STAMP-CAST analysts use the CAST control failure taxonomy to identify and classify control and feedback failures that played a role in the accident in question. The CAST control failure taxonomy includes:

- Inadequate enforcement of safety constraints (control actions)
- Inadequate execution of control actions
- Inadequate or missing feedback.

CAST analyses include determination of ‘context’, ‘mental model flaws’, and ‘coordination’ as classification taxonomy categories in order to cater to the human element since the method originated in the engineering domain (Leveson, 2004). An example CAST analysis output relating to train-person collisions involving trackworkers working in the rail industry is presented in Appendix 2. For this case study, a control structure was adapted from previous work (Read et al., 2019) and subsequently used to analyse a collision whereby a passenger train struck and fatally injured a track worker who was part of a work group removing rubbish from the tracks at a railway station. The control structure shown in Appendix 2 provides an extract of control failures and their classification within the CAST taxonomy.

5.3 Development and implementation of safety interventions

When taking a systems thinking approach, safety interventions should attempt to address multiple issues across the work system rather than just attempting to fix ‘broken components’ (Dekker, 2011). For OHS issues, integrated networks of interventions are required as opposed to individual fixes (Goode et al., 2016). This is based on the notion that, whilst an individual component fix may have some impact initially, other conditions across the system left unaddressed will continue to influence behaviour. A simple example of this can be seen in the often-used safety intervention of a new procedure designed to ensure that workers perform a particular task in the safest possible manner. Whilst this may have the initial impact of restricting work performance as desired, other untreated conditions such as an excessive workload, staff shortages, inadequate equipment, poor supervision, inappropriate targets, and a poor safety culture will invariably push performance towards the safety boundary. The new procedure may have an initial impact as workers strive to work in line with it, however, the other conditions will eventually create performance variability. Instead, what is required is a network of interventions across the work system that address the conditions which influence worker behaviour.

Developing appropriate OHS interventions therefore involves consideration of the network of contributory factors that interact to create the health or safety issue (either identified via risk assessment or accident analysis). Often there are powerful 'leverage points' that can be targeted when developing OHS interventions. Leverage points represent areas in a system where small interventions can create large and significant effects on the system's behaviour (Meadows, 2008). Leverage points can be identified by looking at the higher levels of AcciMap analyses for contributory factors that are highly connected and consistently identified across accidents. For example, based on a review and synthesis of over 5,500 contributory factors identified in published AcciMap analyses, Salmon et al., (2020) (section 5.2.1) suggested that training, experience and competence of supervisors and managers, risk assessment and management, and government policy, legislation and regulation represent key leverage points to focus on when developing OHS interventions.

Few methods exist to support the development of systems thinking-based OHS interventions. One such method is PreventiMap, which was developed to work in conjunction with AcciMap (Goode et al., 2016). PreventiMap is used to identify and depict the network of interventions that is required to respond to critical safety issues (Goode, et al., 2016). PreventiMaps are typically developed based on an AcciMap analysis of a particular issue, with the output intended to drive the development and implementation of effective interventions. PreventiMaps use the same hierarchical structure and levels as ActorMap and AcciMap and show what interventions are required at each level of the system in question to prevent or manage a particular safety issue. The interventions are linked in a network showing how interventions at one level can support those at other levels. A generic PreventiMap is presented in Figure 8. An applied example where the ActorMap, AcciMap and PreventiMap methods were used to address work-related violence in hospitals can be found in Salmon et al. (2021).

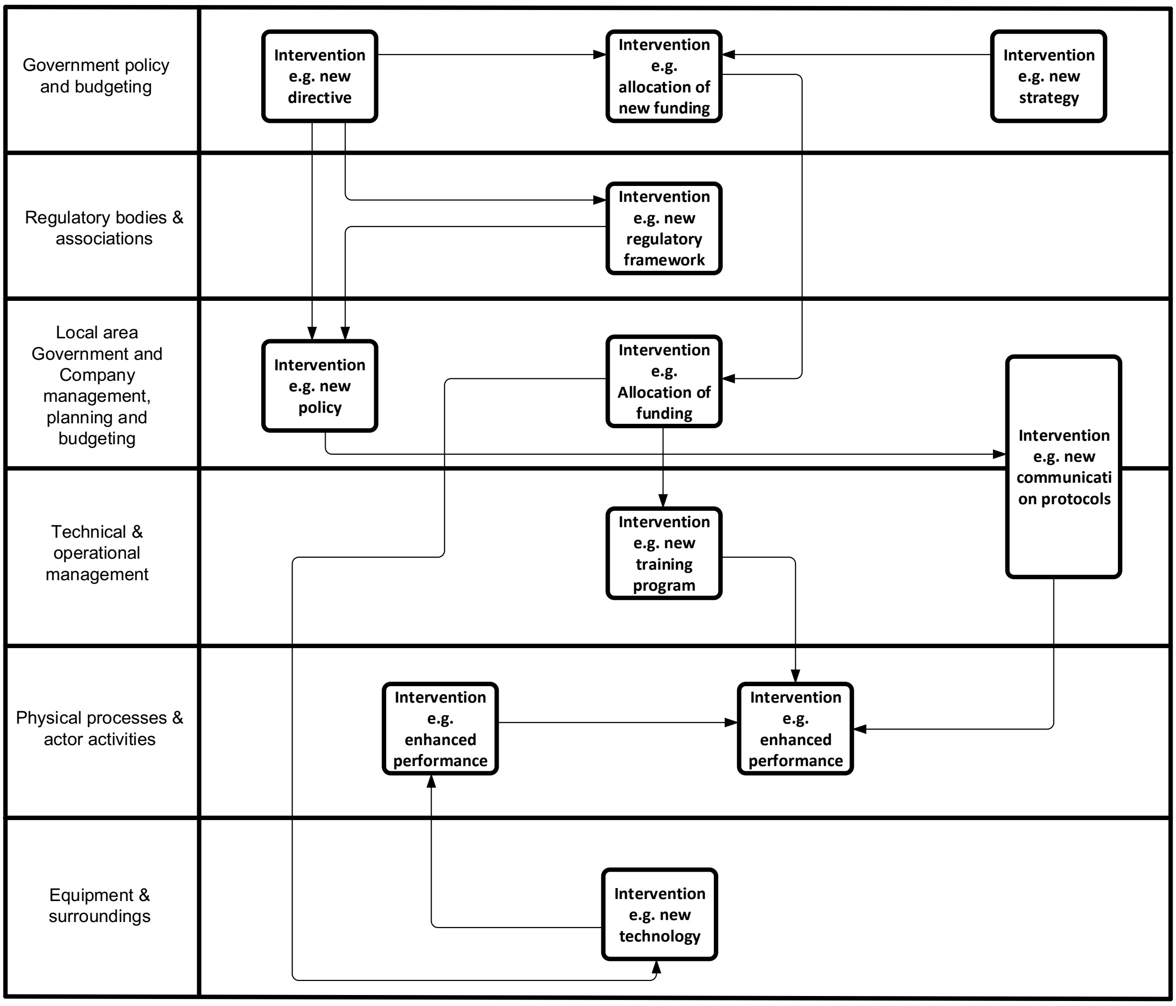

Figure 8: Generic PreventiMap (Salmon et al., 2021, p. 9)

6 Implications for OHS practice

Although the systems thinking approach is now dominant in safety science research, there remains a research-practice gap whereby the state-of-the-art models and methods described in this chapter are yet to be fully embraced by practicing OHS professionals. Read et al. (2021) proposed a way forward that aims to help OHS professionals move beyond a focus on human error and fixing broken components to embrace systems thinking. OHS professionals should consider these recommendations as core to their OHS practice.

A way forward for OHS practice (and research)

- Reject 'human error' as a cause of accidents and adverse events. Focus on how the system failed and interventions that increase the system's capacity to manage disturbances and performance variability.
- Reject countermeasures focused on individual components. Advocate for networks of interventions that respond to system-wide issues.
- Reject simplistic explanations for accidents. Acknowledge that rationality is bounded and avoid the trap of hindsight.
- Acknowledge that humans are assets and problem solvers operating in imperfect and complex environments, usually with good intentions, and never intending for accidents to occur.
- Avoid blame-laden terminology. Instead of 'human error' or 'violation', use neutral or factual terms (e.g. decision, action, event, consequence).
- Seek to identify performance variability at the component and system level. Intervene to support positive variability. (e.g. adaptation) and reduce negative variability (e.g. drift).
- Adopt a systems perspective and embrace systems thinking methods. Continue to develop and adapt systems methods to be scalable and usable in practice.
- Educate colleagues in other disciplines (e.g. engineering and design) and broader institutions (e.g. media, the courts, politicians). Introduce complexity science, systems perspectives and systems thinking methods.
- Incorporate complexity science, systems perspectives and systems thinking methods into OHS capability frameworks. Support the next generation of OHS professionals to continue the shift towards systems perspectives.

(Adapted from Read et al., 2020)

It is important to note that various other systems thinking-based methods are available to support OHS management , such as the Functional Resonance Method (FRAM; Hollnagel, 2012), the Event Analysis of Systemic Teamwork (EAST) (Stanton et al., 2018), and the Networked Hazard Analysis and Risk Management System (Net-HARMS, Dallat et al., 2018). Practical guidance on these methods can be found in Salmon et al.'s (2023) handbook of systems thinking methods. The reader is encouraged to explore methods described in this chapter and Salmon et al. (2022) and consider their use as part of OHS activities.

7 Summary

This chapter has provided an overview of the systems thinking approach to OHS and core systems thinking-based methods for risk assessment, accident analysis, and the development of OHS interventions. While the methods described have important strengths when used in isolation, the approaches are most useful when applied in an integrated manner as part of a systems thinking approach to OHS management. Such an approach will enable organisations to use outputs from risk assessments to direct accident analysis activities, with the outputs from accident analysis efforts then supporting the development of appropriate OHS interventions. Accident analysis outputs should provide feedback to risk assessment processes to support the identification of risks and development of effective controls. We hope that this chapter contributes to a process of change, and facilitates a stronger and more coherent application of systems thinking in OHS.

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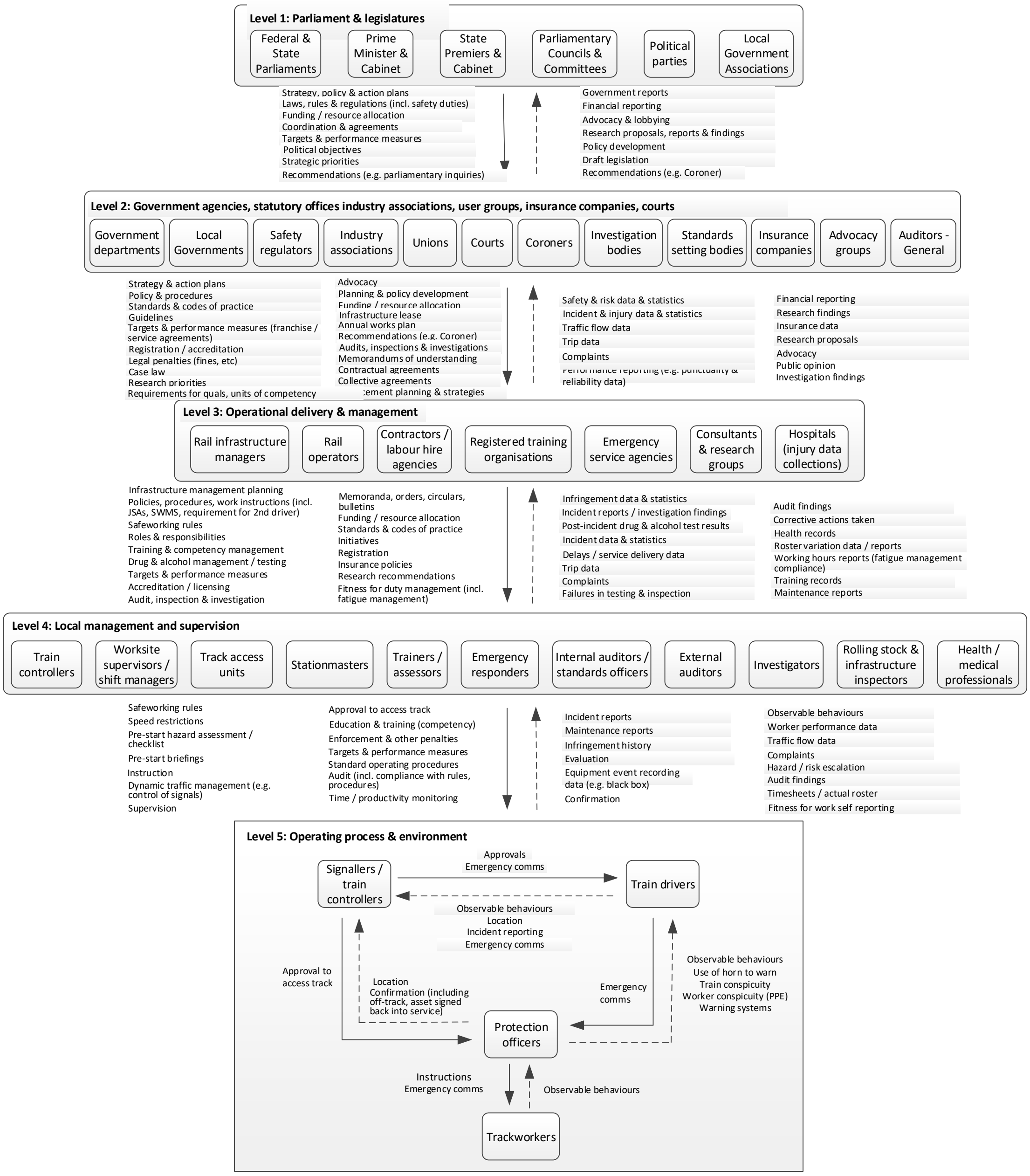
Appendix 1: The System-Theoretic Process Analysis (STPA) method

Example STPA output

From (agent)	To (agent)	Control action/feedback (from control structure model)	Action or feedback required but not provided	Unsafe action or feedback provided	Incorrect timing or order	Stopped too soon/applied too long
Operations management	Human controller	Work instructions	Work instructions are not provided leading to unsafe variance in work practices	Work instructions are provided but they are poorly designed and could encourage unsafe work practices	The development and implementation of work instructions is delayed, leading to unsafe variance in work practices	Work instructions are outdated and no longer fit for purpose. This results in unsafe work practices
Company	Operations management	Safety policy	Safety policy is not provided leading to a lack of control over work practices	Safety policy is provided but it is poorly designed and could encourage unsafe work practices	The development and implementation of safety policy is delayed, leading to unsafe variance in work practices	Safety policy is outdated and is no longer fit for purpose. This results in unsafe work practices
Human controller	Operations management	Audit reports	Audit reporting is not undertaken meaning work hazards are not identified, reported on, or removed	N/A	Audit reporting is delayed meaning work hazards are not dealt with in a timely manner	Auditing is rushed meaning that all hazards are not identified and reported

Appendix 2: Causal Analysis based on Systems Theory (CAST) method

Example CAST control structure for train-person collisions involving trackworkers



Extract of CAST analysis for train-person collision involving trackworkers

From	To	Control/ feedback	Contributory factor	Control failure classification
Train controller	Protection officer	Approval to access track	The train controller had not applied blocking facilities when he told the protection officer that blocks were on.	Inadequate enforcement of constraints: Control action was missing due to distraction by other tasks and performance affected by fatigue due to a lengthy period of irregular shifts, working during a circadian low period and reduced sleep.
Protection officer	Train controller	Confirmation	The protection officer did not seek confirmation that the worksite protection was fully implemented by the train controller.	Inadequate or missing feedback: Due to a communication flaw, the protection officer assumed there was no more rail traffic overnight.
Rail infrastructure manager	Train controller	Fitness for duty management	The train controller had recently returned from a length period of sick leave, without undergoing a health assessment.	Inadequate enforcement of constraints: The hazard associated with returning from leave did not appear to be recognised.
Train controller	Train drivers	Emergency communications	The train controller did not use the train radio system to give an emergency alert to drivers that trackworkers were in the vicinity	Inadequate execution of control action: The train driver appeared to hold an incorrect process model in the belief that it would be more efficient to warn the workers to vacate the track than to warn train drivers.