Adaptation as a source of safety in complex socio-technical systems: A literature review and model development

Craig J. Fostera,b, Katherine L. Plantb, Neville A. Stantonb

a NATS, 4000 Parkway, Whiteley, Hampshire PO15 7FL, UK

b Transportation Research Group, Faculty of Engineering and Physical Sciences, Boldrewood Campus, University of Southampton, Burgess Road, Southampton SO16 7QF, UK

# Abstract

Recent advances in safety science point towards a different approach to the management of risk within safety-related industries that focusses on successfully harnessing the adaptations present within complex socio-technical systems. However, adaptation is a concept with a variety of interpretations that impairs the ability of industrial practitioners to understand and apply this concept to the management of safety. We present a systematic review of the safety literature using a grounded theory approach from a variety of industrial domains and theoretical standpoints to identify the key features within complex socio-technical systems that describe how adaptation and safety are related. A model for adaptation, developed from these ideas, is then described. This model is then used to explain the response of UK oceanic air traffic controllers to the closure of US airspace following the terrorist attacks in the US on the 11th September 2001. The case study highlights how the model aids an enquiry into the features of adaptation that are present within complex socio-technical systems. The review also identifies the need for further research to assist industrial practitioners connect the role of adaptation at the level of the individual to the adaptive capacity at the level of the organisation.

**Keywords**: adaptation, safety, resilience, high reliability, air traffic control

# Introduction

On the morning of the 11th September 2001, as the terrorist attacks in New York and Washington were unfolding, some 5000 kilometres away for the oceanic air traffic controllers at the NATS centre in Prestwick, Scotland the day had started like any other. As news began to filter through it became clear that this was not going to be an ordinary shift. At 14:05 GMT the Air Traffic Control (ATC) Command Center in Washington issued a message that closed US airspace with immediate effect due to the emergency situation. There were 441 aircraft in the airspace on that day. All aircraft that were already more than halfway across the ocean were forced to divert towards Canada, however any aircraft that was nearer to Europe would need to turn back and return (Harrison, 2002).

On the North Atlantic, air traffic controllers cannot use radar to provide a surveillance picture of aircraft locations nor Very High Frequency radio to effect clear and rapid communications to aircraft once they pass beyond the range of these systems. Instead, controllers use less reliable High Frequency radio communication relayed from stations in Ireland and, where available, short text and data messaging services via satellite to provide aircraft position reports and communication (with many minutes between reports). The safe control of aircraft is achieved by the organisation of aircraft into an organised track structure (OTS) with aircraft entering oceanic airspace at set times and speeds with subsequent aircraft following behind on the same structured route in separations measured in longitudinally in time and 1000 feet vertically. These minimum separation standards ensure the safety of aircraft and reduce the risk of mid-air collisions. The organised tracks were separated by 60 nautical miles (Nm) laterally in 2001 and the position of waypoints on the route changes daily based on the prevailing weather conditions and the position of the North Atlantic jet-stream (Beauchamp, 2013).

An oceanic turnback is normal work for controllers; people get sick or aircraft suffer technical failures and need to return. However, on the 11th September 2001 a contingency procedure that was written for a single aircraft suddenly had to be applied to all aircraft needing to return. Forty-five aircraft were instructed to commence a turnback and return to UK airspace; at least four aircraft declared emergencies with one declaring a mayday. Against the backdrop of the enormity of the unfolding situation in the US and the uncertainty it caused, NATS oceanic controllers initiated possibly the most complex and challenging air traffic control operation in the organisation’s history. The air traffic control operation in the UK on that day (the successful management of a pressurised, uncertain and demanding situation) is a story of adaptation.

Adaptation is an important theme in safety management in a number of industrial domains. It encompasses the ability of complex systems to self-organise, reconcile conflicting goals, re-evaluate priorities and innovate and cope with new external demands (Holling, 1973; Reiman, Rollenhagen, Pietikäinen, & Heikkilä, 2015). It also refers to the tacit acceptance of broken rules and stretched boundaries to achieve safety performance (Hale & Borys, 2013a). Advances in safety science point towards these alternative conceptualisations and of a different approach to safety management which focusses on successfully harnessing the adaptations present within complex socio-technical systems (Dekker, 2003).

Two theoretical foundations form the basis for these advances and have relevance to our review. Firstly, the thinking of Rasmussen (1997) has become highly influential and presents a powerful insight into the understanding of hazards, error and safety (for a review see Le Coze (2014)). Of interest to our discussion is Rasmussen’s theory of migration towards the boundaries of safe performance. This dynamic model describes the feasible operating envelope of a socio-technical system as being bounded on three sides. The location of the operating point is influenced by gradients that push away from the boundaries of workload and economic failure and towards a unacceptable performance or accident boundary. The location of the accident boundary is not unambiguously known therefore a safe operating margin is generally defined and organisations attempt to keep the operating point away from this margin. Intentionally crossing the safety margin line i.e., the organisation realises that it is operating at increased risk, violates the accepted norms of the organisation and generates a reaction to restore the operating point to a position on the right side of the line. The position of the margin line is not fixed and is influenced by factors in the organisation such as risk appetite, risk tolerance, recency of accidents and organisational memory. Safety can therefore be considered as the interdependency of the location of the operating point, its motion within the operating envelope, its tendency to cross the margin and the relationship of the margin with the accident. For a more detailed discussion within the context of healthcare see Cook & Rasmussen (2005).

Secondly, the work of Weick and Sutcliffe (2001, 2007, 2015) generated a theory that describes features of high reliability organisations (HRO) and was built upon an analysis of the number of US high risk industries: air traffic control, nuclear power and US Navy carrier operations. They explored how certain organisations are able to sustain almost error-free performance over long periods of time. The analysis highlighted five characteristics that appeared common across industries that cope with complexity and uncertainty:

1. Pre-occupation with failure: the use of incident reporting and investigation to support learning
2. Reluctance to simplify: the collection and analysis of information, the avoidance of assumptions and an appreciation of the systemic nature of failures
3. Sensitivity to operations: the anticipation of possible failures, taking a bigger picture view of the system and using views from the front-line to provide information about the status of operations
4. Commitment to resilience: the ability to bounce-back from adversity and to learn from the past and from other industries
5. Deference to expertise: the capability of the organisation to enact structural changes to respond to an emergency

Whilst these two theoretical viewpoints present possibly conflicting ideas about how organisations managing socio-technical systems are able to adapt in the face of complexity, recent work, for example by by Le Coze (2015), has sought to bridge the divide. However, what is common in these theoretical views is the underlying idea of adaptation. We present a systematic review of the safety-related literature to examine adaptation as a concept in safety management and then adopt a grounded theory approach to the identification of the core concepts. The model that is developed is then used to explore the nature of adaptation as a source of safety in a complex socio-technical system, such as air traffic management (ATM), with reference to the case study based on the response of NATS oceanic controllers to the closure of US airspace on 11th September 2001.

# Method

In order to avoid the limitations of other literature reviews in the field such as highly specific inclusion or exclusion criteria, narrow domain and journal focus (Patriarca, Bergström, Di Gravio, & Costantino, 2018), this analysis takes a broad and expansive approach to surveying the literature. The major schools of thought in Safety Science, for example Resilience Engineering (for an overview see Righi, Saurin & Wachs (2015)) and High Reliability Organisations (Weick, 1987), may use their own language and terminology to describe adaptation and papers subscribing to this view may reflect those or similar terms. Therefore, an analysis solely focusing on those terms aligned to one particular school may present a limited interpretation of adaptation or affirm a particular view. The premise for the review is that adaptation may be described in the literature using a variety of similar but subtly different terms or described in ways that do not have cognisance of, subscribe to, or build upon a particular school of scientific thought. Thus, we have adopted a method that casts a wide net to try to bridge industries, schools and domains using a broad characterisation of terminology. This expansive and iterative approach is useful when building knowledge and generating theories and promotes the emergence of meaningful findings from the literature (Finfgeld-Connett & Johnson, 2013). To that end, an iteratively developed list of inclusion terms characterising the core premise of adaptation in the context of the safety of complex socio-technical systems was combined using logical operators to create a comprehensive and compound search query for the SCOPUS database (described in Appendix 1). SCOPUS is the largest abstract and citation database of peer-reviewed literature and supports the use of large and complex search queries to search both titles and abstracts of a broad range of journals.

To restrict the number of papers to a manageable amount and focus on the specific topic and premise, a list of exclusion terms was developed based on commonly occurring terms in the abstracts. The terms selected were specific enough to eliminate those papers that were clearly of no relevance to the search without being too general to potentially remove papers of possible interest. For example, medical papers meeting the initial search terms discussing the safety of, for example, viral adaptations in humans, could be excluded by removing papers with viral in the title or abstract. The full list of exclusion terms is included in Appendix 1. Further exclusion criteria were generated by limiting the papers to publications from 61 journals in fields of relevance to the domain, for example, human factors, ergonomics, medicine, nuclear energy, transportation and social sciences among others. The selection of journals was refined based on the number of papers meeting the search criteria from that journal, exploration of the cited references to determine their relevance to the review and using the judgement of the authors. The search was further limited to articles in the English language.

By developing the search in this way, it is inevitable that some papers of relevance may have been excluded. Examples could include papers that use particularly esoteric, humorous or highly generalised terms in the titles or abstracts. Furthermore, the search is limited to those journals where SCOPUS provides coverage. The search was limited to the published peer-reviewed academic literature. Whilst books and conference proceedings possibly provide an indication of emerging trends in a research domain and the reporting of industrial results, with a such a wide search scope, a comprehensive book review, would generate an unmanageable number of results. The review was conducted based on SCOPUS entries returned in January 2018.

Once a core dataset of papers was identified from the search query, a review of the paper abstracts was conducted to identify the likely relevance of the paper to the literature review. A smaller subset of papers of apparent high relevance based on the abstracts was therefore identified and these were read in detail to identify the purpose, methods, theories, findings, results and recommendations with relevance to the core idea of adaptation as a source of safety for complex socio-technical systems. This detailed reading provided a further opportunity to refine the set of papers to those of high relevance for use in the development of a model for the literature.

The high relevance papers were then analysed using the grounded theory approach of Wolfswinkel, Furtmueller & Wilderom (2013). This approach to analysing papers uses an open and iterative coding technique to identify the core concepts in the literature that emerge from a reading of the texts. This approach was successfully adopted by Rafferty, Stanton & Walker (2010), Parnell, Stanton & Plant (2017) and by Heikoop, de Winter, van Arem & Stanton (2016) who developed models for military fratricide, driver distraction and automated driving respectively to create parsimonious models of the literature in these domains.

# Results

The initial SCOPUS search returned 336 papers which formed a core dataset for analysis from across 20 journals. A review of the abstracts of the 336 papers identified an initial 149 papers that appeared to be relevant to the literature review. One duplicate paper was identified as a re-print with a subtly different title, one paper had an abstract in English but was in French and therefore these 2 were excluded. One paper was identified as being part two in a series of two and therefore part one was added. This created a dataset numbering 148.

The detailed reading of these 148 papers helped refine the dataset further so that the SCOPUS search returns were eventually reduced to a final set of 119 papers from 15 journals.

## Analysis of the literature

### Development of the literature

The growth in the discussion of adaptation in the context of the safety of complex socio-technical systems can be seen in Figure 1 and highlights the emergence of adaptation as a topic within the safety literature.

Figure 1: Count of papers by year of publication

### Publication sources

Figure 2 shows that the Safety Science and Ergonomics titles are the homes for discussion of adaptation although there is a broad coverage of the topic across the 15 journals and some of these may fall outside the usual sources examined. This potentially highlights the novelty of this approach in illustrating that a narrow focus on a keyword or domain may miss important research being conducted in parallel domains or journals.

Figure 2: Publication sources

### Theoretical underpinnings

The detailed reading of the 119 papers allowed an identification of the theoretical foundations for the research. Of the 119 papers examined in detail, 27 (23%) were classified as being of a theoretical nature whilst the remaining 92 (77%) were empirical (including literature reviews, methods reviews, primary research papers and case studies). Across the papers a number of theoretical viewpoints are considered either singly or in comparison: 18 (15%) papers built upon the HRO viewpoint, 52 (44%) developed ideas founded on the Resilience Engineering school whilst 29 (24%) papers described ideas related to adaptation but did not subscribe to a theoretical basis. Other papers built upon or examined Reason’s ideas of organisational safety (30, 25%), used Human Factors or Ergonomics viewpoints (28, 24%) or examined Perrow’s Normal Accident Theory (11, 9%).

### Factor elicitation

Figure 3 shows the results of the grounded theory approach to identify the factors present in the literature .

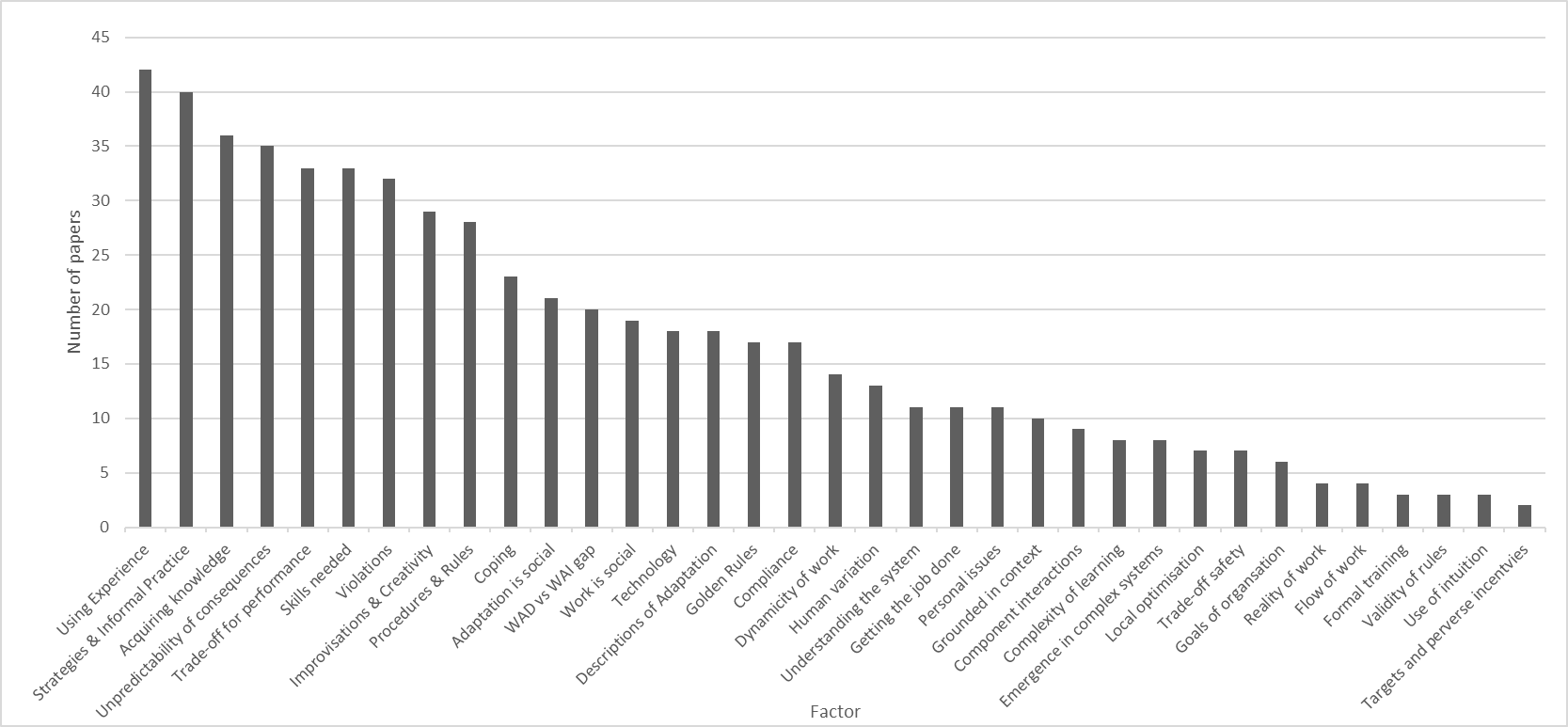


Figure 3: Ordered chart of conceptual factor and prevalence in the literature

The grounded theory approach identified 35 factors (see Figure 3) which demonstrates that there is a wide spread of conceptual ideas across the literature. However, a discernible split (highlighted by the dashed vertical line in Figure 3) in the identified factors occurs after the first nine factors based on the number of papers (i.e., featured in over 25 journal papers). Therefore, we consider that a parsimonious model for safety in complex socio-technical systems exists based on these nine factors: Using Experience (42), Strategies & Informal Knowledge (40), Acquiring Knowledge (36), Unpredictability of Consequences (35), Trade-off for Performance (33), Skills Needed (33), Violations (32), Improvisations & Creativity (29) and Procedures & Rules (28).

### Factor interconnections

Having identified the nine factors, we examine how the literature connects them. Appendix 2 illustrates the number of papers that draw connections between the factors using an interconnection matrix. Figure 4 shows a network diagram built from this matrix. The strength of the links between the factors (number of papers making the connection) is shown by the relative thickness and darkness of the lines connecting them. Factors with few papers drawing a link between them therefore have a thin, pale line, factors with higher numbers of papers making the link have a relatively thicker, darker line indicating a stronger link in the literature. The size of the node in the network diagram has been scaled by its the general importance to the literature measured by the number of links to other factors.

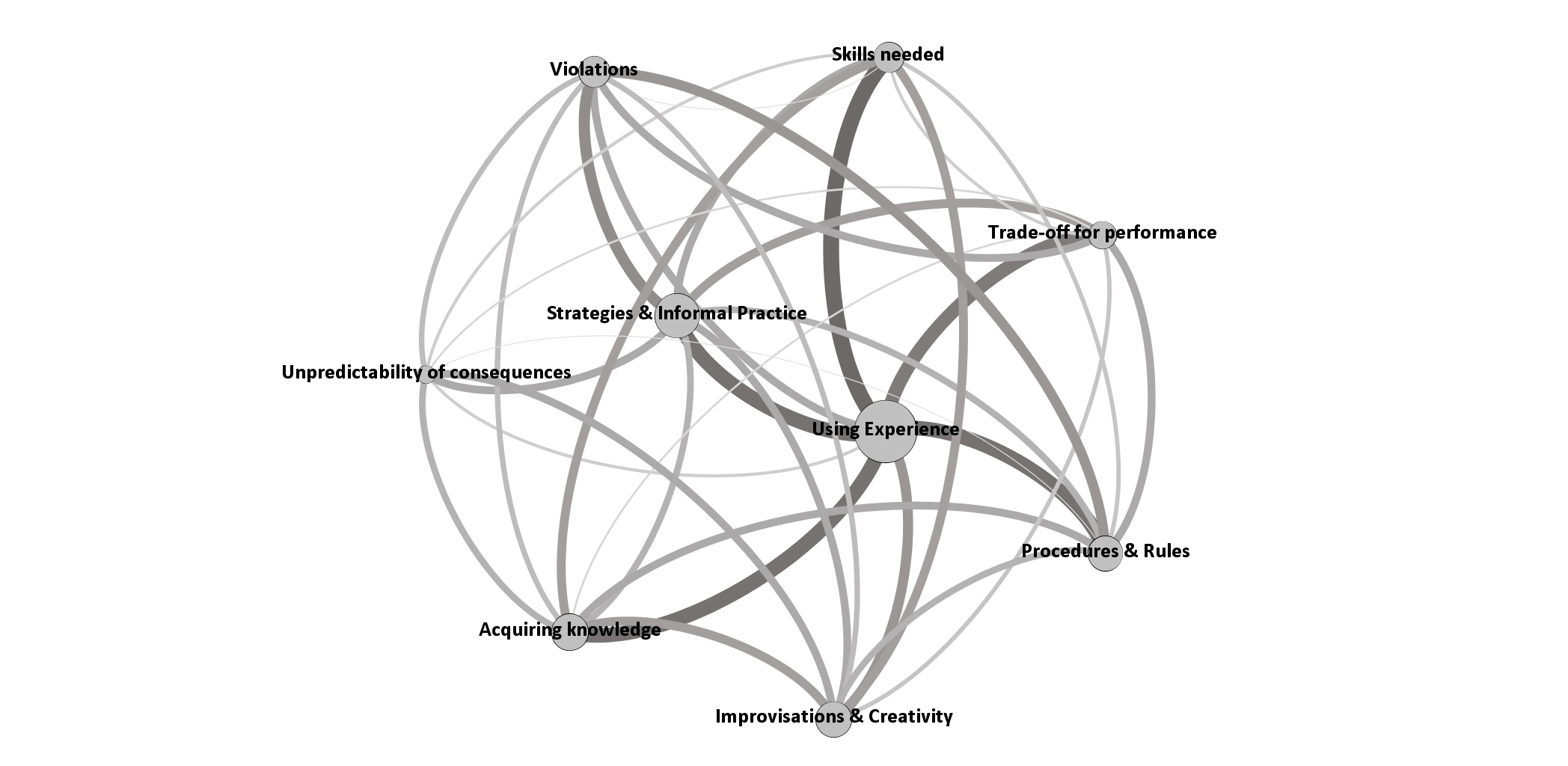


Figure 4: Network diagram of 9 factors of adaptation

The network diagram provides insight into the importance and connection of ideas in the literature. Figure 4 highlights that the challenges of decision making (Trade-off for performance) in the presence of uncertainty (Unpredictability of consequences) is an area of the literature with weaker connections particularly with regard to the ‘Skills needed’ to make the trade-off. In contrast, the ideas of experience and strategies are well connected to each other and to the other factors identified indicating that this is an area emphasised in the literature.

# A model for adaptation

The main aim of a socio-technical system is that, through the actions of its interconnected sub-systems, objectives are to be achieved (Morel & Chauvin, 2006) but often goals will conflict, such as to simultaneously meet both safety and production needs. Therefore the core challenge for operators in such systems is the issue of choice and in making a decision to reconcile these conflicts (Huber, van Wijgerden, de Witt, & Dekker, 2009; Rasmussen, 1997). The response to having the choice is to adapt and the nine factors that emerge from the review of the literature has been explored to understand how adaptation manifests within a socio-technical system.

## Factor 1: Using experience

The use of experience is the most common factor in the identified literature. This factor describes how the capability to adapt in the complex work environment implies a certain level of experience in the system. The literature describes how novices in the system may use the rules that exist and look to the hierarchies of the work environment for guidance (Crichton, 2005; Hale & Borys, 2013a; Langer & Braithwaite, 2016). Novices use the training they have received whilst practised operators draw on their experiences (Grant, Checkland, Bowie, & Guthrie, 2017). For example, novices lack of experience may mean that, whereas experienced operators can spot the cues and appreciate what is critical, novices may misunderstand the signals and struggle to prioritise their actions (Malakis, Kontogiannis, & Kirwan, 2010b; Saward & Stanton, 2018). The ability to perceive the signals supports operators in considering a broader picture of the system and avoid locally sub-optimising due to a narrow focus (Matton, Paubel, Cegarra, & Raufaste, 2016). With experience comes analogies, pattern recognition and similarity matching that can be tested against the acquired lore of the system and the heuristics that have been developed so that these may be applied to the context (Carvalho, Gomes, Huber, & Vidal, 2009; Mulvihill et al., 2016). Experience also supports communication by providing the network of contacts on which to draw and the confidence to ask for help (Kontogiannis, 2012; Rasmussen, 1997; Woodcock, 2014). The focus on the individual’s experiences, motivations and perceptions and the collective understanding of the system are a core focus of the Resilience Engineering school (Benchekroun & Pierlot, 2012). However, the literature also highlights the alternative possibility: that experience can breed over-confidence, pride in risk-taking, professional arrogance and ego that feeds a hero complex. Operators can get stuck in their ways and then cannot or will not adapt (Bagnara, Parlangeli, & Tartaglia, 2010; Cañas, Quesada, Antolí, & Fajardo, 2003; Dillon, Tinsley, & Burns, 2014; Phipps et al., 2008; Rochlin, 1999; Roy, 2003).

Yet the ability to adapt is seen as the hallmark of experience and expertise. The use of judgement, the capability to solve problems under uncertainty and pressure creates a sense of pride, of self-worth and of professional or individual identity and the ability to ‘get the job done’ is gratefully accepted by management (Debono et al., 2013; Gomes, Huber, Borges, & De Carvalho, 2015; Huber et al., 2009; Kirwan, 2001; Mickelson & Holden, 2018; Pettersen & Schulman, 2015). But the burden of rules in the system can undermine this sense of craftmanship and devalue experience (Stoop & Dekker, 2012). Thus organisations should place competence and experience at the heart of the work, rather than solely relying on rules and procedures, leaving room for the ability to adapt to uncertainty and variation (Hale & Borys, 2013b).

## Factor 2: Strategies & Informal Practice

Whilst the literature is clear that adaptation can relate to breaching the rules to achieve a goal (see Factor 7), a distinction is also identified from violations in the inconsequential and normal adaptations in work that are not classed as rule breaches. These strategies and informal practices that emerge through the conduct of work form the second factor of the model. Adaptation is often referred to as ubiquitous and inconsequential (Holden et al., 2013; Huber et al., 2009). It is part of normal work and the everyday actions to address the rigidity of complex, highly optimised systems (Amalberti, 2001). It often takes the form of strategies and informal practices that emerge through the patterns of behaviour and routines of the work environment. The surveyed literature suggests that human abilities to multi-task are severely limited thus cognitive work must be regulated to changing circumstances, by the active selection of strategies resulting in constant trade-offs and reprioritisations (Carvalho et al., 2009; Loft, Sanderson, Neal, & Mooij, 2007; Matton et al., 2016). However, the wider literature is clear that human multitasking is a myth, particularly when performing novel tasks (for an example see Loukopoulos, Dismukes and Barshi (2009)). Rather than multitasking, people are switching between different tasks, albeit rapidly. Adaptation may be considered to be part of finding the right balance: meeting the demands, variations and pressures whilst working within the rules of the system (Crichton, 2005; Saward & Stanton, 2017; Stroeve, van Doorn, & Everdij, 2015). The ideas of Sperandio (1971) influence many authors and the concepts of situated, active management of workload emphasising feedback and feed-forward loops to support the selection of the strategy to be adopted based on a belief of being in control, are evident in many authors’ thinking (Loft et al., 2007; Malakis, Kontogiannis, & Kirwan, 2010a). Authors cite the efficiency-thoroughness trade-off (ETTO) of Hollnagel (2010) as one strategy that can be employed to cope (Carvalho et al., 2009; Grant et al., 2017). This can include the cutting of corners to conserve awareness and use less effort (Sauer, Wastell, Hockey, & Earle, 2003), altering the speed of work to get the job done or the distribution of work between individuals (Grant et al., 2017; Schöbel & Manzey, 2011).

All rules have exceptions because humans, and the systems within which they work, are complex which means that rules and procedures cannot cover all eventualities. Rules and procedures can never fully resolve all the uncertainties of the work environment, so can never be sufficient for every context (Bagnara et al., 2010; Hale & Borys, 2013b; Kontogiannis, 2012; Schöbel & Manzey, 2011; Woodcock, 2014). Therefore, whilst vital, it should be recognised that the descriptions in procedures will always be incomplete (Pettersen & Aase, 2008) and formal processes require informal knowledge to enable them to work given the realities of the work environment and the local context (Grant et al., 2017). The experience of using informal strategies allows them to become near effort-free, supporting the efficiency of work. Adaptations, trade-offs and workarounds can therefore cascade creating the need for more adjustments to continue to be efficient. As the gap is exacerbated the system becomes akin to a living organism (Jordan et al., 2009; Lindblad, Flink, & Ekstedt, 2017; Sarter & Woods, 1997). Additional procedures may be introduced to attempt to address informal practice and incomplete specifications to close the gap but these can just add more complexity to the system (Huber et al., 2009; Kontogiannis, 2012). Thus, there are two sides to adaptation: a work-flow may be improved through adaptation, but if this workaround becomes routine then it masks the underlying deficiency in the system (Lindblad et al., 2017).

## Factor 3: Acquiring knowledge

The skills needed to develop strategies for adaptation and the experience to apply them are largely built up on-the-job. The literature does not describe instances of formal training in adaptation or the skills necessary to deliver it. Instead, authors discuss two processes that we describe in the third factor: feedback from the system to build competence through practice and the sharing of knowledge from others.

The knowledge and judgement to adapt is acquired and learnt through practice. The ability to appreciate the patterns of work, recognise the signals and perform a similarity match to what worked before is largely learned through feedback from the system (Kontogiannis, 2012; Woodcock, 2014). Similarly, an appreciation of the constraints within the environment, the scale of demand and pressures and learning to cope with the boundaries is acquired through observation and interaction with the system (Cañas et al., 2003; Manley, Martin, Jackson, & Wright, 2016; Stoop & Dekker, 2012). Yet, inevitably, with inexperienced operators, mistakes will occur as these boundaries are explored – yet failure is part of the learning process (Brewster et al., 2016; Sheridan, 2008). To acquire skills through trial-and-error needs variation, since it is hard to learn what could happen in a stable system, and feedback, to provide a process to build knowledge of what works for a variety of contexts (Pettersen & Aase, 2008). Simulation is one means by which the skills to adapt can be practiced, the patterns and expectations set and the structures of work honed since trial and error may not be permissible in the live environment (Johnson, Guediri, Kilkenny, & Clough, 2011; Le Coze, 2015; Macrae & Draycott, 2016).

Adaptation is also built through a shared understanding of the system and acquired through relationships and interactions with others by learning from their experiences to then apply that knowledge (Anderson et al., 2012; Jordan et al., 2009; Kontogiannis, 2012; Macrae & Draycott, 2016). The stories the organisation tells itself of previous errors or accidents, the heroism of others or simply a discussion that empowers the group and builds the social conception of safety are all important processes that develop competence in the system and experience upon which to draw (Chou & Wu, 2014; Debono et al., 2013; Pannick et al., 2017; Rochlin, 1999). Again, the literature also considers the alternative that the cascade of learning from one operator to the next can disconnect the procedures or the design intent from practice. Similarly, it can encourage bad habits or actions that may, unknowingly, increase risk (Bagnara et al., 2010; Dahl, 2013).

## Factor 4: Unpredictability of consequences

Work needs to be done but is grounded within a specific context and adaptation is the evolution of responses to variations in the work environment. For socio-technical systems, this context is one of complexity, non-linearity, uncertainty and emergence (Pumpuni-Lenss, Blackburn, & Garstenauer, 2017; Roberts, Mazzuchi, & Sarkani, 2016). Although work environments have structure, complex socio-technical systems are characterised by a multitude of interconnections between interrelated functions each having a mutual interdependence that generates an emergent complexity (Bagnara et al., 2010; Cedergren, Johansson, & Hassel, 2017; Pumpuni-Lenss et al., 2017). To make decisions and adapt to changing demands is to attempt to understand a complex system and to try to appreciate the emergent relationships between the components, including the humans in the system and their social interactions, rather than just understanding the components themselves (Dainoff, 2017; Larsson, Dekker, & Tingvall, 2010; Leveson, 2004; Rasmussen, 1997; Ray-Sannerud, Leyshon, & Vallevik, 2015). However, decisions and choices must be made in the face of this complexity so humans approximate their understanding through linear thinking (Amalberti, 2001) but the nature of decision-making in complex systems is that reality is more complex than can be envisaged and linear-thinking is insufficient (Lindblad et al., 2017; Reason, 1995). The dynamism of complex systems means that a description of the system cannot be written down before it changes (Patriarca, Di Gravio, & Costantino, 2017). It is impossible for the individual to fully anticipate the flow of work solely from knowledge of initial conditions. Similarly, it is impossible to understand how the constituent functions complement each other to produce safety, or other outcomes, due to the inherent complexity resulting from the activities, interactions, variation and uniqueness that exists (Duca & Attaianese, 2012; Kleiner, Hettinger, DeJoy, Huang, & Love, 2015; Santos et al., 2016). Adaptation in complex socio-technical systems occurs in a context of partial knowledge where the true state of the system is opaque, awareness of the results of actions may be lost, prediction is impossible and learning difficult because there are no causal links or directly attributable feedback (Catchpole et al., 2018; Cedergren et al., 2017; Jordan et al., 2009; Kontogiannis, 2012; Langer & Braithwaite, 2016; Pettersen & Aase, 2008; Sarter & Woods, 1997; Taylor, Lawton, Slater, & Foy, 2013). Building on Perrow (1984), many authors describe how complexity creates cognitive demands that are beyond an individual person’s comprehension (Clarke, 2005; Gomes et al., 2015).

Ashby’s (1956) notion of requisite variety is an important concept to support an understanding of how control over complex systems is affected. In order to deal properly with the diversity of problems in an environment, the repertoire of possible responses must be just as diverse. This is generally interpreted as being part of the role of the human to provide the additional degrees of freedom in the system necessary to counter variation and to support a level of creativity and adaptation to whatever challenges may emerge (Le Coze, 2015; Paté‐Cornell, 1993; Sheridan, 2008).

## Factor 5: Trade-off for performance

The fifth factor identified in the literature is related to how adaptation is the decision, conscious or unconscious, to make a trade-off. Goal conflicts create pressure (Lawton, 1998) from the need to address competing demands with safety becoming just another goal to be managed as part of the broader context of decision-making in normal work (Rasmussen, 1997). Safety, therefore, relates to this balance; how much resource is willing to be traded-off from other goals to the prevention of accidents (Aurino, 2000; Wilson et al., 2009).

The literature describes many types of performance trade-offs that include: the speed of work, workload, commercial demands, incentives and targets, time, schedules, and communication (Grant et al., 2017; Khawaja, Chen, & Marcus, 2012; Plumb, Travaglia, Nugus, & Braithwaite, 2011; Sauer et al., 2003). Adaptation and trade-offs are required when resources are scarce, such as insufficient funds to purchase appropriate equipment and making do with an improvised solution (Huang & Gramopadhye, 2014) or continuing to fly with an unsafe aircraft to avoid maintenance downtime (Gomes et al., 2015). Single use medical equipment may be re-used due to an awareness of the cost of a replacement (Phipps et al., 2008), patients may skip a dose of medication trading the risk from not following a medication regimen with the impact on personal finances or, even, other life goals such as personal comfort and the enjoyment of life (Mickelson & Holden, 2018).

The adaptive decision of trading-off may “satisfice”, (a concept introduced by Simon (1957)), whereby operators attempt to address multiple competing options by searching through possible responses and selecting the least bad, or good enough, option across multiple goals that achieves a basic threshold of acceptability. This approach can be a useful strategy that manages risk by choosing an option that achieves a goal in a range of possible, but uncertain, scenarios. Thus a critical need may be met although the overall goal may not be maximised (Rasmussen, 1997).

The design of the system itself is always a compromise and the pressures and demands that result require trade-offs which expose human frailties (Reason, 1995). Trade-offs to resolve goal conflicts can accumulate into a downward spiral of increasing cognitive demand that is linked to error (Catchpole et al., 2018). Whilst most of the time the trade-off works, sometimes it has safety implications (Vogt, Leonhardt, Köper, & Pennig, 2010) and trying to resolve goal conflicts through trade-offs is commonly reported as contributing to incidents (Hobbs & Williamson, 2003).

## Factor 6: Skills needed

The changing needs of the work environment create a requirement for the individual to have, or to have acquired, experiences and certain skills to support their ability to adapt. The sixth factor explores what the literature considers to be the skills needed for adaptation. Operators use the cues and signals from systems to assimilate many diverse indicators and sources of information. From this they build a picture in order to detect and monitor potential issues. The ability to anticipate enables operators of systems to sense impending danger, predict possible future states, and plan ahead (Gaillard, 1993; Malakis et al., 2010a; Paté-Cornell, 2012) which is essential to maintain control (Amalberti, 2001). These signals may be secondary or confirmatory in nature, such as the implicit cues in others (i.e. the tell-tale leg twitch), and supports pre-empting their actions for adopting different strategies (Malakis et al., 2010b; Sarter & Woods, 1997), and can extend beyond the current task (Saward & Stanton, 2017).

Individuals are able to appreciate the patterns in the complexity and search through a stock of potential responses to find an applicable strategy (Loft et al., 2007). Interpreting the signals requires knowledge of the system and its rules and then the wherewithal to make a judgement, often in the presence of uncertainty, of an appropriate course of action (Mulvihill et al., 2016; Paté‐Cornell, 1993). But when the procedure does not work, or the learned strategy cannot be applied to the unforeseen, the ability to cope and adapt draws on skills of creativity, innovation, problem solving and flexibility (Phipps et al., 2008; Reinartz, 1993; Ritz, Kleindienst, Brüngger, & Koch, 2015; Vicente, 2002). If these skills are then found wanting, the last skill that is identified is the ability to communicate, to resolve the uncertainty in the system by drawing upon the experience of others through cooperation, consensus and teamwork (Aurino, 2000; Malakis et al., 2010b; Renkema, Broekhuis, & Ahaus, 2014; Woodcock, 2014). Some authors refer to individuals or the group having a ‘mindfulness’ of the system that describes their heightened awareness of the system and being alert to the need to adapt (Carvalho & Ferreira, 2012; Crichton, 2005; Hale & Borys, 2013a; Huber et al., 2009) and this concept is promoted in HROs (Le Coze, 2015). Yet this idea of mindfulness also extends back onto the individual to describe the idea of having an awareness of one’s own capability and the capacity to be reflexive and self-critical, to build on experience and learn for the future (Macrae & Draycott, 2016; Rochlin, 1999).

## Factor 7: Violations

Violations are the deliberate deviation from a rule that has previously been declared to be safe and approved for the task. Reason (1990) presents the view that different types of violations exist: intentional and unintentional (Dahl, 2013). We do not deal with unintentional violations further since this falls into the purview of discussions on error, whether or not such a notion is still valid. Violations can be considered differently to other unsafe acts since violations have motivations (Hobbs & Williamson, 2003). They arise due to the differences between governance and practice (Phipps et al., 2008) and can be positive despite the negative connotations of the language (Reader & Gillespie, 2013).

Violations can be grouped into the routine and the exceptional (Hobbs & Williamson, 2003). Exceptional violations are addressed in the ‘Improvisation and Creativity’ factor of the model (see Factor 8). Routine violations are believed to improve the system, for example a work-around to improve the efficiency or flow of work (Debono et al., 2013). They can also address procedural limitations that create extra work (Huang & Gramopadhye, 2014) through the omission of steps in a procedure, informal practices and the use of equipment beyond its original design intent (Hobbs & Williamson, 2003). In highly optimised systems, rules or constraints become less effective when they get in the way of normal work and, as they become more unwieldy, violations inevitably occur when managing conflicting demands and pressures (Amalberti, 2001; Gisladottir, Ganin, Keisler, Kepner, & Linkov, 2017; Gomes et al., 2015; Phipps et al., 2008; Reason, 1995; Rochlin, 1999; Thomas, Phipps, & Ashcroft, 2016). Violations therefore result from a well-intentioned loyalty to the overall goals of the system (Lawton, 1998).

Practice and repetition of the same task can breed a familiarity that can lead to violations (Debono et al., 2013). The challenge for professionals working in complex systems is that routine work does not need procedures (Dahl, 2013). Violations can occur where operators believe the consequences to be negligible or where the violation is understood to create risk but this is believed to be manageable. Consequently, experts often make risk-based decisions and only apply the spirit of the rule (Hale & Borys, 2013a; Lindblad et al., 2017; Nyssen & Côte, 2010; Stroeve et al., 2015). This is encapsulated in the idea of Normalisation of Deviance (Vaughan, 2016) where people become so used to violations that they do not consider them to be deviant even when they stray beyond their own perceptions and boundary for risk. Yet, despite this, the notion that violations are necessary to achieve system performance is validated through ideas such as ‘work-to-rule’: the tacit acceptance, by both management and workers alike, of the need for violations (Leveson, 2004). Management turn a blind eye to violations since the front-line is generally granted a degree of autonomy to act, enabled by a trust in their professionalism, by managers who may have an incomplete appreciation of the system (Debono et al., 2013). Indeed, violations are frequently excluded from risk management processes and are not included in models of the organisation because they are deliberate and highlight a limitation in the work environment that the organisation may be reluctant to acknowledge (Hobbs & Williamson, 2003). Audits of rule adherence therefore focus on the quality and compliance to the procedure, not necessarily seeking to understand the context of the work and the more systemic discussion of why the rule was broken in the first place (Mackenzie & Holmstrom, 2009).

## Factor 8: Improvisation & Creativity

The eighth factor builds upon the concept of exceptional violations observed in complex systems when individuals are placed under unusual demands, however, to draw a distinction, we discuss these using the more positive language of improvisation and creativity. Procedures cannot necessarily be wholly relied upon in an emergency and additional skills are often drawn upon (Paté‐Cornell, 1993). Rasmussen’s (1983) taxonomy of human behaviour supports an understanding of the responses that range from: automatic, skill-based behaviours; the rule-based use of experience to provide a template for a response to known situations, and; the knowledge-based response to new situations where creativity and innovation are needed. Frontline operators use their knowledge and expertise to creatively improvise and cope with the unexpected and the resulting pressures (Hale & Borys, 2013b; Phipps et al., 2008). During emergencies operators are required to intervene to contain the situation, adjusting their performance to compensate for the issues in the system and recover the system to a safe state (Amalberti, 2001; Malakis et al., 2010a). First, extant procedures and training are applied, as a source for a possible response, then, if the available procedures are incomplete for the context, alternative responses are arrived upon through a process that is innovative, creative and uses heuristics (Jordan et al., 2009; Reinartz, 1993; Ritz et al., 2015; Stroeve et al., 2015). Thus adaptation to disturbances is reactive innovation in context, in the moment, and is reliant on the skill, prior knowledge and resources available (Holden, Schubert, & Mickelson, 2015; Macrae & Draycott, 2016).

In a disturbance the presence of decision makers at the front-line is an important source of safety. The autonomy that the front-line has, and the immediate feedback available by virtue of being at the sharp-end, enables operators to act to ensure goals are achieved in a rapidly evolving situation. This can result in adaptation through the reorganisation, or self-organisation, of labour where tasks are reallocated and additional resources and skills come to the fore. Experts use holistic knowledge of the system, adopt leadership positions and generate new communication links across the hierarchy as the flow of decision-making is altered, flexibility is improved and rigidity in the system is addressed (Bagnara et al., 2010; Paté‐Cornell, 1993).The resilience of systems to disturbances is largely based upon the human ability to absorb, adapt and restore in the event of surprise (Kirwan, 2001; Pettersen & Schulman, 2015; Stroeve et al., 2015). Organisations are directed to plan for surprise by supporting the emergence of innovative responses that cope with the unforeseen and provide flexibility, slack or additional capacity in the system that can be used to recover (Benchekroun & Pierlot, 2012; Cedergren et al., 2017; Cornelissen, Salmon, McClure, & Stanton, 2013).

## Factor 9: Procedures & Rules

The nature of decision making in complex socio-technical systems is influenced by the presence of rules and procedures. The general belief is that safety comes from minimising uncertainty and through the control of work. To help guide decision-making and ensure the safety of complex socio-technical systems, policies, rules, procedures and risk management processes are common (Larsson et al., 2010; Schöbel & Manzey, 2011). The aim is to motivate, guide, educate, influence and constrain the behaviour of front-line operators (Bagnara et al., 2010). Work is usually understood as a decomposition of tasks and described in a procedure with the procedures forming part of a system of barriers to catch unsafe acts in the belief that safety emerges from the layers of defences put in place (Naweed & Rose, 2015; Rasmussen, 1997; Reason, 1995). Procedures and rules therefore control behaviour by trying to identify the good practices that address variation and minimise risks (Nyssen & Côte, 2010; Reason, 1995). They can be tailored to the perceived level of operator competence in the system (Hale & Borys, 2013b; Langer & Braithwaite, 2016) and this is reciprocated with novices more likely to stick to the rules (Woodcock, 2014).

Rules do not, in general, describe the efficiency or quality needed (Dahl & Olsen, 2013). Indeed, describing a set of procedures as safe reflects the subjective judgement of the operators based on their capability to enact the procedures (Rochlin, 1999). Whilst procedures may be useful, or even vital, in keeping operators safe, and the need for procedures may be socially ingrained (Pettersen & Aase, 2008; Thomas et al., 2016), seeking to standardise can be detrimental to safety (Debono et al., 2013). A ‘safety first’ or compliance-based attitude can breed additional procedures that add complexity (Wilson et al., 2009) and poorly thought through procedures can cause more harm than good (Farrington-Darby, Pickup, & Wilson, 2005). Procedures, however, support adaptation by being the first thing tried in the presence of uncertainty or disturbances (Ritz et al., 2015). They provide a tried and tested path through previously identified situations. Therefore, rules that give no flexibility to operators create issues of compliance in situations of goal conflicts, yet goal-based rules, that support adaptation, provide a compromise between compliance and flexibility that can support safety (Hale & Borys, 2013a).

## Theoretical mapping

Our model of the literature identifies nine factors that describe adaptation in the context of the safety of socio-technical systems and these have been described with reference to the discussions in relevant papers. In the introduction we reviewed some of the underlying theoretical advances in safety science and these theories can be seen to support the factors that have been identified.

Factor 2 (Strategies & Informal Practice), Factor 3 (Acquiring Knowledge) and Factor 5 (Trade-off for performance) all appear to be strongly linked to Rasmussen’s ideas of migration to the boundaries. Trade-offs relates to the degrees of freedom possessed by operators to meet the economic and efficiency pressures from the organisation. Similarly, the pressure of workload and the desire for individual efficiency relates to the Strategies & Informal Practice and Acquiring Knowledge factors where efficiencies to reduce workload pressures may be identified and passed on from operator to operator. The complex nature of pressures, the unpredictable nature of the resulting variations in system performance and the imperceptibility of the accident are all features of Rasmussen’s thinking and can be seen in Factor 4 (Unpredictability of Consequences). There is also relevance to violations (Factor 7) as a response to pressures from conflicting goals and procedures & rules (Factor 9).

Theoretical parallels can also be drawn to factors that relate to the principles identified in HROs. Unpredictability of consequences (Factor 4) is a core idea of HRO theory and all of the five HRO principles, summarised in the introduction, align since HROs are concerned with managing the unexpected. Factor 6 (Skills needed) and Factor 3 (Acquiring knowledge) can be seen to align to HRO theory since organisations are observed to have collective mindfulness of the state of the system and be committed to resilience through learning the lessons of how to cope. Factor 7 (Violations) and Factor 8 (Improvisations & Creativity) both relate to the HRO principle of deference to expertise.

# Application of the model: a case study of adaptation in air traffic control

The grounded theory approach to the development of the model has provided an initial literature-based exploration of the factors associated with adaptation in complex socio-technical systems. It has identified that adaptation is work conducted in a context that is unpredictable and that involves an explicit, or implicit, trade-off against conflicting goals. It is a decision, conscious or unconscious, to violate a rule or procedure or to improvise and work-around a deficiency in the system. Adaptation requires a set of skills and competencies to support the decision-making processes that build upon previous knowledge and experience. However, in exploring the potential of the model it is first necessary to understand its validity through application to a case study. The application of case studies is a common approach in Human Factors research to understand the ability of a theoretical model to adequately represent real-world experiences for example in road (Parnell, Stanton, & Plant, 2016), aviation (Plant & Stanton, 2012) and the military (Rafferty et al., 2010).

As a preliminary validation of the model, we return to the discussion of the implications for UK air traffic controllers following the closure of US airspace as a result of the terrorist attacks on New York and Washington on the 11th September 2001. We present a consideration of the factors in the model with reference to published material presented by NATS experts to International Civil Aviation Organisation working groups, the legal record file for aircraft positioning, entries in the NATS incident reporting system, contemporaneous watch logs and informal discussions. Each factor will be discussed in the context of the case study and the links between the factors will be highlighted.

## Using experience

The air traffic control operation is built around a hierarchy in terms of the roles of the different controllers, from watch managers, supervisors, controllers to assistants. However, in an emergency situation, it is natural for leaders to emerge based on their experience and personality. On 11th September 2001, the experience of individuals supported the efficient adaptation and restructuring of the operation to the demands being placed upon it. As the operation had to rapidly cope with a sudden escalation in demand from aircraft requesting return routes, aircraft emergencies and use of the turnback procedure, the normally serene operations room became highly animated and louder, one of the key indicators in air traffic control of an escalation in workload, as the level of discussion increased. Controllers and assistants who had experience of other roles that they previously held, whilst possibly not currently ‘valid’, knew enough to be able to identify the signals from those aspects in the operation that required attention and to help those who were valid but clearly becoming overwhelmed by the task at hand. On 11th September 2001, the availability of experience in others enabled a watch-level strategy of increased flexibility to address individual demands as they manifested.

## Strategies & Informal practice

Air traffic control, like other safety related industries, uses a culture of story-telling and apprenticeship to pass on experiences and develop informal practices. Whilst the turnback procedure was practised, the context in which it was being used required informal knowledge to make it work. Given the exceptional uncertainty that existed the checks made on aircraft routings needed to be continually rechecked against the trajectories of other aircraft as these changed. The delays in the communication system, that are normally acceptable, can be problematic in multiple turnback scenarios since by the time a route was checked and validated the aircraft was no longer in a position to carry it out, for example having turned in the alternative direction. The time involved in planning a conflict-free return trajectory can exacerbate the delays in communication. Controllers had to increase the efficiency of operations, by generating more efficient checking strategies and drawing on extra resources, to keep pace with the escalating complexity whilst still being thorough in assessing aircraft routes for conflicts.

## Acquiring knowledge

Controllers spend many years developing the knowledge and skills that they need to be controllers. This training ensures that they are competent to manage air traffic in a variety of situations. However, once they have completed their training they become ‘valid’ on a sector through a process akin to an apprenticeship where what has been formally learned is practically applied. But one of the main elements of this apprenticeship is the passing on of strategies from more experienced controllers to novices. Controllers also acquire knowledge of how to adapt to a variety of circumstances through normal everyday work. The work of being a controller involves considerable variation in a normal day: requests for route changes, weather patterns, new procedures, trials and emergencies all bring their own challenges that require their skills to adapt and deliver a safe service. These everyday adaptations provide an environment that supports iterative development of strategies and practice in adaptation that can be applied in unusual or more taxing situations. Controllers prepare for possible emergency situations on an annual and recurrent basis through formalised and mandatory training sessions that help them to develop strategies to respond to surprise. This enables them to practice what has worked for others, through shared lessons learning exercises, and communicate with their colleagues in a shared setting to support their collegiate attitude to safety.

## Unpredictability of consequences

As the events of 11th September unfolded, there was considerable uncertainty in the air traffic control room at Prestwick. The possibility of attacks in the UK and whether UK airspace should also close as a precaution was discussed. Although there was no closure, the heightened tension generated uncertainty about what political decisions might be made and how they might be enacted. NATS controllers work jointly with their counterparts in the UK military and this ensured their close cooperation and maintained effective communication between the civil and military service to reduce some of the unpredictability. As aircraft adopted the turnback procedure the technical limitations of the surveillance and communication equipment for managing the air traffic operation become apparent affecting controller’s knowledge about the state of the overall air traffic system. As the closure is communicated, it is not clear what aircraft will do and the operations room is flooded with messages and information, creating a rapid increase in workload for the controllers on duty. Furthermore, throughout the description of the turnback procedure there is considerable leeway and room for interpretation which means that, whilst the procedure covers a multitude of possible circumstances, it introduces uncertainty in the controller’s understanding of what the pilot of the aircraft adopting the contingent procedure intends to do. For example, use of the phrase ‘whenever operationally feasible’ provide pilots with flexibility but creates uncertainty of the timing of the action. Use of the phrase ‘where possible’ again provides uncertainty about what exact course of action will be taken. The procedure also provides guidelines for what should be done but recognises that factors that may be apparent to the aircrew will dictate a more appropriate course of action: for example, preferring to turn towards a possible diversion airfield. The adaptation model therefore highlights the links between procedures and uncertainty. The procedure is written to be flexible but the unpredictability that is consequently introduced causes a potential problem when it is adopted by more than one aircraft in the airspace. The turnback procedure was adopted by approximately 45 aircraft in the hour following the announcement of the closure of US airspace. As is immediately apparent, if two aircraft both adopt the turnback procedure, and turn off their minimum separated routes towards each other to adopt a return route halfway between and also deviate from their assigned vertical level in the same direction, then they can come into conflict.

## Trade-off for performance

The turnback procedure effectively creates a new tolerable separation standard of 30Nm and 500ft (half the original minimum) as aircraft come off the OTS and adopt a reciprocal return route that is halfway between other tracks. It can be seen that the level of safety that the normal minimum separation provides is being traded because of the more pressing safety needs of the aircraft adopting the procedure. The reduction in separation and the consequent increase in conflict risk is deemed tolerable given the overriding goal of safety and the higher risk from not turning back. Similarly, the needs of retaining the ordered predictable structure and flow to manage the uncertainty in the operation give way to more pressing needs of getting aircraft back before lack of fuel becomes an issue. Furthermore, other trade-offs existed including separating the returning aircraft from aircraft on the adjacent tracks equally. A lateral offset of 20Nm (one-third of the standard) could have been adopted that would have possibly increased the potential risk, the returning aircraft would be closer to one of the tracks, but could have accommodated the remote possibility of two aircraft turning back from adjacent tracks towards each other.

## Skills needed

Air traffic controllers are highly trained professionals subject to recurrent competency checks. In addition to their knowledge about the technical system and procedures, a number of additional non-technical skills are also part of the key capabilities of these individuals. Whilst a controller acts as an individual in making decisions and maintaining control over the traffic they are responsible for, they are also part of a wider team that has a shared conception of the goals of ATC. A number of improvised actions on 11th September 2001 can be seen as supporting this view: the individual mindfulness and anticipation of the acts of others based on a heightened awareness of the cues and signals of possible danger helped support the collective effort and successful adaptation to the increase in pressure in the operation. Whilst controllers must also be decisive, they also use their skills of delegation, making creative use of available resources, placing their trust in their colleagues to help them and being open to constructive challenge to support problem solving.

## Violations

The legal record file for aircraft on the OTS was examined by NATS experts to extrapolate the positions of aircraft turning back and their return trajectories. If two aircraft breach the minimum prescribed separation of 60Nm laterally, 10 minutes in trail (effectively 60Nm for most aircraft) then this is defined as a Loss of Standard Separation Pair (LOSSP). Given the reduced separation that the turnback procedure creates, some aircraft passed each other with less than the required minimum separation. There were 16 pairs of aircraft where the minimum estimated separation violated the required minimum. With an open and effective reporting culture and in normal circumstances, a LOSSP would generate mandatory incident reports from the controllers involved and possibly also from the pilots or airline. This would be investigated by the NATS investigation team to understand the circumstances, determine causes, learn lessons and make recommendations. This process is informed by training and governed by rules, standards and legal processes (for example relating to timing and anonymity). The NATS incident reporting database was queried for the incident reports relating to events on 11th September. There is one oceanic entry for that day that is as follows: “Due closure of American airspace, there were multiple turnbacks some necessitating the application of less than standard separation”. The violations of minimum separation in this instance were ignored, the actions of the NATS controllers in achieving a safe outcome were gratefully accepted and no further action was taken other than the analytical review presented to the International Civil Aviation Organisation oversight group some seven months later.

## Improvisation & Creativity

The control room has sufficient staff to support the expected level of demand and to support the legally required controller rest breaks to minimise the risks from fatigue. Controller duty hours are also regulated, in the same way to pilots, to ensure that a minimum number of hours are conducted, to retain familiarity and competence, and that a maximum number is not exceeded, to manage the risks of accumulated fatigue. When not actively required or when they are taking their legally required breaks, duty controllers unwind away from the operations room. As the situation escalated, controllers who were mid-break returned to the operation with news of what was occurring from television reports and then stayed to assist their colleagues as the turnback commenced. This is expected behaviour and the resilience of the operation is enhanced by being able to actively bring additional resources to bear. The ability to adapt to demands at near breaking point was considerably enhanced by the improvised and reflex actions of controllers who had completed their duties and were on their way home and by other controllers not rostered on for that day. Many off-duty controllers, on turning on their radios and televisions and hearing of the closure of US airspace, could appreciate the implications for their on-duty colleagues. They got in their cars and drove to the control centre and proceeded to act as assistants, moving information around the operation, provided a second pair of eyes to check the working controller, acting as relief and as sounding boards for strategies to manage the demand. License and operating hour restrictions became secondary considerations as the improvised new work structure emerged. In an additional complication for the operation, coordination was required with other air traffic control centres and airports in the UK so that they could prepare for the sudden influx of additional aircraft. On contacting one airport to understand how many diversions they could handle controllers recall being told that they should just send as many as necessary, the airport would improvise and cope.

## Procedures & Rules

The procedures and rules for aircraft on the North Atlantic attempt to provide a degree of certainty to what is an inherently uncertain air traffic environment. The use of comparatively large separation standards reflects a degree of caution and attempts to ensure that, in the event of error or failure, aircraft remain safely apart. The principles of order and flow are retained through the use of speed and time control for entry into the airspace, and the use of an organised and separated route structure that all aircraft conform to ensures that aircraft enter and leave airspace safely. To further reduce uncertainty, standardised phraseology and message formats are used to communicate between controllers and pilots. The timing of position reports also follows an expected pattern. The North Atlantic Minimum Navigation Performance Standard Airspace Operations Manual describes the contingency turnback procedure to be adopted when an aircraft needs to return. The aircraft should initially deviate by turning left or right by 90 degrees. The general principle is that the aircraft should be offset from its assigned route by 30Nm (halfway between the two routes) and climb or descend to a level that is also midway between other assigned levels (i.e. by 500 or 1000ft depending on the separation standard in force). The procedure effectively places an aircraft adopting the turnback at the midpoint vertically and horizontally from other aircraft on a route separated by half the prescribed separation standard. As has been discussed in the other factors, the implications for more than one aircraft needing to return, or even the remote possibility of all aircraft needing to return, had not been seriously considered. The procedure’s description was limited by the imagination of the designers, yet, the capability of the controllers to adapt the procedure and their working methods ensured that the challenges of that day, reported by some controllers to have been the most extreme in their experience, were met and all aircraft turning back returned safely without incident.

## Interconnections

In addition to reviewing the usefulness of the adaptation model factors themselves, the case study discussion draws out some of the interconnections between the factors as identified by the literature. Results from a review of the case study from the perspective of factor interconnectivity are shown in Figure 5. This again highlights the potential of the model for uncovering these additional features of the wider socio-technical system that support safety.

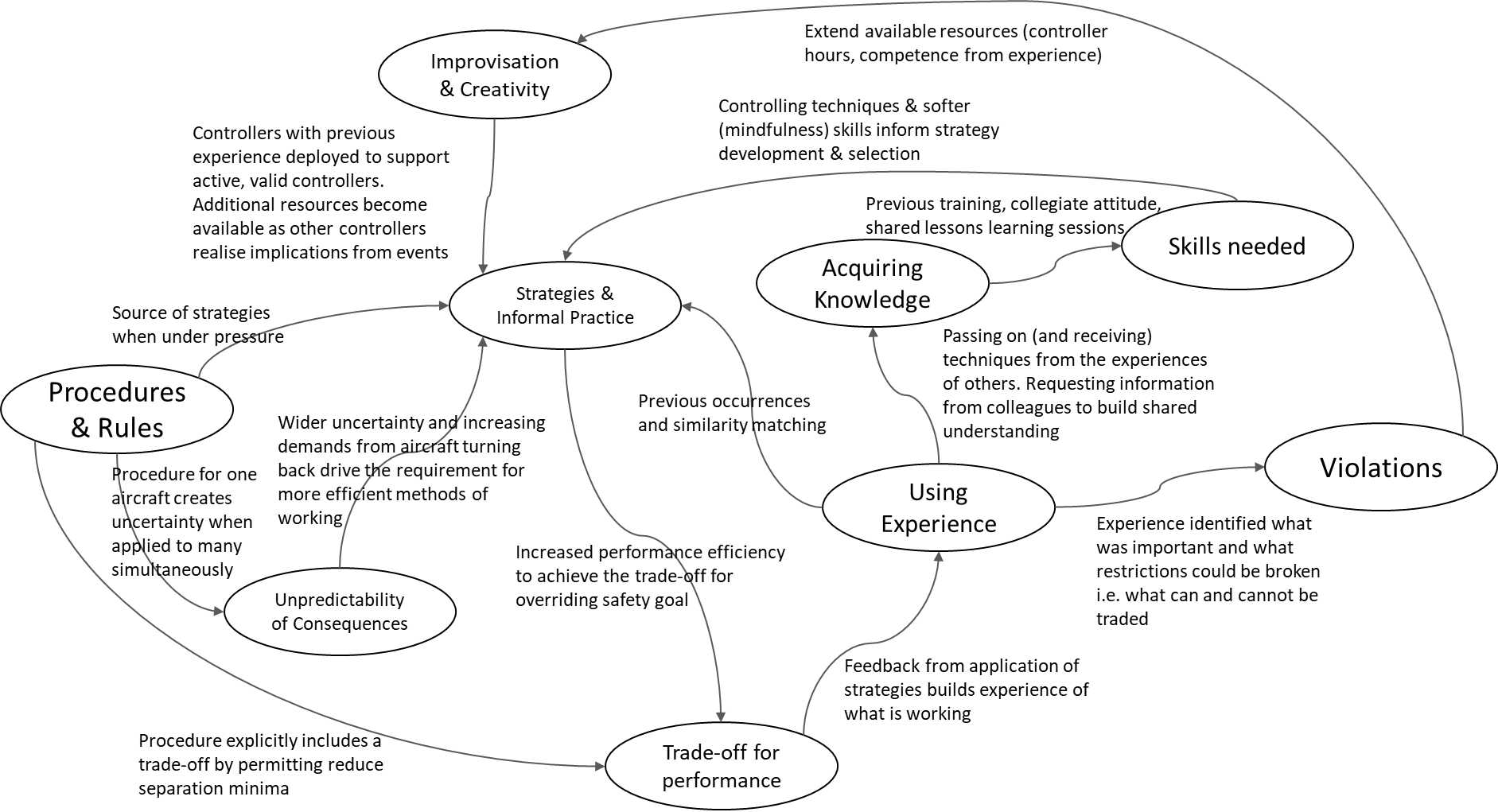


Figure : Features of the case study identified by interconnections in the adaptation model

## Summary

In common with many Human Factors methods, the adaptation model presents a systemic exploration taking into account a multitude of factors in the work environment and provides prompts for the consideration of number of ideas that more traditional, failure-focused, methods may ignore. Additionally, the interconnections between the factors in the model provide further richness to the enquiry to prompt examination of one factor’s relationship to another. However, it can be seen that the discussion can leap between abstraction layers in the system: from organisation, to team, to individual – reflecting the complex interrelationships between the layers of the system’s hierarchy. Therefore, the model could be enhanced with structured methodological approaches to the examination of adaptation factors in, and across, these organisational layers that we now discuss in the implications of the study.

# General Discussion & Implications

Accident reviews suggest a non-linearity in complex systems (Grabowski et al., 2009) meaning that fixed standards and linear thinking are insufficient (De Lessio, Cardin, Astaman, & Djie, 2015). Yet error, the post-facto re-evaluation of a decision, is still the prevailing paradigm even though systems are increasingly recognised as non-linear: where cause-and-effect relationships breakdown (Aurino, 2000; Sheridan, 2008). It therefore appears contradictory to emphasise that human task performance should be orientated to system-wide goals when the individual has no control over the outcome (Alexander et al., 2001) and the goal is lost in the complexity (Cedergren et al., 2017). There is considerable dogma in current safety processes which create cultures of compliance and consistency yet many studies suggest that adaptation provides key benefits to the management of safety in complex socio-technical systems (Dekker & Pitzer, 2016).

There is therefore a need for further development of the ideas of adaptation if further progress is to be made in the management of increasingly complex systems in a variety of domains. The model highlights the key factors from the safety literature that are relevant to this discussion: the relevance of context and the appreciation of complexity and unpredictability, the need to make trade-offs where goals conflict, the reliance on the skills, knowledge and experience of humans, that rules exist but may be broken for a variety of reasons. It also reinforces the view that human variability supports the adaptations necessary to mitigate the variability in the work – that people create safety.

The application of the adaptation model has shown that it is possible to be explicit on how adaptation is a source of safety. Whilst the literature may describe adaptation as ubiquitous and normal, the application of the model has supported an exploration of adaptation to make it observable. Making adaptation visible to safety managers means that the component features can be identified and developed within a system. This addresses a key weakness in the literature: the link between the organisation and the individual. Much of the literature emphasises the role of humans in supporting safety and pronounces with normative actions that organisations should focus on the individual. However, there is little in the way of discussion of the idea of connecting the individual’s role in adaptation to the team’s role and to the organisation’s role – the micro-to-meso-to-macro translation of adaptation (Grote, Weyer, & Stanton, 2014) – that we also identify as a limitation from the case study. For example, graceful extensibility, the capability to stretch at or near to system boundaries and continue to deliver system outcomes when surprise occurs, can be thought of at the different levels of the organisational hierarchy; yet how can organisations better understand the features of their system that support this capability (Woods, 2018)? Whilst an organisation may appreciate the role of humans, there is limited discussion in the literature of the implications of these ideas for organisations and by what means adaptation can be monitored, supported and cherished in uncertain and complex systems.

One potential avenue for further research in support of these issues builds upon a central premise of ‘Safety II’ that redefines safety as not ‘avoiding things that go wrong’ but an emphasis on ‘what goes right’ (Hollnagel, 2010). The consequence of this definition is that it requires an understanding of adaptation, as a feature of why things go right in normal work, at different levels in the organisational hierarchy. The capability to adjust is an important indicator of safety as a dynamic activity created through the conduct of work (Huber et al., 2009; Pettersen & Aase, 2008) that if made observable can connect organisational hierarchies to adaptation as a key safety concept. However, the literature also highlights that observational techniques, to acquire data on adaptation, need operators familiar with the work. In ultra-safe and stretched systems this resource can be prohibitively expensive. However, increasingly, modern technologies make available the quantitative data of how work is actually done through system records and other ‘data exhaust’ that could be examined for adaptation. This is a relatively unexplored area of possible understanding of adaptation (Foster, 2015; Ouyang, Wu, & Huang, 2018; van Gulijk, Hughes, Figueres-Esteban, Dacre, & Harrison, 2015). Yet in ultra-safe systems that are so successful so often, these datasets of success in normal work will be very large. Therefore, alternative analytical techniques, that may not have been traditionally applied in the safety domain, are needed to make sense of this quantitative data that should then be coupled with systemic methodologies that leverage qualitative data from subject matter experts. Initial ideas in this vein have been advocated for ATM in the NATS Safety Strategy (Foster, Espig, Smoker, & Dillon, 2014). However, a framework is needed to bridge the gap between grounded safety theory for complex socio-technical systems and possible novel techniques for understanding the data generated by humans adapting whilst doing work. The adaptation model presented here, may assist in uncovering, monitoring and supporting the ability to adapt in complex systems.

# Conclusions

Recent advances in safety science are moving towards a different approach to the management of risk within the safety-related industries. This new approach focusses on capitalising upon the adaptations operating within socio-technical systems. We have described a systematic review of the safety literature using a grounded theory approach from a variety of industrial domains and theoretical stand-points. This review has identified key features within socio-technical systems that describe how adaptation has operated and related to safety. A model for adaptation has been developed using these ideas to explore UK oceanic air traffic controllers’ response to the closure of US airspace following the terrorist attacks in the US on the 11th September 2001. This model seems to have applicability to a variety of safety-related domains. It can provide a bridge between theory and practice for the management of adaptation in support of the safety for socio-technical systems.

## Acknowledgements

This work is part-funded by NATS and the authors are grateful for the contributions of NATS experts to the development and interpretation of the case study.

# Appendix 1: Search term logic

## Inclusion Terms

The search query was developed based upon a structure of joined terminology sets where each set contained a number of terms informed either from common synonyms for the core term or based on an iterative review of abstracts and domain knowledge of the authors to identify additional terms commonly used in the literature. Wildcard characters were also used to capture variations in expression and SCOPUS includes an intrinsic capability to capture plurals and alternative spellings (e.g. between British and American English). Within the SCOPUS query, the terms in each set were split with OR statements, the sets themselves were separated with AND statements so that to be included in the search results a paper must have one of the terms from each set.

{safety} AND {domain} AND {object} AND {object context} AND {adaptation}

The list of terms used in each set is shown in Table 1 along with example terms which are captured through the use of wildcard characters.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Safety | | Domain | | Object | | Object Context | Adaptation | |
| Safe\* | Safe, Safety | Complex\* | Complex, Complexity | Human |  | Factor | Adapt\* | Adaptation, Adaption,  Adaptability, Adaptable |
| Risk |  | Socio-technical |  | Operator |  | Performance | Variat\* | Variation, Variability |
| Fail\* | Fail, Failure | Sociotechnical |  | Controller |  | Behaviour | Flexibility |  |
| Accident\* | Accident, Accidental | Dynamic\* | Dynamic, Dynamicity | Engineer |  | Reliability | Adjust\* | Adjust, Adjustment, Adjustability |
| Incident |  | Organization\* | Organization, Organizational | Staff |  | Error | Transform\* | Transform, Transforming,  Transformation |
|  |  | Engineering |  | Agent |  | Strategies | Cope |  |
|  |  | Ultrasafe |  | Procedur\* | Procedure, Procedural |  | Coping |  |
|  |  | Ultra-safe |  | System |  |  | Modif\* | Modification, Modify, Modifying |
|  |  |  |  | Automation |  |  | Improvis\* | Improvise, Improvisation |
|  |  |  |  | Tool |  |  | Alteration |  |
|  |  |  |  | Technology |  |  | Anticipat\* | Anticipate, Anticipation |
|  |  |  |  |  |  |  | Shift |  |
|  |  |  |  |  |  |  | Trade-off |  |
|  |  |  |  |  |  |  | Resilien\* | Resilience, Resilient |
|  |  |  |  |  |  |  | Drift |  |
|  |  |  |  |  |  |  | Judgement |  |
|  |  |  |  |  |  |  | Compensat\* | Compensate, Compensation |
|  |  |  |  |  |  |  | Interven\* | Intervene, Intervention |
|  |  |  |  |  |  |  | Optimization |  |
|  |  |  |  |  |  |  | Violation |  |
|  |  |  |  |  |  |  | Prevent\* | Prevented, Prevention |
|  |  |  |  |  |  |  | Recover\* | Recover, Recovery |

Table 1: Search term logic

## Exclusion Terms

The following terms (with wildcards) were used as exclusion criteria within the titles and abstracts.

"climate change" OR climatic OR seismic OR habitat OR insect OR bird OR prey OR foraging OR viral OR bacteria\* OR parasit\* OR infect\* OR patho\* OR disease OR \*cancer OR carcino\* OR hiv OR aids OR plasm\* OR lesion OR genetic OR sex\* OR reproduction OR men OR women OR male OR female OR adult OR infant OR enzyme OR protein OR receptor OR cell\* OR serum OR muscle OR muscul\* OR osteo\* OR cardio\* OR laparo\* OR verteb\* OR vascul\* OR epidemio\* OR retina\* OR renal\* OR adreno\* OR tissue OR pheno\* OR cyto\* OR chemo\* OR chloro\* OR amino\* OR nucleo\* OR schizo\* OR cerebro\* OR spatio\* OR pseudo\* OR \*dna\* OR \*rna\* OR microb\* OR vitro\* OR halog\* OR chloro\* OR nitro\* OR toxic\* OR cortex OR fpga OR fuzzy OR internet OR polymer OR textile OR"signal processing"

# Appendix 2: Interconnections matrix

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Using Experience | Strategies & Informal Practice | Acquiring knowledge | Unpredictability of consequences | Trade-off for performance | Skills needed | Violations | Improvisations & Creativity | Procedures & Rules |
| Using Experience |  |  |  |  |  |  |  |  |  |
| Strategies & Informal Practice | 19 |  |  |  |  |  |  |  |  |
| Acquiring knowledge | 19 | 12 |  |  |  |  |  |  |  |
| Unpredictability of consequences | 9 | 13 | 12 |  |  |  |  |  |  |
| Trade-off for performance | 18 | 14 | 8 | 8 |  |  |  |  |  |
| Skills needed | 20 | 13 | 14 | 9 | 9 |  |  |  |  |
| Violations | 13 | 16 | 11 | 11 | 13 | 7 |  |  |  |
| Improvisations & Creativity | 15 | 13 | 14 | 13 | 10 | 14 | 11 |  |  |
| Procedures & Rules | 19 | 12 | 13 | 7 | 13 | 10 | 15 | 12 |  |

Table 2:Interconnections of factors matrix

# References

Alexander, J. A., Waters, T. M., Boykin, S., Burns, L. R., Shortell, S. M., Gillies, R. R., … Zuckerman, H. S. (2001). Risk assumption and physician alignment with health care organizations. *Medical Care*, *39*(7 SUPPL.), I46–I61. Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-0035404352&partnerID=40&md5=dda3bfe3436037842bda7987672bbf29

Amalberti, R. (2001). The paradoxes of almost totally safe transportation systems. *Safety Science*, *37*(2–3), 109–126. https://doi.org/10.1016/S0925-7535(00)00045-X

Anderson, R. A., Corazzini, K., Porter, K., Daily, K., McDaniel Jr, R. R., & Colón-Emeric, C. (2012). CONNECT for quality: Protocol of a cluster randomized controlled trial to improve fall prevention in nursing homes. *Implementation Science*, *7*(1). https://doi.org/10.1186/1748-5908-7-11

Ashby, W. R. (1956). Cybernetics and Requisite Variety. *An Introduction to Cybernetics*.

Aurino, D. E. M. (2000). Human factors and aviation safety: What the industry has, what the industry needs. *Ergonomics*, *43*(7), 952–959. https://doi.org/10.1080/001401300409134

Bagnara, S., Parlangeli, O., & Tartaglia, R. (2010). Are hospitals becoming high reliability organizations? *Applied Ergonomics*, *41*(5), 713–718. https://doi.org/10.1016/j.apergo.2009.12.009

Beauchamp, P. (2013). Memories of 9/11 - NATS Blog. Retrieved October 19, 2018, from https://nats.aero/blog/2013/09/memories-of-911/

Benchekroun, T. H., & Pierlot, S. (2012). Whistleblowers: An essential resource for the sustainable prevention of risks in sociotechnical systems. *Work*, *41*(SUPPL.1), 3051–3061. https://doi.org/10.3233/WOR-2012-0563-3051

Brewster, A. L., Cherlin, E. J., Ndumele, C. D., Collins, D., Burgess, J. F., Charns, M. P., … Curry, L. A. (2016). What works in readmissions reduction how hospitals improve performance. *Medical Care*, *54*(6), 600–607. https://doi.org/10.1097/MLR.0000000000000530

Cañas, J. J., Quesada, J. F., Antolí, A., & Fajardo, I. (2003). Cognitive flexibility and adaptability to environmental changes in dynamic complex problem-solving tasks. *Ergonomics*, *46*(5), 482–501. https://doi.org/10.1080/0014013031000061640

Carvalho, P. V. R. de, & Ferreira, B. (2012). Modeling activities in air traffic control systems: Antecedents and consequences of a mid-air collision. *Work*, *41*(SUPPL.1), 232–239. https://doi.org/10.3233/WOR-2012-0162-232

Carvalho, P. V. R. de, Gomes, J. O., Huber, G. J., & Vidal, M. C. (2009). Normal people working in normal organizations with normal equipment: System safety and cognition in a mid-air collision. *Applied Ergonomics*, *40*(3), 325–340. https://doi.org/10.1016/j.apergo.2008.11.013

Catchpole, K. R., Hallett, E., Curtis, S., Mirchi, T., Souders, C. P., & Anger, J. T. (2018). Diagnosing barriers to safety and efficiency in robotic surgery. *Ergonomics*, *61*(1), 26–39. https://doi.org/10.1080/00140139.2017.1298845

Cedergren, A., Johansson, J., & Hassel, H. (2017). Challenges to critical infrastructure resilience in an institutionally fragmented setting. *Safety Science*. Centre for Critical Infrastructure Protection Research (CenCIP), Lund University Centre for Risk Assessment and Management (LUCRAM), Lund University, Sweden: Elsevier B.V. https://doi.org/10.1016/j.ssci.2017.12.025

Chou, J.-S., & Wu, J.-H. (2014). Success factors of enhanced disaster resilience in urban community. *Natural Hazards*, *74*(2), 661–686. https://doi.org/10.1007/s11069-014-1206-4

Clarke, D. M. (2005). Human redundancy in complex, hazardous systems: A theoretical framework. *Safety Science*, *43*(9), 655–677. https://doi.org/10.1016/j.ssci.2005.05.003

Cook, R. I., & Rasmussen, J. (2005). “Going solid’’’: a model of system dynamics and consequences for patient safety.” *Quality & Safety in Health Care*, *14*(2), 130–134. https://doi.org/10.1136/qshc.2003.009530

Cornelissen, M., Salmon, P. M., McClure, R., & Stanton, N. A. (2013). Using cognitive work analysis and the strategies analysis diagram to understand variability in road user behaviour at intersections. *Ergonomics*, *56*(5), 764–780. https://doi.org/10.1080/00140139.2013.768707

Crichton, M. (2005). Attitudes to teamwork, leadership, and stress in oil industry drilling teams. *Safety Science*, *43*(9), 679–696. https://doi.org/10.1016/j.ssci.2005.08.020

Dahl, T. (2013). Safety compliance in a highly regulated environment: A case study of workers’ knowledge of rules and procedures within the petroleum industry. *Safety Science*, *60*, 185–195. https://doi.org/10.1016/j.ssci.2013.07.020

Dahl, T., & Olsen, E. (2013). Safety compliance on offshore platforms: A multi-sample survey on the role of perceived leadership involvement and work climate. *Safety Science*, *54*, 17–26. https://doi.org/10.1016/j.ssci.2012.11.003

Dainoff, M. J. (2017). A sociotechnical approach to occupational safety. *Work*, *56*(3), 359–370. https://doi.org/10.3233/WOR-172500

De Lessio, M. P., Cardin, M.-A., Astaman, A., & Djie, V. (2015). A Process to Analyze Strategic Design and Management Decisions under Uncertainty in Complex Entrepreneurial Systems. *Systems Engineering*, *18*(6), 604–624. https://doi.org/10.1002/sys.21330

Debono, D. S., Greenfield, D., Travaglia, J. F., Long, J. C., Black, D., Johnson, J., & Braithwaite, J. (2013). Nurses’ workarounds in acute healthcare settings: A scoping review. *BMC Health Services Research*, *13*(1). https://doi.org/10.1186/1472-6963-13-175

Dekker, S. (2003). Failure to adapt or adaptations that fail: Contrasting models on procedures and safety. *Applied Ergonomics*, *34*(3), 233–238. https://doi.org/10.1016/S0003-6870(03)00031-0

Dekker, S., & Pitzer, C. (2016). Examining the asymptote in safety progress: A literature Review. *International Journal of Occupational Safety and Ergonomics*, *22*(1), 57–65. https://doi.org/10.1080/10803548.2015.1112104

Dillon, R. L., Tinsley, C. H., & Burns, W. J. (2014). Near-misses and future disaster preparedness. *Risk Analysis*, *34*(10), 1907–1922. https://doi.org/10.1111/risa.12209

Duca, G., & Attaianese, E. (2012). The realistic consideration of human factors in model based simulation tools for the air traffic control domain. *Work*, *41*(SUPPL.1), 145–150. https://doi.org/10.3233/WOR-2012-0149-145

Farrington-Darby, T., Pickup, L., & Wilson, J. R. (2005). Safety culture in railway maintenance. *Safety Science*, *43*(1), 39–60. https://doi.org/10.1016/j.ssci.2004.09.003

Finfgeld-Connett, D., & Johnson, E. D. (2013). Literature Search Strategies for Conducting Knowledge-building and Theory-generating Qualitative Systematic Reviews: Discussion Paper. *Journal of Advanced Nursing*, *69*(1), 194–204. https://doi.org/10.1111/j.1365-2648.2012.06037

Foster, C. (2015). Applying success-based assurance techniques to the safety of air traffic control. *10th IET System Safety and Cyber-Security Conference 2015*, 6 .-6 . https://doi.org/10.1049/cp.2015.0290

Foster, C., Espig, S., Smoker, A., & Dillon, R. (2014). *The Future of Safety in ATM*. Retrieved from https://www.nats.aero/wp-content/uploads/2014/05/TheFutureOfSafetyInATM2014.pdf

Gaillard, A. W. K. (1993). Comparing the concepts of mental load and stress. *Ergonomics*, *36*(9), 991–1005. https://doi.org/10.1080/00140139308967972

Gisladottir, V., Ganin, A. A., Keisler, J. M., Kepner, J., & Linkov, I. (2017). Resilience of Cyber Systems with Over- and Underregulation. *Risk Analysis*, *37*(9), 1644–1651. https://doi.org/10.1111/risa.12729

Gomes, J. O., Huber, G. J., Borges, M. R. S., & De Carvalho, P. V. R. (2015). Ergonomics, safety, and resilience in the helicopter offshore transportation system of Campos Basin. *Work*, *51*(3), 513–535. https://doi.org/10.3233/WOR-152021

Grabowski, M., You, Z., Zhou, Z., Song, H., Steward, M., & Steward, B. (2009). Human and organizational error data challenges in complex, large-scale systems. *Safety Science*, *47*(8), 1185–1194. https://doi.org/10.1016/j.ssci.2009.01.008

Grant, S., Checkland, K., Bowie, P., & Guthrie, B. (2017). The role of informal dimensions of safety in high-volume organisational routines: An ethnographic study of test results handling in UK general practice. *Implementation Science*, *12*(1). https://doi.org/10.1186/s13012-017-0586-8

Grote, G., Weyer, J., & Stanton, N. A. (2014). Beyond human-centred automation - concepts for human-machine interaction in multi-layered networks. *Ergonomics*. Taylor & Francis. https://doi.org/10.1080/00140139.2014.890748

Hale, A., & Borys, D. (2013a). Working to rule, or working safely? Part 1: A state of the art review. *Safety Science*, *55*, 207–221. https://doi.org/10.1016/j.ssci.2012.05.011

Hale, A., & Borys, D. (2013b). Working to rule or working safely? Part 2: The management of safety rules and procedures. *Safety Science*, *55*, 222–231. https://doi.org/10.1016/j.ssci.2012.05.013

Harrison, C. (2002). *General Discussion and Analysis of Events Occuring in Oceanic Airspace on September 11 2001* (No. ICAO NAT SPG/38 MWG WP/9).

Heikoop, D. D., de Winter, J. C. F., van Arem, B., & Stanton, N. A. (2016). Psychological constructs in driving automation: a consensus model and critical comment on construct proliferation. *Theoretical Issues in Ergonomics Science*, *17*(3), 284–303. https://doi.org/10.1080/1463922X.2015.1101507

Hobbs, A., & Williamson, A. (2003). Associations between errors and contributing factors in aircraft maintenance. *Human Factors*, *45*(2), 186–201. https://doi.org/10.1518/hfes.45.2.186.27244

Holden, R. J., Carayon, P., Gurses, A. P., Hoonakker, P., Hundt, A. S., Ozok, A. A., & Rivera-Rodriguez, A. J. (2013). SEIPS 2.0: a human factors framework for studying and improving the work of healthcare professionals and patients. *Ergonomics*, *56*(11), 1669–1686. https://doi.org/10.1080/00140139.2013.838643

Holden, R. J., Schubert, C. C., & Mickelson, R. S. (2015). The patient work system: An analysis of self-care performance barriers among elderly heart failure patients and their informal caregivers. *Applied Ergonomics*, *47*, 133–150. https://doi.org/10.1016/j.apergo.2014.09.009

Holling, C. S. (1973). Resilience and Stability of Ecological Systems. *Annual Review of Ecology and Systematics*, *4*(1), 1–23. https://doi.org/10.1146/annurev.es.04.110173.000245

Hollnagel, E. (2010). *The ETTO Principle: Efficiency-Thoroughness Trade-Off. Why Things That Go Right Sometimes Go Wrong*. *Risk Analysis*. https://doi.org/10.1111/j.1539-6924.2009.01333.x

Huang, Y.-H., & Gramopadhye, A. K. (2014). Systematic engineering tools for describing and improving medication administration processes at rural healthcare facilities. *Applied Ergonomics*, *45*(6), 1712–1724. https://doi.org/10.1016/j.apergo.2014.06.003

Huber, S., van Wijgerden, I., de Witt, A., & Dekker, S. W. A. (2009). Learning from organizational incidents: Resilience engineering for high-risk process environments. *Process Safety Progress*, *28*(1), 90–95. https://doi.org/10.1002/prs.10286

Johnson, S. J., Guediri, S. M., Kilkenny, C., & Clough, P. J. (2011). Development and validation of a virtual reality simulator: Human factors input to interventional radiology training. *Human Factors*, *53*(6), 612–625. https://doi.org/10.1177/0018720811425042

Jordan, M. E., Lanham, H. J., Crabtree, B. F., Nutting, P. A., Miller, W. L., Stange, K. C., & McDaniel, R. R. (2009). The role of conversation in health care interventions: Enabling sensemaking and learning. *Implementation Science*, *4*(1). https://doi.org/10.1186/1748-5908-4-15

Khawaja, M. A., Chen, F., & Marcus, N. (2012). Analysis of collaborative communication for linguistic cues of cognitive load. *Human Factors*, *54*(4), 518–529. https://doi.org/10.1177/0018720811431258

Kirwan, B. (2001). The role of the controller in the accelerating industry of air traffic management. *Safety Science*, *37*(2–3), 151–185. https://doi.org/10.1016/S0925-7535(00)00047-3

Kleiner, B. M., Hettinger, L. J., DeJoy, D. M., Huang, Y.-H., & Love, P. E. D. (2015). Sociotechnical attributes of safe and unsafe work systems. *Ergonomics*, *58*(4), 635–649. https://doi.org/10.1080/00140139.2015.1009175

Kontogiannis, T. (2012). Modeling patterns of breakdown (or archetypes) of human and organizational processes in accidents using system dynamics. *Safety Science*, *50*(4), 931–944. https://doi.org/10.1016/j.ssci.2011.12.011

Langer, M., & Braithwaite, G. R. (2016). The development and deployment of a maintenance operations safety survey. *Human Factors*, *58*(7), 986–1006. https://doi.org/10.1177/0018720816656085

Larsson, P., Dekker, S. W. A., & Tingvall, C. (2010). The need for a systems theory approach to road safety. *Safety Science*, *48*(9), 1167–1174. https://doi.org/10.1016/j.ssci.2009.10.006

Lawton, R. (1998). Not working to rule: Understanding procedural violations at work. *Safety Science*, *28*(2), 77–95. https://doi.org/10.1016/S0925-7535(97)00073-8

Le Coze, J. C. (2014). Reflecting on Jens Rasmussen’s legacy. A strong program for a hard problem. *Safety Science*, *71*(PB). https://doi.org/10.1016/j.ssci.2014.03.015

Le Coze, J. C. (2015). Vive la diversit??! High Reliability Organisation (HRO) and Resilience Engineering (RE). *Safety Science*. https://doi.org/10.1016/j.ssci.2016.04.006

Leveson, N. (2004). A new accident model for engineering safer systems. *Safety Science*, *42*(4), 237–270. https://doi.org/10.1016/S0925-7535(03)00047-X

Lindblad, M., Flink, M., & Ekstedt, M. (2017). Safe medication management in specialized home healthcare - An observational study. *BMC Health Services Research*, *17*(1). https://doi.org/10.1186/s12913-017-2556-x

Loft, S., Sanderson, P., Neal, A., & Mooij, M. (2007). Modeling and predicting mental workload in en route air traffic control: Critical review and broader implications. *Human Factors*, *49*(3), 376–399. https://doi.org/10.1518/001872007X197017

Loukopoulos, L. D., Dismukes, R. K., & Barshi, I. (2009). The Perils of Multitasking. *Flight Safety Foundation*, (August), 18–23. Retrieved from http://flightsafety.org/asw/aug09/asw\_aug09\_p18-23.pdf?dl =1

Mackenzie, C., & Holmstrom, D. (2009). Investigating beyond the human machinery: A closer look at accident causation in high hazard industries. *Process Safety Progress*, *28*(1), 84–89. https://doi.org/10.1002/prs.10283

Macrae, C., & Draycott, T. (2016). Delivering high reliability in maternity care: In situ simulation as a source of organisational resilience. *Safety Science*. Department of Experimental Psychology, University of Oxford, Tinbergen Building, 9 South Parks Road, Oxford OX1 3UD, United Kingdom: Elsevier B.V. https://doi.org/10.1016/j.ssci.2016.10.019

Malakis, S., Kontogiannis, T., & Kirwan, B. (2010a). Managing emergencies and abnormal situations in air traffic control (part I): Taskwork strategies. *Applied Ergonomics*. https://doi.org/10.1016/j.apergo.2009.12.019

Malakis, S., Kontogiannis, T., & Kirwan, B. (2010b). Managing emergencies and abnormal situations in air traffic control (part II): Teamwork strategies. *Applied Ergonomics*, *41*(4), 628–635. https://doi.org/10.1016/j.apergo.2009.12.018

Manley, K., Martin, A., Jackson, C., & Wright, T. (2016). Using systems thinking to identify workforce enablers for a whole systems approach to urgent and emergency care delivery: A multiple case study. *BMC Health Services Research*, *16*(1). https://doi.org/10.1186/s12913-016-1616-y

Matton, N., Paubel, P., Cegarra, J., & Raufaste, E. (2016). Differences in Multitask Resource Reallocation after Change in Task Values. *Human Factors*, *58*(8), 1128–1142. https://doi.org/10.1177/0018720816662543

Mickelson, R. S., & Holden, R. J. (2018). Medication adherence: staying within the boundaries of safety. *Ergonomics*, *61*(1), 82–103. https://doi.org/10.1080/00140139.2017.1301574

Morel, G., & Chauvin, C. (2006). A socio-technical approach of risk management applied to collisions involving fishing vessels. *Safety Science*, *44*(7), 599–619. https://doi.org/10.1016/j.ssci.2006.01.002

Mulvihill, C. M., Salmon, P. M., Beanland, V., Lenné, M. G., Read, G. J. M., Walker, G. H., & Stanton, N. A. (2016). Using the decision ladder to understand road user decision making at actively controlled rail level crossings. *Applied Ergonomics*, *56*, 1–10. https://doi.org/10.1016/j.apergo.2016.02.013

Naweed, A., & Rose, J. (2015). “It’s a Frightful Scenario”: A Study of Tram Collisions on a Mixed-traffic Environment in an Australian Metropolitan Setting. *Procedia Manufacturing*, *3*, 2706–2713. https://doi.org/10.1016/j.promfg.2015.07.666

Nyssen, A.-S., & Côte, V. (2010). Motivational mechanisms at the origin of control task violations: An analytical case study in the pharmaceutical industry. *Ergonomics*, *53*(9), 1076–1084. https://doi.org/10.1080/00140139.2010.505301

Ouyang, Q., Wu, C., & Huang, L. (2018). Methodologies, principles and prospects of applying big data in safety science research. *Safety Science*, *101*(July 2017), 60–71. https://doi.org/10.1016/j.ssci.2017.08.012

Pannick, S., Archer, S., Johnston, M. J., Beveridge, I., Long, S. J., Athanasiou, T., & Sevdalis, N. (2017). Translating concerns into action: A detailed qualitative evaluation of an interdisciplinary intervention on medical wards. *BMJ Open*, *7*(4). https://doi.org/10.1136/bmjopen-2016-014401

Parnell, K. J., Stanton, N. A., & Plant, K. L. (2016). Exploring the mechanisms of distraction from in-vehicle technology: The development of the PARRC model. *Safety Science*, *87*, 25–37. https://doi.org/10.1016/j.ssci.2016.03.014

Parnell, K. J., Stanton, N. A., & Plant, K. L. (2017). What does current research tell us about why drivers engage with technological distractions: A Review. *Driver Distraction and Inattention Conference*, (March), 1–18.

Paté-Cornell, E. (2012). On “Black Swans” and “Perfect Storms”: Risk Analysis and Management When Statistics Are Not Enough. *Risk Analysis*, *32*(11), 1823–1833. https://doi.org/10.1111/j.1539-6924.2011.01787.x

Paté‐Cornell, M. E. (1993). Learning from the Piper Alpha Accident: A Postmortem Analysis of Technical and Organizational Factors. *Risk Analysis*, *13*(2), 215–232. https://doi.org/10.1111/j.1539-6924.1993.tb01071.x

Patriarca, R., Bergström, J., Di Gravio, G., & Costantino, F. (2018). Resilience engineering: Current status of the research and future challenges. *Safety Science*, *102*(October 2017), 79–100. https://doi.org/10.1016/j.ssci.2017.10.005

Patriarca, R., Di Gravio, G., & Costantino, F. (2017). A Monte Carlo evolution of the Functional Resonance Analysis Method (FRAM) to assess performance variability in complex systems. *Safety Science*, *91*, 49–60. https://doi.org/10.1016/j.ssci.2016.07.016

Perrow, C. (1984). *Normal Accidents: Living with High Risk Technologies*. Princeton University Press.

Pettersen, K. A., & Aase, K. (2008). Explaining safe work practices in aviation line maintenance. *Safety Science*, *46*(3), 510–519. https://doi.org/10.1016/j.ssci.2007.06.020

Pettersen, K. A., & Schulman, P. R. (2015). Drift, adaptation, resilience and reliability: Toward an empirical clarification. *Safety Science*. https://doi.org/10.1016/j.ssci.2016.03.004

Phipps, D. L., Parker, D., Pals, E. J. M., Meakin, G. H., Nsoedo, C., & Beatty, P. C. W. (2008). Identifying violation-provoking conditions in a healthcare setting. *Ergonomics*, *51*(11), 1625–1642. https://doi.org/10.1080/00140130802331617

Plant, K. L., & Stanton, N. A. (2012). Why did the pilots shut down the wrong engine? Explaining errors in context using Schema Theory and the Perceptual Cycle Model. *Safety Science*, *50*(2), 300–315. https://doi.org/10.1016/j.ssci.2011.09.005

Plumb, J., Travaglia, J., Nugus, P., & Braithwaite, J. (2011). Professional conceptualisation and accomplishment of patient safety in mental healthcare: An ethnographic approach. *BMC Health Services Research*, *11*. https://doi.org/10.1186/1472-6963-11-100

Pumpuni-Lenss, G., Blackburn, T., & Garstenauer, A. (2017). Resilience in Complex Systems: An Agent-Based Approach. *Systems Engineering*, *20*(2), 158–172. https://doi.org/10.1002/sys.21387

Rafferty, L. A., Stanton, N. A., & Walker, G. H. (2010). The famous five factors in teamwork: A case study of fratricide. *Ergonomics*, *53*(10), 1187–1204. https://doi.org/10.1080/00140139.2010.513450

Rasmussen, J. (1983). Skills, Rules, and Knowledge; Signals, Signs, and Symbols, and Other Distinctions in Human Performance Models. *IEEE Transactions on Systems, Man and Cybernetics*, *SMC*-*13*(3), 257–266. https://doi.org/10.1109/TSMC.1983.6313160

Rasmussen, J. (1997). Risk management in a dynamic society - A modelling problem. *Safety Science*, *27*(2–3), 183–213. https://doi.org/10.1016/S0925-7535(97)00052-0

Ray-Sannerud, B. N., Leyshon, S., & Vallevik, V. B. (2015). Introducing Routine Measurement of Healthcare Worker’s Well-being as a Leading Indicator for Proactive Safety Management Systems Based on Resilience Engineering. *Procedia Manufacturing*, *3*, 319–326. https://doi.org/10.1016/j.promfg.2015.07.163

Reader, T. W., & Gillespie, A. (2013). Patient neglect in healthcare institutions: A systematic review and conceptual model. *BMC Health Services Research*, *13*(1). https://doi.org/10.1186/1472-6963-13-156

Reason, J. (1990). *Human Error*. Cambridge University Press.

Reason, J. (1995). A systems approach to organizational error. *Ergonomics*, *38*(8), 1708–1721. https://doi.org/10.1080/00140139508925221

Reiman, T., Rollenhagen, C., Pietikäinen, E., & Heikkilä, J. (2015). Principles of adaptive management in complex safety-critical organizations. *Safety Science*, *71*(PB), 80–92. https://doi.org/10.1016/j.ssci.2014.07.021

Reinartz, S. J. (1993). An empirical study of team behaviour in a complex and dynamic problem-solving context: A discussion of methodological and analytical aspects. *Ergonomics*, *36*(11), 1281–1290. https://doi.org/10.1080/00140139308967999

Renkema, E., Broekhuis, M., & Ahaus, K. (2014). Conditions that influence the impact of malpractice litigation risk on physicians’ behavior regarding patient safety. *BMC Health Services Research*, *14*. https://doi.org/10.1186/1472-6963-14-38

Righi, A. W., Saurin, T. A., & Wachs, P. (2015). A systematic literature review of resilience engineering: Research areas and a research agenda proposal. *Reliability Engineering and System Safety*, *141*, 142–152. https://doi.org/10.1016/j.ress.2015.03.007

Ritz, F., Kleindienst, C., Brüngger, J., & Koch, J. (2015). Coping with Unexpected Safety-critical Situations - A Concept for Resilient (Simulator) Team training for Control Room Teams. *Procedia Manufacturing*, *3*, 1865–1871. https://doi.org/10.1016/j.promfg.2015.07.228

Roberts, B., Mazzuchi, T., & Sarkani, S. (2016). Engineered Resilience for Complex Systems as a Predictor for Cost Overruns. *Systems Engineering*, *19*(2), 111–132. https://doi.org/10.1002/sys.21339

Rochlin, G. I. (1999). Safe operation as a social construct. *Ergonomics*, *42*(11), 1549–1560. https://doi.org/10.1080/001401399184884

Roy, M. (2003). Self-directed workteams and safety: A winning combination? *Safety Science*, *41*(4), 359–376. https://doi.org/10.1016/S0925-7535(02)00040-1

Santos, A. L. R., Wauben, L. S. G. L., Guilavogui, S., Brezet, J. C., Goossens, R., & Rosseel, P. M. J. (2016). Safety challenges of medical equipment in nurse anaesthetist training in Haiti. *Applied Ergonomics*, *53*, 110–121. https://doi.org/10.1016/j.apergo.2015.06.011

Sarter, N. B., & Woods, D. D. (1997). Team Play with a Powerful and Independent Agent: Operational Experiences and Automation Surprises on the Airbus A-320. *Human Factors*, *39*(4), 553–569. https://doi.org/10.1518/001872097778667997

Sauer, J., Wastell, D. G., Hockey, G. R. J., & Earle, F. (2003). Performance in a Complex Multiple-Task Environment during a Laboratory-Based Simulation of Occasional Night Work. *Human Factors*, *45*(4), 657–669. https://doi.org/10.1518/hfes.45.4.657.27090

Saward, J. R. E., & Stanton, N. A. (2017). Latent error detection: A golden two hours for detection. *Applied Ergonomics*, *59*, 104–113. https://doi.org/10.1016/j.apergo.2016.08.016

Saward, J. R. E., & Stanton, N. A. (2018). Individual latent error detection: Simply stop, look and listen. *Safety Science*, *101*, 305–312. https://doi.org/10.1016/j.ssci.2017.09.023

Schöbel, M., & Manzey, D. (2011). Subjective theories of organizing and learning from events. *Safety Science*, *49*(1), 47–54. https://doi.org/10.1016/j.ssci.2010.03.004

Sheridan, T. B. (2008). Risk, human error, and system resilience: Fundamental ideas. *Human Factors*, *50*(3), 418–426. https://doi.org/10.1518/001872008X250773

Simon, H. A. (1957). Models of Man: Social and Rational. *Book*. https://doi.org/10.2307/1926487

Sperandio, J. C. (1971). Variation of Operator’s Strategies and Regulating Effects on Workload. *Ergonomics*, *14*(5), 571–577. https://doi.org/10.1080/00140137108931277

Stoop, J., & Dekker, S. (2012). Are safety investigations pro-active? *Safety Science*, *50*(6), 1422–1430. https://doi.org/10.1016/j.ssci.2011.03.004

Stroeve, S. H., van Doorn, B. A., & Everdij, M. H. C. (2015). Analysis of the roles of pilots and controllers in the resilience of air traffic management. *Safety Science*, *76*. https://doi.org/10.1016/j.ssci.2015.02.023

Taylor, N., Lawton, R., Slater, B., & Foy, R. (2013). The demonstration of a theory-based approach to the design of localized patient safety interventions. *Implementation Science*, *8*(1). https://doi.org/10.1186/1748-5908-8-123

Thomas, C. E. L., Phipps, D. L., & Ashcroft, D. M. (2016). When procedures meet practice in community pharmacies: Qualitative insights from pharmacists and pharmacy support staff. *BMJ Open*, *6*(6). https://doi.org/10.1136/bmjopen-2015-010851

van Gulijk, C., Hughes, P., Figueres-Esteban, M., Dacre, M., & Harrison, C. (2015). Big Data Risk Analysis for rail safety? *Safety and Reliability of Complex Engineered Systems - Proceedings of the 25th European Safety and Reliability Conference, ESREL 2015*.

Vaughan, D. (2016). *The Challenger Launch Decision: Risky Technology, Culture, and Deviance* (2nd ed.). University of Chicago Press.

Vicente, K. J. (2002). Ecological interface design: Progress and challenges. *Human Factors*, *44*(1), 62–78. https://doi.org/10.1518/0018720024494829

Vogt, J., Leonhardt, J., Köper, B., & Pennig, S. (2010). Human factors in safety and business management. *Ergonomics*, *53*(2), 149–163. https://doi.org/10.1080/00140130903248801

Weick, K. E. (1987). Organizational culture as a source of high reliability. *California Management Review*, *29*(2), 112–127. https://doi.org/10.2307/41165243

Weick, K. E., & Sutcliffe, K. M. (2001). Managing the unexpected: Assuring high performance in an age of complexity. *University of Michigan Business School Management Series.* https://doi.org/10.1108/ws.2002.07951dae.003

Weick, K. E., & Sutcliffe, K. M. (2007). *Managing the unexpected: resilient performance in an age of uncertainty* (2nd ed.). John Wiley & Sons: Jossey Bass.

Weick, K. E., & Sutcliffe, K. M. (2015). *Managing the unexpected : sustained performance in a complex world* (3rd ed.). John Wiley & Sons.

Wilson, J. R., Ryan, B., Schock, A., Ferreira, P., Smith, S., & Pitsopoulos, J. (2009). Understanding safety and production risks in rail engineering planning and protection. *Ergonomics*, *52*(7), 774–790. https://doi.org/10.1080/00140130802642211

Wolfswinkel, J. F., Furtmueller, E., & Wilderom, C. P. M. (2013). Using grounded theory as a method for rigorously reviewing literature. *European Journal of Information Systems*, *22*(1), 45–55. https://doi.org/10.1057/ejis.2011.51

Woodcock, K. (2014). Model of safety inspection. *Safety Science*, *62*, 145–156. https://doi.org/10.1016/j.ssci.2013.08.021

Woods, D. D. (2018). The theory of graceful extensibility: basic rules that govern adaptive systems. *Environment Systems and Decisions*, *38*(4), 433–457. https://doi.org/10.1007/s10669-018-9708-3