A very temporary operating instruction: Uncovering emergence and adaptation in air traffic control

Craig J. Fostera,b, Katherine L. Plantb and 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

The introduction of temporary instructions to amend standard operating procedures, to address emerging safety risks, is an example of the well-intentioned decision-making that occurs every day in organisations that manage safety. These organisations typically assess these changes for potential risks; however, even simple changes can have unpredictable and emergent effects in complex sociotechnical systems. A case study of a procedural change in UK air traffic control, to address the risk from unintentional flight level deviations, is explored through the use of a model of adaptation to understand the unexpected and unpredicted effects of the change and uncover the adaptations that already existed within normal work that were a source of safety. Recommendations on the need for systemic safety methodologies that can identify and enhance the features of sociotechnical systems that support this adaptive capacity are identified with reference to this model for adaptation in complex sociotechnical systems.

**Keywords**: adaptation, emergence, air traffic control, safety assessment, systems thinking

# Introduction

The morning of the 28th October 2013 saw much of Europe hit by a severe, Hurricane-force 12 storm nicknamed St. Jude. High winds were experienced across much of north-western Europe causing trees to be brought down on buildings and powerlines, disrupting transportation by road, rail, maritime and air. At London Heathrow airport that morning, aircraft on approach to land experienced very strong headwinds and were operating at the limits of their standard flight envelopes. Conditions were unusually taxing and many pilots, already experiencing high cockpit workloads, were being forced to make the decision to abort their landing approaches and perform a ‘go-around’ – a standard and practised operating procedure whereby the aircraft will climb away from the airport to be re-sequenced back into the flow of traffic for another landing attempt. On this morning many aircraft elected to ‘go-around’ and return to holding patterns, stacks of circling aircraft near the airport, to wait for the weather to improve prior to trying to land again. A ‘go-around’ may be a relatively uncommon occurrence for an individual pilot (occurring to less than one-third of one-percent of arrivals) and can be mildly concerning for passengers, however for air traffic controllers, it is part of normal operations: there were 735 go-arounds at Heathrow in 2018, roughly twice-per-day (Heathrow Airport, 2018). Storm conditions and go-arounds create additional complexity, task demand and workload in both the cockpit and in the air traffic control operation that is typically dealt with through practised procedures and strategies. In the following discussion, we explore how a combination of high workload, standard procedures and abnormal operating conditions combined to create a situation where two aircraft ended up breaching the required minimum safe separation distances, ground and airborne safety nets were triggered and controller and pilot professionalism was required to resolve a potentially unsafe situation. However, rather than just recount another incident and explore it through the lens of hindsight (Rae, Provan, Aboelssaad, & Alexander, 2020), we go further to additionally explore how the resulting management decisions to intervene to address this known risk, using a minor procedural change, resulted in emergent and unexpected system-level effects that unknowingly impaired normal operations and created knock-on safety issues. Instead of being a story that could naively be reduced to human error or an organisational failing though, we uncover a second story (Woods, Dekker, Cook, Johannesen, & Sarter, 2017) of normal decision-making, limitations in risk assessment approaches and the power of unobserved adaptation in creating safe performance across the wider air traffic control system.

The air transport system, which is considered to be a complex socio-technical system (Harris & Stanton, 2010; Stanton et al., 2019), flexes, copes and adapts to the prevalent conditions and demands placed upon it by variations in the context within which the system must operate (Foster, Plant, & Stanton, 2019; Malakis, Kontogiannis, & Kirwan, 2010; Wickens, Mavor, & McGee, 1997). A key feature of air traffic control along with many other complex sociotechnical systems that manage safety goals is the highly influential role of human operators in creating safety in such systems. This observation is a core idea of Resilience Engineering (Lay, Branlat, & Woods, 2015; Provan, Woods, Dekker, & Rae, 2020) and a central premise of the ‘Safety-II’ ethos (Hollnagel, 2014) that build upon the theoretical foundations established by Rasmussen (1997). Of additional relevance is the work of Weick and Sutcliffe (2007) who described the features of high reliability organisations (HRO) that are able to sustain near-error free performance. A common notion of these developments are the apparent influence of human actors in complex sociotechnical systems and how they act in some way to dampen, to use the language of functional resonance, the variability inherent in complex systems. Their actions prevent and contain emergent effects that can cascade in unpredictable ways to potentially degrade system performance and safety. This capability: to appreciate the context of the system and the changing demands placed upon it in day-to-day operations and to respond with proportionate and appropriate actions that maintain system performance, is termed adaptation and the features that promote it within the system as adaptive capacity (Borys, Else, & Leggett, 2009; Dekker, 2003; Foster et al., 2019; Woods, 2009). The term adaptation captures a multitude of ideas in the literature gathered from an examination of complex systems and includes the ability to self-organise, reconcile conflicting demands, re-evaluate priorities and innovate to cope with a changing context (Holling, 1973). It can also refer to the tacit acceptance of broken rules and stretched boundaries to achieve safe performance although in some cases adaptation can degrade performance and safety (Dahl, 2013; Hale & Borys, 2013b, 2013a). Adaptation also involves the human, frontline worker making continuous, real-time, effortful compensations through trade-offs, informal practices and strategies that become inherent in the work whilst still being dependent on context so that they cannot, in general, be proceduralised (Bagnara, Parlangeli, & Tartaglia, 2010; Dekker, 2003; Gaillard, 1993; Reason, 1995). Furthermore, and of particular relevance for this case study is the ubiquity and normality of adaptation that, whilst recognised and possibly tacitly acknowledged, is generally ‘hidden in plain sight’ (Holden et al., 2013; Huber, van Wijgerden, de Witt, & Dekker, 2009; Leveson, 2004).

To summarise the many diverse discussions of adaptation in the safety literature, Foster, Plant & Stanton (2019) conducted a systematic review and identified nine key factors within sociotechnical systems that that appear relevant and can support a discussion and exploration of the features of the system that support adaptation and how it relates to safety (a representation of the model of the literature is shown in Figure 1). The review also identified that adaptive capabilities exist at different levels of the organisational hierarchy: the individual, team and organisation.

Figure : Model for adaptation as a source of safety in complex sociotechnical systems showing prevalence of factor in literature (node size) and interconnections between factors (line thickness) (Foster et al., 2019)

The adaptation model was initially validated using its nine factors as a systematic keyword trigger to support enquiry into a case study that explored UK oceanic air traffic controllers’ response to the closure of US airspace following the terrorist attacks on the 11th September 2001. This examined adaptation as a systemic response to an external disruption and incidents are important for the examination of adaptative capacities and brittleness (Woods & Cook, 2006). However, adaptation exists in everyday work (Perry & Wears, 2012). The case study explored in the following discussion demonstrates the potential challenges with safety interventions that do not fully appreciate the hidden adaptative capabilities that can exist and help create safety in normal work. If adaptation is not observable, then there is a risk that systems under pressure may unknowingly sacrifice adaptive capabilities in the pursuit of current goals to the detriment of future system safety and performance. The paper explores the circumstances surrounding the unanticipated and emergent effects of an apparently simple and minor procedural change to address a known risk. The model of adaptation is used to better understand and explain the many different facets of adaptation that were present in the case study and the explanatory power of this model is discussed. The paper presents lessons from the safety management frontline and provides a unique insight into the considerations needed when managing safety in an industrial setting.

# Context

## Level Busts due to Altimeter Setting Error

Before exploring the specifics of the incident, it is first necessary to provide more context on the air traffic control operation. Aircraft fly at assigned heights or vertical levels and this forms part of the minimum separation distance (expressed in Nautical Miles (Nm) laterally and feet (ft) vertically) required to safely keep them separated from each other. Near to an airfield aircraft fly at vertical levels that use the local air pressure setting known as the QNH (see Appendix 1 for a glossary of terms used in this paper) and fly at altitudes expressed in thousands of feet (e.g. 5000ft altitude). Using the local pressure causes the aircraft’s altimeter to show the height with reference to the airfield’s altitude, i.e. the altitude of the centre point of the main runway above sea level on landing. The use of a local pressure setting ensures that the aircraft uses the correct height information to land safely. However, air pressure can vary across a region, so to ensure that aircraft are all operating against a common reference pressure the QNH (local) pressure is only used near to the airfield and therefore at a low level. Further away from the airfield (and so at higher levels) a global standard reference pressure is used (1013hPa). The height at which aircraft must change from the local pressure to the standard pressure (or vice versa) is known as the ‘Transition Altitude’ and in the London area this is set at 6000ft. The transition altitude is not globally standardised. To avoid confusion, heights expressed with reference to the Standard Pressure are known as flight levels (FL) and are expressed in hundreds of feet e.g. 8000ft at Standard Pressure is known as flight level 80 (FL80) (EU, 2012).

An example of the potential risks from a failure to change the aircraft’s pressure setting when passing the transition level is shown in Figure 2. Normal procedure for an aircraft climbing away from the airfield after departure is for the aircraft to depart with Barometric Pressure Setting (BPS) set to the local pressure (shown in Figure 1 as 980hPa). As the aircraft climbs through the Transition Altitude of 6000ft, the BPS should then be set to Standard Pressure and the aircraft will then continue to climb and be assigned vertical levels in flight levels (shown in Figure 2 as the dashed lines and flight path). If, for example, the local pressure happens to be equal to the Standard Pressure (i.e. QNH=1013hPa) then the translation from altitude to flight level is simple and 8000ft is the same physical height above the ground as FL80. However, if the local pressure is particularly low for that day then FL80 on Standard Pressure may, in fact, be only a few hundred feet physically above 6000ft on local pressure (as illustrated in Figure 2). As an aircraft climbs through 6000ft the pilot must quickly change the BPS from local pressure to Standard Pressure. In modern jet aircraft that have good climb performance, the time to make this change may only be a few seconds. The consequences of delaying or forgetting to change from local pressure to Standard Pressure are that an aircraft still on local pressure can climb to or through an altitude that corresponds with a Flight Level (on Standard Pressure) that is already occupied by another aircraft (shown in Figure 2 by the solid line). An example used in safety material to illustrate the issue is that “if the QNH [local pressure] was 983hPa, failure to set standard setting (1013hPa) would result in an aircraft climbing 900 feet above its cleared level” (CAA, 2014, p. 2). This failure to follow procedure and to be at a level that has not been assigned is known as a Level Bust and when the cause is not correctly setting Standard Pressure on passing through the Transition Altitude it is known as a Level Bust due to Altimeter Setting Error (ASE).



Figure : Diagrammatic representation of the possible effects of failure to change BPS on passing the transition altitude.

## Storm St. Jude incident

A level bust due to ASE in the London Terminal Manoeuvring Area (TMA) is a real risk. The London TMA is some of the most congested and complex airspace in the world with aircraft operating to and from five major international airports (Heathrow, Gatwick, Stansted, Luton and London City) all within a short distance from each other. Aircraft also operate in transit from mainland Europe to the North Atlantic oceanic air routes to the USA and Canada. Domestic flights, military and regional airfields all add to the traffic mix and complexity.

On the morning of 28th October 2013, the storm nicknamed St. Jude was causing additional complexity to the Heathrow arrival air traffic operation. As is typical of storm conditions, the local air pressure was exceptionally low and causing extreme wind speeds that meant aircraft were operating on the edges of their acceptable tolerances for landing. A Boeing 747 (Aircraft 1) travelling from Asia after a long night flight was on approach to land in strong headwinds. It had already attempted to land once, and the pilots had elected to go-around. Similarly, all five of the aircraft in front of Aircraft 1 in the arrival queue had also gone around. A second aircraft (Aircraft 2) having also gone around within the preceding five minutes was being directed to return to the holding pattern as the pilots wanted to wait for the weather to improve before making another landing attempt. It was at the end of the nightshift for the air traffic control operation although the controller was rested and had taken the legally required fatigue prevention breaks. Flight paths, although not to scale, are shown in Figure 3.

As Aircraft 1 continued its approach the pilots elected to again abort the landing attempt, ‘go around’ and requested to return to the holding pattern. The aircraft was at 5000ft on local pressure and was instructed to climb to 6000ft (incident timings will appear in brackets with reference to the incident replay: 00:00). Aircraft 2 was taking up the BIGGIN hold at FL90 however, since this was not the hold they had used earlier, they requested further information including confirmation of the hold’s name (00:22). This created additional workload for the controller and meant that, along with other instructions to vector aircraft back into an arrival sequence or to the holds, the radio frequency was congested. Only one party can speak on the radio frequency at a time (simplex communications) therefore controllers and pilots must wait for a gap in transmissions to speak and pilots, once spoken to, must repeat back the instruction so that the controller can confirm the instruction has been understood. The ‘party line’ effect is both a useful aid to situational awareness for pilots but when transmissions overlap or are blocked there can be a serious safety consequences and this has been implicated in notable accidents such as Tenerife amongst others (Weick, 1990; Wiener, 1980). After the controller deals with Aircraft 2, Aircraft 1 is also given a heading instruction towards the BIGGIN hold and then instructed (00:40) to climb to FL80 (note this is above the Transition Altitude and so the pilot must change from local pressure to Standard Pressure). The plan is therefore for the two aircraft to be safely separated by 1000ft (FL80 and FL90 respectively) and this is the required minimum vertical separation (the minimum horizontal separation is 3Nm). The controller offers (00:52) an approach to another aircraft since the weather appears to be improving and after this exchange Aircraft 2 again requests confirmation of the BIGGIN holding point (01:12). Whilst this radio exchange is occurring Aircraft 1 climbs through 6000ft but does not change BPS (01:08). The controller can select an aircraft on the radar display and query the BPS of the aircraft since it is a data parameter than is downlinked from the aircraft via the radar system. However, this requires positive action to bring up this window and in a busy situation it might not be used, it is also not permanently left open since it takes up valuable screen space. Aircraft 1 proceeds towards the BIGGIN holding point and continues its climb (from the controller’s perspective) towards FL80 as instructed. However, it then continues to climb through FL80 (01:49) since the local QNH setting which the altimeter is using means 8000ft is above FL80 and closer to FL90 – the level of Aircraft 2 (similar to the situation illustrated in Figure 2). The two aircraft are 10Nm apart and, because of the racetrack nature of the BIGGIN hold Aircraft 2 is turning back towards Aircraft 1.



Figure : Illustration of respective horizontal aircraft tracks with time references (Not to scale)

As Aircraft 1 reaches FL85 (02:15) the pilot queries whether their instruction was to climb to 8000ft on the QNH (local pressure) setting. Simultaneously, the controller identifies the potential conflict and the Short Term Conflict Alert (STCA) safety net activated on the controller’s display with a low-priority white flashing alert. This is an attention-getting device to point out a potential conflict. In this instance the tool identified that the turn of Aircraft 2 and the respective levels and rate of climb/descent will place the aircraft into possible conflict. The two aircraft were separated by 6.5Nm, on reciprocal headings with a combined closing airspeed of greater than 400kts or about 8Nm a minute. The controller reiterated (02:21) that the instruction was “Flight level eight zero [80], standard pressure setting” and then issued an “Avoiding action” instruction to Aircraft 2 in the hold to halt their right-hand turn and turn left out of conflict. In the time it took the controller to rapidly issue these instructions in quick succession the aircraft were now 0.9Nm closer. Aircraft 1 is then (02:32) also given an “Avoiding action” left turn to attempt to also maintain horizontal separation of 3Nm if 1000ft vertical separation cannot be restored. The aircraft were 4.6Nm apart and Aircraft 1 continued to climb to FL88 meaning the aircraft are 200ft vertically apart. As the “Avoiding action” instruction is issued to Aircraft 1, the STCA system escalated the warning level to high and the aircraft symbols flashed red. The controller received no response from Aircraft 1 and repeated the avoiding action instruction (02:39). The aircraft closed by 1Nm in these 9 seconds and were now 3.6Nm and 100ft apart. As separation was lost (the horizontal distance between the aircraft reduced below 3Nm) the avoiding action instruction to Aircraft 2 is repeated (02:46) since, even though the action was readback, there was no evidence of the left-hand turn on the radar display. With apparent exasperation in the controller’s voice, Aircraft 2 responded that they are turning and “have the traffic” (02:50). The controller increased (02:52) the avoiding action turn to Aircraft 1 to try to recover the horizontal separation and ensure that a collision is avoided (since, in avoiding collisions, any separation will do). As both aircraft take the avoiding action turns it is clear that both aircraft have also responded to Traffic alert and Collision Avoidance System (TCAS) Resolution Advisories (RAs). This is the onboard safety net that monitors nearby aircraft and provides alerts and avoiding action guidance to pilots in the vertical direction when deemed necessary. Aircraft 1 had continued to climb and Aircraft 2 had descended in response to these automated instructions. This is later confirmed by the pilot of Aircraft 1 who reports “TCAS RA” to the controller (03:07). The minimum separation between the aircraft was 1.7Nm horizontally and 500ft vertically when 3Nm and 1000ft was required.

## The risk, previous interventions and the pressure to act

The Storm St. Jude incident is a serious, but thankfully infrequent, incident that required controller conflict resolution action and also activated the airborne safety net – a system independent of ground-based Air Traffic Management (ATM) to guard against a failure of ATM to prevent a collision. Level Busts, the failure to adhere to a controller instruction in the vertical dimension, are a key risk to the UK air traffic operation in the London TMA (CAA, 2014). This risk is widely recognised and features in a number of safety initiatives within the wider aviation industry (CAA & NATS, 2014; CAA, 2011). To address this issue, NATS has worked with aircraft manufacturers to enable all aircraft to downlink the BPS data and NATS was integral in developing the use cases and supporting the international standardisation of these parameters so that they can be used in controller tools as a preventative measure: giving the controller the ability to spot the deviation and providing tools in the background to alert them. NATS has worked with the wider industry to conduct studies with airlines on standard operating procedures and used ethnographic, normal observations on the flight deck to identify controller and pilot interface issues and so improve altimeter setting procedures (an example of a study of normal operations has been reported by Stanton et al. (2019)). In the longer-term, programmes such as the redesign of the London TMA airspace structure coupled with raising the Transition Altitude are expected to provide future mitigation of the risk.

The occurrence of levels busts due to ASE, unsurprisingly, correlates with days when air pressure is low. On such days the physical distance between QNH altitudes and flight levels is reduced meaning there is less time available for pilots to make the correct switch from QNH to Standard Pressure (CAA, 2014). Therefore, in anticipation of possible incidents, on days when pressure is low there is an urgency in the operation to take measures or to be on guard for the potential for level busts. At the end of 2013 and the start of 2014, and with the St. Jude incident still fresh in the collective operational mind, the UK experienced a sustained period of low air pressure. Coincident with this, there was a cluster of other level bust incidents that occurred around the transition altitude that were categorised by NATS incident investigators as being linked to ASE.

In common with other safety-related and safety-critical industries, NATS operates a set of safety accountabilities that are held by senior named individuals in the organisation. These accountabilities are designed ensure a focus on safety. However, and as desired, they also drive behaviours. They form part of the safety culture of the organisation and, in keeping with Rasmussen’s (1997) theoretical model, create a pressure to ensure the operating point (the performance of the operation) is a safe margin away from the accident. Despite a safety action plan and possible longer-term initiatives, the mounting evidence of an increase in incidents known to have safety risks coupled with accountability pressures and the culture of the organisation indicated that an intervention was required.

# Intervention: The temporary operating instruction

In early 2014, with the medium-term weather forecast indicating a continuing period of low pressure, there was a belief that what was being done to mitigate the risk was insufficient. Therefore, a strategy was formulated by senior operational managers that to address the possibility of pilots forgetting to change BPS on crossing the Transition Altitude, controllers could remind them by including additional information in a climb instruction on low pressure days. Thus, when the QNH was less than 1000hPa controllers were to be required to alter a normal climb instruction from, for example, “BigJet 123, Climb FL80” so it also included the phrase “Standard Pressure Setting” at the end. Other phrasing options were considered but rejected, for example, including the exact pressure to be set could cause confusion since 1013hPa (ten-thirteen) could be misheard as 1030hPa (ten-thirty) and some pilots may use inches of mercury (InHg) instead of hPa as pressure units. There was no specific issue identified with the existing phraseology and the level bust issue was generally recognised a systemic effect with a number of causal factors. However, with limited available options to address the risk the phraseology change was considered a proportionate, relatively minor, proactive change. It was anticipated that the additional phraseology would serve as a reminder to the pilot to set the standard pressure setting and so reduce the risk of a level bust due to ASE. It was proposed that this change in phraseology was trialled to determine whether it was effective in reducing the instances of level busts due to ASE. However, to ensure the maximum impact from the trial, the change was made mandatory so that controllers had to use it under the stated circumstances.

In accordance with the NATS Safety Management System (SMS), the phraseology change trial was subjected to the normal hazard assessment process that is used for procedural changes in NATS. This assessment process is based on the bow-tie methodology (CGE Risk Management Solutions, 2017) and requires participation from operational subject matter experts along with trained facilitators who have been taught the method by safety experts. The procedure change was assessed and subsequently published in a controller instruction known as a Temporary Operating Instruction (TOI). The TOI was issued to all relevant controllers in February 2014 on a trial basis with a planned end-date 3 months later. Pilots were informed via the equivalent published instruction in a NOtices To AirMan (NOTAM).

## Unexpected consequences

During the first few days of implementation of the TOI nine occurrence and observation reports were filed by controllers within the NATS reporting system – a system used by controllers to report on mandatory safety events but to also raise safety observations about practices within the operation. This is a key element of an open reporting and just culture recognised as a fundamental of safe organisations (Reason, 1995; Weick & Sutcliffe, 2007). Controllers noted that flight crews did not understand the instruction, partly because flight crews had not read or not appreciated the significance of the issued NOTAM. The additional phraseology was not internationally standardised therefore pilots were not expecting to hear it. Phraseology is globally standardised using a few key phrases in the English language with pilots and controllers required to demonstrate proficiency in their use. This common language of ATC is key to ensuring aircraft can operate safely globally and that a party-line effect on radio frequencies aids situational awareness.

Additionally, controllers noted that since the phrase “Standard Pressure Setting” is a pressure instruction, other procedures require that it be read-back by pilots. Therefore, whilst the controller may issue the instruction “BigJet 123, Climb FL80, Standard Pressure Setting” the full instruction including the “Standard Pressure Setting” part was not repeated as had been anticipated by the bow-tie assessment. Controllers also noted the redundancy in the additional phraseology: the words ‘Flight level’ in the instruction mean ‘change altimeter setting’ and therefore adding the new phraseology is merely repetitious. Additional radio exchanges were also needed to explain the instruction if it was queried, with some of these becoming heated due to the conflict between the requirements created by the TOI and the ICAO or Air Navigation Order (ANO) requirements understood by the pilot.

The additional phraseology, requiring 6 additional syllables on both the ground-to-air and air-to-ground communications, needed longer radio calls on an already busy radio frequency. This all created additional workload for the controllers when they are already managing a dynamic and complex airspace sector. This impact had been correctly described in the original risk analysis but the scale of the confusion and the impact on workload had not been truly appreciated nor had the impact on pilot workload been adequately taken into account. The departure phase is a busy period for the flight crew and the additional, unexpected phraseology, can disrupt the flow of work on the flight deck. Previously, controllers had informally developed strategies that added a degree of flexibility. The TOI, by being a mandatory instruction, removed this capability. Controllers were already sensitive to the level bust risk and adapted their work by using variations in phraseology, such as “altimeter setting 1013hPa”, when climbing aircraft against conflicting traffic. In this adapted phrase it is more explicit to the pilot that this is a pressure change instruction and was more readily identified as such by pilots and correctly readback.

The TOI also had other unintended consequences. “Standard Pressure Setting” when spoken quickly on a congested and possibly distorted radio frequency can sound like “Route Direct DETLING”, DETLING being another reporting point in the London TMA. On one occasion an aircraft deviated from its route and the mistake was identified by the controller when the pilot readback “direct to DET… [LING]”.

# Analysis: Identifying Adaptation

As a result of the observations raised by the controllers, a review of the phraseology change trial was rapidly convened and included additional subject matter experts and safety assessment facilitators using the hindsight information from the safety observations. This review concluded that, whilst the use of phraseology options may or may not have been effective, it was apparent that the ‘one-size-fits-all’ approach of the TOI was unsustainable from a controller workload perspective. It concluded that on the balance of risks the TOI should be withdrawn.

Subsequent to the review of the risks of the TOI, a separate analysis was conducted to try to better understand and reflect on the lessons of the introduction of the TOI. It was clear that the trial had unintentionally impaired controller flexibility and constrained unwritten practices and controlling styles that had evolved to manage the risk of level busts. The story of the TOI therefore provides a window into the nature of safety management in sociotechnical systems and the challenges of identifying and making sense of the adaptations present in complex work that have a role in creating safety.

To begin to understand the circumstances surrounding the TOI, the nine factors of the adaptation model (Foster et al., 2019) have been used to explore the features of adaptation that were present. Contemporaneous accounts from those involved, the TOI, safety notices and other documentation describing the evolution of the TOI, incident data, weather data and safety observations were made available by NATS to support the analysis. This analysis was conducted by the first author using the descriptions of the nine adaptation factors and the supporting literature. This is akin to a keyword-based ecological study of the available materials to make sense of the adaptive capacities present in the system and how adaptation was, or was not, considered within the development and introduction of the TOI. Two perspectives have been taken, the individual level and the organisational level since both the micro and macro levels of the organisational hierarchy are involved. The following paragraphs describe the salient points from this analysis with reference to each of the nine factors. Summaries of the nine factors are included in Appendix 3.

## Using Experience

The ability of human operators to use their experience is a hallmark of their capability to achieve the goals of complex work. Practised operators are able to draw on these experiences to identify the signals and cues and appreciate critical information (Carvalho, Gomes, Huber, & Vidal, 2009; S. Grant, Checkland, Bowie, & Guthrie, 2017; Saward & Stanton, 2018). In the case of TOI, there was general awareness in the operation that low pressure days can cause problems for the operation based on prior experiences. Similarly, the acquired lore and general heuristics gained from experience meant that controllers typically anticipated the potential for low (or high) English language proficiency and adapted the phraseology used accordingly. Similarly, controller experience brings an awareness of the potential for pilot unfamiliarity with UK procedures related to the transition altitude (i.e. US carriers were mentioned in the original bow-tie). This experience-based ability to adapt and use the controllers’ judgement to flexibly tailor the phraseology and timing of instructions based on the signals and cues available on low pressure days may have been a source of professional pride. This was potentially harmed by the introduction of the TOI by what was seen as a redundant, reductionist instruction. This could undermine the sense of craftmanship and devalued experience held by professionals (Stoop & Dekker, 2012). It is also possible that by raising observations controllers were indicating their reluctance to use the phraseology as a result of this perception.

It is recognised that organisations should try to harness this experience and competence, rather than rely on mandatory oversimplifying instructions (Hale & Borys, 2013b). Therefore, to improve work it is necessary to involve those who do the work. However, frontline involvement in the development of the TOI was limited meaning that the range of experience across the operation was not included in the analysis. In contrast, the need to do something to address the risk, as highlighted by the Storm St. Jude incident and the predicted sustained period of low pressure, used the first-hand, prior experience of senior managers since most had previously been controllers. This experience potentially provided an awareness of the power of rules and procedures as levers to change the system (Nyssen & Côte, 2010; Reason, 1995).

Lastly, previous experience gives accountable managers an appreciation of what is within the envelope of control for the organisation, for example requiring the introduction of a trial of a new instruction, and what is not within their immediate scope for action, i.e. achieving harmonisation of transition altitudes in a global industry.

## Strategies and Informal Practice

Strategies and informal practices are borne out of creative tailoring of the work to the context to improve the flow of work and to address perceived safety risks. Continual adjustments are necessary to cope with the variability in demands and overcome the rigidity of complex and highly optimised systems such as air traffic control (Amalberti, 2001). Performance of the same task or activity will therefore vary with context and controllers use informal practices and strategies that have emerged from the patterns of behaviour and the routines of work to achieve constant trade-offs and task reprioritisations (Loft, Sanderson, Neal, & Mooij, 2007; Matton, Paubel, Cegarra, & Raufaste, 2016). The exact tailoring of the phraseology used by the controllers (and pilots) is developed informally and uses shortcuts and workarounds to improve the flow of work as illustrated by the transcript of the Storm St. Jude incident (see Appendix 2). Whilst the control instruction phraseology is standardised, other features of the means of communication such as the pace of speech and annunciation are developed informally. Additionally, the use of multiple control instructions in a single radio transmission is also reduced based on the controllers’ anticipation of a pilot’s language proficiency. However, whilst phraseology and radio telephony is deliberately tailored by controllers senior managers may not be aware of this work-as-done and may use their understanding of the work-as-imagined (the rules and procedures) to inform their decision making. The TOI highlights the issues of making changes based on a ‘work-as-imagined’ systems view. Observational techniques and feedback from the operation may have identified the limitations of the TOI and alternative approaches to risk mitigation could have been proposed. Alternatively, a manager’s understanding of the work-as-done may be borne out of their own personal experiences, practices and strategies. The TOI required all instructions to contain the new phraseology and therefore removed the source of flexibility provided by these informal strategies. It therefore impaired the adaptive capabilities provided by the informal practices that were used by controllers to dampen performance variability in pilots.

## Acquiring Knowledge

Subsequent to the withdrawal of the TOI, a safety notice, a different type of instruction to controllers, was issued that highlighted the level bust issue and the range of operating techniques available to controllers and that were already applied in day-to-day work to protect the operation from the risk of level busts. The safety notice also reiterated some suggested risk mitigation actions including other phraseology options (e.g. reiterating the words flight level), changes to controlling style and also a suggestion to take into consideration the cockpit workload. In part, the safety notice highlights the adaptations that are available to the people in the system and shares knowledge across the operational community. This builds upon previous learning from earlier incident summaries and briefing sessions that discuss incidents and safety issues to help develop the collegiate response of controllers to such situations. The literature acknowledges that skills in adaptation are built up through this shared understanding, relationships and interactions with others (Jordan et al., 2009; Macrae & Draycott, 2016). Essentially, the safety notice implicitly recognises that adaptation occurs, describes some of the features of the system that provide this adaptive capacity and effectively acknowledges that controllers adapt and that they should keep on adapting. This is in contrast to the original TOI that presented a prescriptive, reductionist approach to the management of the safety risk rather than the goal-orientated, flexible approach used in normal work and identified in the safety notice.

If there are cultural barriers that impair the disclosure of the work-as-done by the frontline to their managers then it can be difficult for managers to acquire the information, such as the informal strategies and emergent controller styles, to formulate safety interventions. However, in this case that challenge was in reconciling the many different voices from the operation (some supportive, some providing challenge) into a coherent plan of action that was in accordance with senior manager’s safety accountabilities and the consequent pressure to act (Le Coze, 2019).

## Unpredictability of Consequences

Complex systems often produce emergent behaviours that a linear mindset or reductionist approach cannot resolve (Bagnara et al., 2010; Cedergren, Johansson, & Hassel, 2017; Pumpuni-Lenss, Blackburn, & Garstenauer, 2017). The reported controller observations and incident reports highlighted the emergent workload issues with the additional phraseology and the effect this had on slowing the flow of work and reducing the available time on the radio communication frequency. Rules and procedures are at the heart of air traffic control; however, but it is not immediately clear what the implications of changing a rule may be on the nature of work and the TOI deployed reductionist and linear simplifications to the problem that proved insufficient (Lindblad, Flink, & Ekstedt, 2017; Reason, 1995). The removal of an undocumented source of flexibility in the operation, that supported the targeting of safety-related actions, was also not well understood and can be interpreted as an example of constraining the operation’s requisite variety (Ashby, 1956). The initial risk assessment of the TOI identified the potential for workload issues but the mitigation described was to split controlling sectors, use more controllers to manage the same volume of airspace, and this is a standard controller workload reduction strategy employed in the operation. However, whilst considered possible this mitigation was not feasible to deploy tactically into an already busy operation. Furthermore, whilst alternative phraseology options had been considered and rejected due to the possibility of misunderstanding or confusion, the deployed phrase added an unrecognised source of brittleness to the system by sounding similar to the DETLING reporting point. Lastly, undocumented assumptions were made on the homogeneity of airline procedures and it was assumed that pilots would all react to the phrase in the same way. However, the different national rules and the interpretations of those rules in airline procedures created the circumstances for unpredictable results.

## Trade-off for Performance

Competing demands create goal conflicts and pressures in complex sociotechnical systems (Lawton, 1998; Rasmussen, 1997). People working in complex systems apply trade-offs to attempt to address multiple competing options and to cope with the demands and complexity stemming from the uncertainty of outcome. This factor prompts consideration of how people make trade-offs from their point of view and tries to understand how they balance efficiency and thoroughness (Hollnagel, 2009). There are inherent trade-offs in the flight deck and air traffic control operations (Sperandio, 1971). Prior to the introduction of the TOI, controllers made numerous subtle trade-offs in their use of language (phraseology, pace, structure of instructions, targeting of aircraft, prioritisation of tasks) recognising that time on congested frequencies can be a scarce resource. Trade-offs such as this are typically required in situations where resources are scarce (S. Grant et al., 2017; Plumb, Travaglia, Nugus, & Braithwaite, 2011; Sauer, Wastell, Hockey, & Earle, 2003). Similarly, the publication of the NOTAM for the pilot community was a necessary notification of the change to pilots but, as observed, it was not sufficient since with many NOTAMs and limited briefing time it was clear that some pilots had not fully appreciated the change introduced in the trial.

The TOI itself can also be interpreted as a trade-off. The air traffic domain achieves a balance between the formality and structure of procedures and the necessary flexibility to support safe operations since a procedure cannot be written to cover every eventuality (Dahl, 2013; Hale & Borys, 2013b). The pre-existing flexibility in the application of phraseology was, if it had been observed or appreciated, traded for more formal and consistent phraseology.

At an organisational level, the decision to continue with an airspace design that can induce this risk, is a trade-off given the complexity and cost of redesigning the airspace around London and the demands on resources for competing development programmes and customer priorities. A future change of the transition level will also be a trade-off since at whatever altitude it is defined the surrounding flight levels will be lost from the airspace for example with a 6000ft transition altitude, 7000ft is not used. Therefore, with a higher transition altitude, available cruising levels or stacking levels could be made unavailable with knock on impacts to the efficiency of the operation. There is no easy choice as there are no ‘free’ levels to choose. Similarly, the design of work itself (the procedures, equipment, staffing and training) is always a trade-off amongst safety, efficiency, capacity and cost drivers (Reason, 1995).

## Skills Needed

The literature identifies the requirement for individuals working in complex sociotechnical systems to have the skills to support their ability to adapt to the variety of contexts in normal work. The ability to anticipate danger, assimilate diverse cues and sources of information and assimilate this into plans and actions is a core trait (Gaillard, 1993; Mulvihill et al., 2016; Paté-Cornell, 2012). Controllers had knowledge of the air traffic control system and its rules but also used their judgement to select the most appropriate course of action to manage the perceived risk of level busts achieving a ‘mindfulness’ of the system (Carvalho & Ferreira, 2012; Crichton, 2005; Huber et al., 2009). This ability is done with such regularity is becomes a skill-based activity – learned and optimised until it is performed by rote (Rasmussen, 1983).

Similarly, pilot actions on receipt of a ATC clearance and the action to implement it into aircraft systems may also be also skill-based activities. However, given the different implementations of transition altitude globally, the input of a change in BPS is rule-based and requires more cognitive effort to accomplish.

## Violations

No one intends to deviate from their assigned flight level or to not change BPS when required therefore, actions should be understood in context, and a non-judgmental ‘systems language’ is helpful in understanding the work and identifying areas for improvement.

The lack of strict adherence to ICAO standardised phraseology at all times and the shortcutting of phraseology technically violates procedures and, as observed in the incident transcript, there are various shortcuts used, particularly in readbacks. These can be classed as routine violations to improve the efficiency and flow of work (Debono et al., 2013; Hobbs & Williamson, 2003) and these may be tacitly accepted as necessary to achieve high performance (Leveson, 2004). So, whilst some violations of phraseology are accepted, the TOI created a subtle conflict between the adherence to the rules and the flow of work.

The phraseology change, since it was interpreted by regulators as a pressure change instruction, therefore required a complete readback by pilots. However, since it introduced non-standard phraseology (believed to be an acceptable violation of the language compact between controllers and pilots) this requirement was not consistently adhered to by pilots. The repeated requests for pilots to readback the pressure change element of the phrase, and so comply with the other procedural requirement, impaired the flow of work.

## Improvisation & Creativity

With evidence of changing risks from recent incidents and impending long periods of low pressure causally associated with level busts there was a pressure on those with safety accountabilities to reassess the existing safety action plans to address the risk. The TOI was a novel approach that had not previously been attempted but was within the remit and power of the organisation to address. The TOI challenged the normalisation of the risk. Whilst frontline operators are readily acknowledged as using their knowledge and expertise to creatively improvise to changing contexts (Hale & Borys, 2013b; Phipps et al., 2008), in this case it can be observed that the senior managers and procedure designers were also empowered to be creative to address the perceived risks.

## Procedures & Rules

The TOI can be seen as an example of the general belief in rules as a means of minimising uncertainty, variability and as an attempt to control work and to motivate and influence the behaviours of the frontline (Bagnara et al., 2010). The TOI decomposes the controller task and proscribes a reinforced phraseology to attempt to strengthen barriers (Naweed & Rose, 2015; Reason, 1995). The use of the phraseology was an attempt to instil a perceived good practice into standard procedures and so reduce a risks in the operation (Nyssen & Côte, 2010). However, and as seen in the case study, standardising in this way can be detrimental to safety (Debono et al., 2013). Whilst the change introduced in the TOI looked simple, it added an additional rule with associated caveats and applicability constraints to an already rule-laden operation. This poses a risk of possible violations where the rule gives no flexibility to operators in situations that present goal conflicts (Hale & Borys, 2013a). In contrast, the safety notice issued subsequent to the withdrawal of the TOI provided a goal-based rule that supported adaptation by promoting the informal techniques already used and by striking a better balance between compliance and flexibility.

## Factor Interactions and Summary

In addition to considering the adaptation factors in isolation, it is possible to also consider the interactions between the factors with relevance to the case study. The discussion above contains many example of the interplay between factors. For example, the analysis has highlighted the perception by senior managers [Using Experience] of the power of formalised instructions as safety interventions [Procedures and Rules]. The transcript highlights that the formality of standardised phraseology [Procedures and Rules] works in tandem with the informal [Strategies and Informal Practice] to create a shared situational awareness between pilot and controller. In turn these strategies [Strategies and Informal Practice] are developed from experience [Using Experience].

The application of the nine factors in the adaptation model, taking into consideration both the individual and organisational levels, highlights, retrospectively, some of the adaptive features in the system that support safety which also may not be readily observable. The factors also prompt an alternative language and mind-set that hints at a ‘total system’ view which is sociotechnical rather than just viewing people, procedures and equipment in isolation. The factors guide a conversation about the interconnectivity of the components in the system and possibly provide a way of probing for unintended consequences. Furthermore, the analysis of features of the system move beyond a pure discussion of safety and into the aspects of the system that generate high levels of performance such as the adaptations to improve the flow of work.

# Discussion

In contrast to much of the safety literature that tends to focus on accident analysis (Brooker, 2008; Paté‐Cornell, 1993; Perrow, 1984; Vaughan, 2016), this paper has described a situation that can be considered almost normal in organisations that manage safety risks: the decision-making surrounding actions to address a known risk in the presence of a strong safety culture, personal accountabilities and complex interactions. There is concern that a reliance solely on extreme events for safety learning may be inappropriate (Dekker, 2011; E. Grant, Salmon, Stevens, Goode, & Read, 2018) and there are clearly lessons to be learned through the examination of the less extreme and more mundane decisions that form ‘safety work’ and are part of everyday life for such organisations (Rae et al., 2020; Stanton et al., 2019). In this case, a systemic analysis has drawn divergent conclusions regarding a decision to address a safety issue. The application of a novel trial procedural change to address a known risk, as illustrated by the Storm St. Jude incident, could have been successful. Yet, with hindsight, it can be determined that it was not. Nevertheless, when seeking to learn lessons from case studies such as this, safety practitioners must guard against hindsight bias and the tendency, on retrospection, to wrongly believe that any errors of commission should have been anticipated (Le Coze, 2019; Woods, 2009).

Managers in safety-related organisations must achieve a complex balancing act between the need to address evident safety issues (highlighted through investigations of incidents and other leading indicators of safety risk) in accordance with their accountabilities and the limitations on their possible actions due to the underlying complexity and dynamism of that system (Le Coze, 2019). A typical reaction of ‘telling and directing’ to control a risk may be appropriate in some circumstances. But in areas of high uncertainty and complexity, a more process-rule approach (such as the subsequent Safety Notice) rather than an action-rule (the TOI) may be more appropriate (Hale & Borys, 2013b). Further guidance is therefore needed to inform decision-makers on how to choose which approach and then specify the design of, and provide the assurance for, the safety intervention so as to avoid mal-adaptive changes being introduced. As has been described, even well-intentioned changes that appear to strengthen the response of the system to certain events could make the system brittle with respect to other contexts (Amalberti, 2001; Woods, 2002, 2009).

The safety observations reported from the front-line as events unfolded subsequent to the introduction of the TOI describe the emergence of issues with the TOI and, as Paget terms, the “becoming mistaken” of the act of introducing the TOI (as cited in Weick & Sutcliffe, 2015, p. 48). The analysis of the reported safety observations and the review of the motivations for the TOI, the decision-making and the risk assessment lead to obvious questions of whether what happened could have been foreseen and prevented. Thus, the case study illustrates two problems for the management of safety in complex sociotechnical systems: the emergence of unintended consequences and the unobservability of adaptation as a source of safety. However, the post-event analysis using the adaptation model suggests possible avenues for improvements to safety management and the assessment of changes that could undermine pre-existing adaptative capacity.

The adaptation model identifies nine key factors that were synthesised from the literature related to adaptation as source of safety in complex sociotechnical systems. These factors explore the relevance of context, complexity and unpredictability, the need to make trade-offs where goals conflict, the reliance on the skills, knowledge and experience of people and that whilst rules exist they 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 nine factors to the case study begins to draw out the adaptations and the adaptive capacity present in the system.

This analysis highlights the fundamental role of people in the system as adaptive buffers able to change to cope with varying context and the value of their experience and professionalism to the safety of the system (Carvalho et al., 2009; Kirwan, 2001). The role of people in adapting to the environment or changing the context to meet their goals is widely recognised in sociotechnical systems research (Leveson, 2011; Rasmussen, 1997). The controllers at the heart of the system were already sensitive to the cues of elevated risks and acted to dampen the impact of variations that existed to achieve conflicting goals and make trade-offs (Larsson, Dekker, & Tingvall, 2010). The requisite variety (Ashby, 1956) that they possessed to apply their professional judgement and experience allowed for adaptive, targeted, strategies and informal practices to address perceived and previously shared risks in the system and create safety (e.g. modifying the transmitted instruction for aircraft that they could predict or have learned might be unfamiliar with UK procedures) (Cornelissen, Salmon, McClure, & Stanton, 2013). The TOI, unknowingly, impaired this adaptive capacity by removing an aspect of this freedom (Gomes, Huber, Borges, & De Carvalho, 2015; Pettersen & Aase, 2008) and introducing a procedural change that added more formality and structure to communications in certain circumstances. The TOI case study illustrates the tension between the natural variations in human performance and the perceived need for regularity and predictability in the system (Reason, Parker, & Lawton, 1998). Whilst the intention was to strengthen the response of the system in an area of known risk, it made the system more brittle in other areas (Amalberti, 2001). The TOI also introduced non-standard phraseology which, whilst not a violation in itself, challenged the social compact between pilot and controller and, similarly, the one-size-fits-all approach of the TOI was seen to be weakening their shared professional pride (Carvalho, De Souza, & Gomes, 2012; Thomas, Phipps, & Ashcroft, 2016).

Despite its failings, the assessment conducted prior to the introduction of the change took advantage of available subject matter experts and frontline employees. The need for frontline involvement in the assessment of safety risks and the benefits of engaging and listening to the frontline in the analysis of the safety of changes is a widely accepted requirement (Dov Zohar, 1980; Hale & Borys, 2013b; Jordan et al., 2009; Mackenzie & Holmstrom, 2009; Pannick et al., 2017; Reader & O’Connor, 2014). The exploration of the case study with the adaptation factors confirms the need for user involvement in both the specification and risk assessment of safety management interventions which should include a clear articulation of the intended goal. Whilst the informal strategies in everyday use may have been widely shared across the operations room they were not adequately declared or understood in the specification of the procedural change and the risk assessment. Yet, when they became apparent through the safety observations and later analysis, they were acknowledged and reinforced in the safety notice issued subsequent to the withdrawal of the TOI.

For many problems, a linear paradigm such as that used in the risk assessment conducted prior to the introduction of the TOI, may be appropriate, cost effective, timely and powerful (Wilson, 2014). Nevertheless, the unanticipated consequences from the TOI case illustrate that there is clearly a transition where properties of the system cannot be inferred from its components, risks cannot be identified with functional decomposition and so a more systems-thinking approach must be considered if emergent outcomes are to be identified and avoided (Johnson, 2006; Salmon, Walker, Gemma, Goode, & Stanton, 2017; Stanton, Salmon, & Walker, 2017; Walker, Salmon, Bedinger, & Stanton, 2017). However, systems thinking approaches require expansive data collection and analysis (Salmon & Lenné, 2015). Yet, if the system has an ability to adapt to variations and different contexts and this adaptation is a source of safety, then there are clearly issues with designing and assuring system interventions if the features of the system that support this adaptive capacity, and the adaptation itself, remain hidden or difficult to observe (Nemeth, Cook, & Woods, 2004; Patterson & Wears, 2015; Wears & Hettinger, 2014). Features of the system that support both performance and safety could be impaired, strategies and informal practices could be unduly constrained or experience and professionalism undermined by interventions that do not appreciate the adaptations present in the system (Wears & Hettinger, 2014; Woods, 2018).

Many authors discuss the importance of sociotechnical methods, including field observations and ethnographic analysis, to uncover the features of the system that contribute to the resilience of the system so as to avoid inadvertently disrupting the strategies that exist and provide such resilience (de Vries & Bligård, 2019; Hollnagel, 2014; Nemeth et al., 2004; Rasmussen, 1997; Waterson et al., 2015). The adaptation model factors provide some specificity to this enquiry by suggesting that prior to the introduction of safety interventions, the decision-making process would benefit from a deeper understanding of the variations in context, the extent of the adoption of coping and risk anticipation strategies in the work-as-done and how experience is used by operators to manage risk and achieve the trade-offs between safety and other system goals (Gomes et al., 2015). Approaches to collecting this data should seek to uncover these potentially unwritten, undeclared, implicit practices in everyday use and use this information to support risk management decision-making. In organisations with open reporting cultures this may be available from the observations raised by the frontline (such as those raised during the early days of the TOI trial). Similarly, ethnographic techniques may be used in the operation to observe adaptive behaviours, albeit recognising their limitations in detecting violations of procedures and informal practices due to over-the-shoulder effects and other biases (Revell & Stanton, 2012). With increases in the availability of data from the technology used by the frontline, the digital records of the conduct of normal work could also be examined for adaptation and this is an area worthy of further research (Foster, 2015; van Gulijk, Hughes, Figueres-Esteban, Dacre, & Harrison, 2015; Walker & Strathie, 2016). However, quantitative data about the work cannot be studied in isolation from the operators conducting the work (Reiman & Rollenhagen, 2014). There is still a need to make sense of this quantitative data and to marry it to the qualitative data from subject matter experts who understand the conflicts and trade-offs, how experience and skill are applied and to uncover the networks of knowledge sharing about the risks and the possible mitigation actions available. The adaptation model also prompts safety practitioners to engage with the frontline to better understand these perspectives.

Organisational and management pressures can have a strong influence on decision-making (Stoop & Dekker, 2012) and the adaptation model supports an appreciation of these effects. The TOI was a novel and simple intervention to the management of a wider aviation risk. The culture of the organisation and the accountabilities and commitment of managers to act on leading indicators of safety in full knowledge of the risks that were present is also a powerful and effective means of managing risks (Flin, Mearns, O’Connor, & Bryden, 2000). ATC rules and procedures, amended using administrative controls such as TOIs, are within the domain of an organisation to shape; therefore, a minor procedural change has a natural attractiveness for managers seeking to intervene on the system (Dahl, 2013; Hale & Borys, 2013b; Reason et al., 1998). However, careful selection of the right intervention is needed to achieve the desired goal. Whilst the phraseology change was a well-intended and simple addition of a few words to an ATC instruction and was only to be used in certain circumstances, it was reductionist (seeking to improve one component) rather than systemic (looking at the total system and the interactions between the components). The adaptation model suggests pausing to consider the possibility for mal-adaptive, undesirable, emergent, network-level effects.

The adaptation model has been used to support a ‘thinking-in-systems’ approach. With its natural focus on the human and the exploration of adaptive capabilities in normal work, not just in response to disruptions or incidents, the adaptation model potential supports both the Resilience Engineering and High Reliability Organisations schools. The model has been applied directly to the case study materials made available in an ecological and flexible fashion. This approach suggests that the model may exhibit domain neutrality and could be repeatable and the results replicable. However, further research is warranted to explore and validate the potential combination of the adaptation model with structured Human Factors approaches and methods used in the design of safety interventions and that are grounded in the practice of safety management (Rae et al., 2020). Additionally, whilst applied retrospectively in this case study, further validation of the descriptive power of the adaptation model in anticipating risks is needed.

# Conclusions

Managers in safety-related organisations must consider a variety of indicators of risk and act upon recommendations from incident investigations with tailored and proportionate risk management decisions to ensure the safety of the operations with which they are entrusted and accountable. One of the fundamental tools within their scope for action is the modification of the procedures of work. However, this case study has highlighted the potential for unanticipated and emergent effects when the adaptations that play a role in the safety of the operation are not observed and unintentionally impaired. Adaptation is recognised as a source of safety in complex sociotechnical systems, such as air traffic control, however whilst being considered ubiquitous, it is also hard to observe. Yet the flexibility and resilient capabilities that adaptation provides are implicitly acknowledged as necessary for delivering safety and performance goals. A case study that explores a risk management decision taken to address a known safety risk in UK air traffic control operations has described the unanticipated emergent safety effects, maladaptive impacts and explored the unobservable adaptation that existed within the system. The analysis of the case study illustrates how the balance between procedural prescription and the capacity to adapt can be upset. The adaptation model supports the identification and exploration of the factors describing adaptation. These findings reinforce the accepted role of humans in delivering a flexible capability to cope with changing contexts, to appreciate the signals of risk and respond with proportionate, but informal, strategies and practices. The model also prompts a discussion of how these adaptations can be made observable and so inform the design and assurance of risk management interventions.

# Acknowledgements

This work is funded by NATS and was originally motivated by a series workshops facilitated by Steven Shorrock from Eurocontrol. The authors are also grateful to the contribution of current and former NATS experts including Christine Deamer, Bill Leipnik, Lee Boulton, Simon Taylor, Roger Dillon and Anthony Smoker.

# Appendix 1: Glossary of terms

Table : Glossary of terms (descriptions marked \* taken from [www.skybrary.aero](http://www.skybrary.aero))

|  |  |  |
| --- | --- | --- |
| Term | Acronym or Abbreviation | Description |
| Altimeter Setting Error | ASE | The difference between the altitude indicated by the altimeter display, assuming a correct altimeter barometric setting, and the pressure altitude corresponding to the undisturbed ambient pressure.\* |
| Altitude |  | The vertical distance of an object measured from mean sea level.\* |
| Barometric Pressure Setting | BPS | Aircraft pressure altimeters indicate the elevation of the aircraft above a defined datum. The datum selected depends on the barometric pressure set on the altimeter.\* |
| Flight Level | FL | A surface of constant atmosphere pressure which is related to a specific pressure datum, 1013.2hPa, and is separated from other such surfaces by specific pressure intervals.\*Expressed as hundreds of feet (e.g. FL80) |
| Level Bust |  | Any unauthorised vertical deviation of more than 300 feet from an ATC flight clearance.\* |
| NOtices To AirMen | NOTAM | A notice containing information concerning the establishment, condition or change in any aeronautical facility, service, procedure or hazard, the timely knowledge of which is essential to personnel concerned with flight operations.\* |
| Quadrant Nautical Height | QNH | The pressure set on the subscale of the altimeter so that the instrument indicates its height above sea level. The altimeter will read runway elevation when the aircraft is on the runway.\* |
| Safety Notice |  | An advisory instruction to controllers to raise awareness of specific safety issues |
| Short Term Conflict Alert | STCA | A ground-based safety net intended to assist the controller in preventing collision between aircraft by generating, in a timely manner, an alert of a potential or actual infringement of separation minima.\* |
| Standard Pressure |  | 1013hPa |
| Temporary Operating Instruction | TOI | An amendment to normal operating procedures for controllers |
| Traffic alert and Collision Avoidance System | TCAS | ACAS II is an aircraft system based on Secondary Surveillance Radar (SSR) transponder signals. ACAS II interrogates the Mode C and Mode S transponders of nearby aircraft (‘intruders’) and from the replies tracks their altitude and range and issues alerts to the pilots, as appropriate.The only commercially available implementations of ICAO standard for ACAS II (Airborne Collision Avoidance System) is TCAS II version 7.1.\* |
| Transition Altitude | TA | The altitude at or below which the vertical position of an aircraft is controlled by reference to altitudes. |

# Appendix 2: Storm St. Jude Incident Transcript

Table 3: Transcription of ATC and aircraft communications with key commentary – timings with reference to replay recording, aircraft names deidentified in communications using square brackets

|  |  |  |  |
| --- | --- | --- | --- |
| Time (mm:ss) | Operator | Communications | Comment |
| 00:00 | Aircraft 1 | Climb six thousand feet [Aircraft 1] | Current altitude: 5000ftBPS: 980hPa.This is the pilot responding to the ATC instruction to climb and is the point where the replay recording starts. |
| 00:02 | ATC | [Aircraft 3] Take up the hold at OKHAM |  |
| 00:05 | Aircraft 3 | Hold OKHAM [Aircraft 3] |  |
| 00:06 | ATC | [Aircraft 2] can you take up the hold at BIGGIN? |  |
| 00:11 | Aircraft 2 | Affirmative | Note that Aircraft 2 had previously been routed via the OCKHAM hold |
| 00:12 | ATC | Roger, resume own navigation. Take up the hold at BIGGIN |  |
| 00:22 | Aircraft 2 | Just confirm that [err] Bravo India Golf | Bravo India Golf = BIG meaning the BIGGIN hold |
| 00:24 | ATC | [Aircraft 2] Affirm. Hold Bravo India Golf | Aircraft 2 turns right towards the BIGGIN hold. Aircraft 2 at FL86 climbing to FL90 where it remains until 02:54 |
| 00:29 | Aircraft 2 | [Aircraft 2] | The pilot of Aircraft 2 acknowledges the instruction with an incomplete readback that is just their callsign |
| 00:30 | ATC | [Aircraft 1] Turn left heading one six zero degrees | ATC are turning Aircraft 1 towards the BIGGIN hold. Aircraft 1’s inbound track had routed the aircraft via the LAMBOURNE hold previously. |
| 00:35 | Aircraft 1 | Left one six zero degrees [Aircraft 1] | Aircraft 1 at 5400ft climbing at 1056ft/min |
| 00:40 | ATC | [Aircraft 1] climb flight level eight zero | This is the ATC instruction to climb Aircraft 1 to the lowest level in the BIGGIN hold but through the Transition Altitude at 6000ft.Note that this climb instruction has been split from the previous heading instruction to reduce the potential for confusion |
| 00:42 | Aircraft 1 | Climb flight level eight zero [Aircraft 1] | The instruction is correctly readback |
| 00:52 | ATC | [Aircraft 4] The last two seven four sevens going in have landed do you wanna try another approach? |  |
| 00:57 | Aircraft 4 | We’d like to go back to the OCKHAM hold initially and err… we’ll keep you advised [Aircraft 4] |  |
| 01:01 | ATC | [Aircraft 4] Roger |  |
| 01:04 | ATC | [Aircraft 4] Turn left, turn left heading two seven zero degrees |  |
| 01:08 | Aircraft 4 | [Aircraft 4] turn left heading two seven zero degrees | At this point Aircraft 1 has reached 6100ft climbing to FL80 and should be changing BPS from 980 to 1013hPa. |
| 01:12 | Aircraft 2 | Just confirm the about track to hold at BIGGIN for [Aircraft 2] | There is no gap between the previous communication and this communication |
| 01:20 | ATC | [Aircraft 2] It’s three zero three heading inbound to BIGGIN | Aircraft 1 is at 7300ft on BPS 980 and has not changed setting |
| 01:25 | Aircraft 2 | Ground three oh three [Aircraft 2] | Clipped and non-standard phraseology used |
| 01:34 | ATC | [Aircraft 4] climb to altitude six thousand feet |  |
| 01:42 | ATC | [Aircraft 4] climb to altitude six thousand feet | Repeating the previous transmission |
| 01:45 | Aircraft 4 | [Aircraft 4] Climb altitude six thousand feet | Aircraft 1 now at 7900ft on BPS 980, climbing 1568ft/min and heading 164 degreesAircraft 2 at FL90 heading 216 and continuing to turn right |
| 01:49 |  |  | Aircraft 1 reaches 8000ft on BPS 980 and is climbing at 1600ft/min. |
| 01:54 | ATC | [Aircraft 4] were you happy to hold at BIGGIN? |  |
| 01:58 | Aircraft 4 | Err… [Aircraft 4] Roger hold at BIGGIN | Swapping the hold from OCKHAM to BIGGIN |
| 02:01 | ATC | Take a heading of two seven zero degrees and we’ll coordinate a hold at BIGGIN for you |  |
| 02:05 |  |  | Aircraft 1 changes BPS to 1013 having reached 8300ft. |
| 02:06 | Aircraft 4 | Roger we’re turning onto heading of two seven zero and standing by [Aircraft 4] |  |
| 02:15 | Aircraft 1 | [Aircraft 1] err confirm maintain eight thousand feet on QNH nine eight zero? | Aircraft 1 has continued to climb and is at FL85. This transmission is made by the Flight Officer not the Captain. Mid transmission the STCA ground-based safety net activates with a low-level alert. Separation between Aircraft 1 and Aircraft 2 is 6.9Nm and 317ft at the start of the transmission but drops to 6.1Nm by the end. |
| 02:21 | ATC | [Aircraft 1] flight level eight zero, flight level eight zero standard pressure setting | This transmission blends into the previous without a pause.Note the reference to and use of the phrase ‘standard pressure setting’. |
| 02:25 | ATC | [Aircraft 2] avoiding action turn left immediately heading two one zero degrees | Immediately follows previous transmission. ‘Avoiding action’ is a UK-specific terminology to indicate the urgency of the instruction, ‘immediately’ is the internationally standardised phraseology. Both are used. |
| 02:29 | Aircraft 2 | Left heading two one zero [Aircraft 2] | This transmission is heavily distorted and with echo possibly due to both pilots on Aircraft 2 transmitting at the same time. Horizontal separation is 5.1Nm. Aircraft 1 is on heading 160 degrees, Aircraft 2 is heading 278 degrees in a right-hand turn |
| 02:32 | ATC | [Aircraft 1] avoiding action turn left immediately heading zero six zero degrees | Horizontal separation is 4.6Nm as the STCA alert increases to high severity. Aircraft 1 reaches FL88. |
| 02:39 | ATC | [Aircraft 1] turn left heading zero six zero degrees avoiding action  | By the end of the transmission horizontal separation has reduced to 3.6Nm. Headings are 156 degrees and 294 degrees  |
| 02:46 | ATC | [Aircraft 2] turn left immediately heading two one zero degrees | Separation is 3Nm at the start of this transmission and minimum required separation will be lost. Aircraft 1 is at FL89 |
| 02:50 | Aircraft 2 | Left heading two one zero we have the traffic [Aircraft 2] | Separation is 2.5Nm. Aircraft 1 at FL88.This is the first response from either aircraft since 02:29 |
| 02:52 | ATC | [Aircraft 1] turn left heading zero five zero degrees avoiding action | Separation is 2.0Nm and Aircraft 1 has begun a left turn and is now on 124 degrees at FL89 whilst Aircraft 2 has descended to FL88 (the aircraft have crossed in the vertical dimension). |
| 02:56 | Aircraft 1 | [Aircraft 1] | Aircraft 2 has begun its left-hand turn. STCA reduces the severity of the alert to low as the aircraft begin to turn parallel to each other at 1.7Nm separation but now with 500ft vertical separation as Aircraft 1 reaches FL91 and Aircraft 2 descends to FL86. This is a clipped response but indicates that Aircraft 1 has heard the instruction. |
| 03:07 | Aircraft 1 | [Aircraft 1] TCAS RA | Aircraft 1 has reached FL93. Aircraft 2 is at FL84 and separation has increased to 1.9Nm. It is clear that Aircraft 1 has responded to a TCAS Climb RA and this is probably the first opportunity to report this to the controller. |
| 03:11 | ATC | Roger | Minimum separation has been restored as the aircraft are 2.4Nm and 1100ft apart. |

# Appendix 3: Summary of Adaptation Model Factors

Insert table here if needed.

# References

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

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

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

Borys, D., Else, D., & Leggett, S. (2009). The fifth age of safety: The adaptive age. *Journal of Health Services Research and Policy*, *1*(1), 19–27.

Brooker, P. (2008). The Uberlingen accident: Macro-level safety lessons. *Safety Science*, *46*(10), 1483–1508. https://doi.org/10.1016/j.ssci.2007.10.001

CAA. (2011). *CAA Paper 2011/03: CAA “Significant Seven” Task Force Reports*. Retrieved from https://publicapps.caa.co.uk/docs/33/2011\_03.pdf

CAA. (2014). Safety Notice SN–2014/004 Level Busts: Hazards and Defences. Retrieved January 6, 2020, from https://publicapps.caa.co.uk/docs/33/SafetyNotice2014004.pdf

CAA & NATS. (2014). CAP 1186 Level Busts - Information for Pilots and Controllers. Retrieved January 6, 2020, from http://publicapps.caa.co.uk/docs/33/CAP 1186 Level Bust leaflet.pdf

Carvalho, P. V. R. de, De Souza, A. P., & Gomes, J. O. (2012). A computerized system to monitor resilience indicators in organizations. *Work*, *41*(SUPPL.1), 2803–2809. https://doi.org/10.3233/WOR-2012-0527-2803

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

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

CGE Risk Management Solutions. (2017). The history of bow-tie. Retrieved February 5, 2020, from https://www.cgerisk.com/knowledgebase/The\_history\_of\_bowtie

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

de Vries, L., & Bligård, L. O. (2019). Visualising safety: The potential for using sociotechnical systems models in prospective safety assessment and design. *Safety Science*, *111*(October 2017), 80–93. https://doi.org/10.1016/j.ssci.2018.09.003

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. W. A. (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. W. A. (2011). *Drift into failure*. *Farnham: Ashgate*. Retrieved from https://gowerpublishing.com/pdf/leaflets/Drift-into-Failure-2011.pdf

Dov Zohar. (1980). Safety climate in industrial organizations: Theoretical and applied implications. *Journal of Applied Psychology*, *65*(1), 96–102. https://doi.org/10.1037/0021-9010.65.1.96

EU. Commission Implementing Regulation (EU) No 923/2012, Pub. L. No. (EU) No. 923/2012 (2012). Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32012R0923&from=EN

Flin, R., Mearns, K., O’Connor, P., & Bryden, R. (2000). Measuring safety climate: Identifying the common features. *Safety Science*, *34*(1–3), 177–192. https://doi.org/10.1016/S0925-7535(00)00012-6

Foster, C. J. (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. J., Plant, K. L., & Stanton, N. A. (2019). Adaptation as a source of safety in complex socio-technical systems: A literature review and model development. *Safety Science*, *118*(May), 617–631. https://doi.org/10.1016/j.ssci.2019.05.035

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

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

Grant, E., Salmon, P. M., Stevens, N. J., Goode, N., & Read, G. J. (2018). Back to the future: What do accident causation models tell us about accident prediction? *Safety Science*. https://doi.org/10.1016/j.ssci.2017.12.018

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

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

Harris, D., & Stanton, N. A. (2010). Aviation as a system of systems: Preface to the special issue of human factors in aviation. *Ergonomics*, *53*(2), 145–148. https://doi.org/10.1080/00140130903521587

Heathrow Airport. (2018). *Airspace and Noise Performance - Annual Report 2018*. Retrieved from https://www.heathrow.com/content/dam/heathrow/web/common/documents/company/local-community/noise/reports-and-statistics/reports/airspace-and-noise-performance-reports/annual-reports/LHR-ANP-AR2018-approved(online).pdf

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

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. (2009). The ETTO Principle--Efficiency-Thoroughness Trade-Off.

Hollnagel, E. (2014). *Safety-I and safety-II: The past and future of safety management*. Ashgate Publishing Ltd.

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, C. W. (2006). What are emergent properties and how do they affect the engineering of complex systems? *Reliability Engineering and System Safety*, *91*, 1475–1481. https://doi.org/10.1016/j.ress.2006.01.008

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

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

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

Lay, E., Branlat, M., & Woods, Z. (2015). A practitioner’s experiences operationalizing Resilience Engineering. *Reliability Engineering and System Safety*, *141*, 63–73. https://doi.org/10.1016/j.ress.2015.03.015

Le Coze, J. C. (2019). Safety as strategy: Mistakes, failures and fiascos in high-risk systems. *Safety Science*, *116*(December 2017), 259–274. https://doi.org/10.1016/j.ssci.2019.02.023

Leveson, N. G. (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

Leveson, N. G. (2011). Applying systems thinking to analyze and learn from events. *Safety Science*, *49*(1), 55–64. https://doi.org/10.1016/j.ssci.2009.12.021

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

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. (2010). 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

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

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

Nemeth, C. P., Cook, R. I., & Woods, D. D. (2004). The messy details: Insights from the study of technical work in healthcare. *IEEE Transactions on Systems, Man, and Cybernetics Part A:Systems and Humans.*, *34*(6), 689–692. https://doi.org/10.1109/TSMCA.2004.836802

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

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

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

Patterson, M. D., & Wears, R. L. (2015). Resilience and precarious success. *Reliability Engineering and System Safety*, *141*, 45–53. https://doi.org/10.1016/j.ress.2015.03.014

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

Perry, S. J., & Wears, R. L. (2012). Underground adaptations: case studies from health care. *Cognition, Technology & Work*, *14*, 253–260. https://doi.org/10.1007/s10111-011-0207-2

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

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

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

Provan, D. J., Woods, D. D., Dekker, S. W. A., & Rae, A. J. (2020). Safety II professionals: How resilience engineering can transform safety practice. *Reliability Engineering & System Safety*, *195*(August 2018), 106740. https://doi.org/10.1016/j.ress.2019.106740

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

Rae, A., Provan, D., Aboelssaad, H., & Alexander, R. (2020). A manifesto for Reality-based Safety Science. *Safety Science*, *126*(January), 104654. https://doi.org/10.1016/j.ssci.2020.104654

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

Reader, T. W., & O’Connor, P. (2014). The Deepwater Horizon explosion: Non-technical skills, safety culture, and system complexity. *Journal of Risk Research*, *17*(3), 405–424. https://doi.org/10.1080/13669877.2013.815652

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

Reason, J., Parker, D., & Lawton, R. (1998). Organizational controls and safety: The varieties of rule-related behaviour. *Journal of Occupational and Organizational Psychology*, *71*(4), 289–304. https://doi.org/10.1111/j.2044-8325.1998.tb00678.x

Reiman, T., & Rollenhagen, C. (2014). Does the concept of safety culture help or hinder systems thinking in safety? *Accident Analysis and Prevention*, *68*, 5–15. https://doi.org/10.1016/j.aap.2013.10.033

Revell, K. M. A., & Stanton, N. A. (2012). Models of models: Filtering and bias rings in depiction of knowledge structures and their implications for design. *Ergonomics*, *55*(9), 1073–1092. https://doi.org/10.1080/00140139.2012.692818

Salmon, P. M., & Lenné, M. G. (2015). Miles away or just around the corner? Systems thinking in road safety research and practice. *Accident Analysis and Prevention*, *74*, 243–249. https://doi.org/10.1016/j.aap.2014.08.001

Salmon, P. M., Walker, G. H., Gemma, G. J., Goode, N., & Stanton, N. A. (2017). Fitting methods to paradigms: are ergonomics methods fit for systems thinking? *Ergonomics*, *60*(2), 194–205. https://doi.org/10.1080/00140139.2015.1103385

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. (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

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

Stanton, N. A., Plant, K. L., Revell, K. M. A., Griffin, T. G. C., Moffat, S., & Stanton, M. (2019). Distributed cognition in aviation operations: a gate-to-gate study with implications for distributed crewing. *Ergonomics*, *62*(2), 138–155. https://doi.org/10.1080/00140139.2018.1520917

Stanton, N. A., Salmon, P. M., & Walker, G. H. (2017). Editorial New paradigms in ergonomics. *Ergonomics*, *60*(2), 151–156. https://doi.org/10.1080/00140139.2016.1240373

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

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.

Walker, G. H., Salmon, P. M., Bedinger, M., & Stanton, N. A. (2017). Quantum ergonomics: shifting the paradigm of the systems agenda. *Ergonomics*, *60*(2), 157–166. https://doi.org/10.1080/00140139.2016.1231840

Walker, G. H., & Strathie, A. (2016). Big data and ergonomics methods: A new paradigm for tackling strategic transport safety risks. *Applied Ergonomics*, *53*, 298–311. https://doi.org/10.1016/j.apergo.2015.09.008

Waterson, P., Robertson, M. M., Cooke, N. J., Militello, L., Roth, E., & Stanton, N. A. (2015). Defining the methodological challenges and opportunities for an effective science of sociotechnical systems and safety. *Ergonomics*, *58*(4), 565–599. https://doi.org/10.1080/00140139.2015.1015622

Wears, R. L., & Hettinger, A. Z. (2014). The tragedy of adaptability. *Annals of Emergency Medicine*, *63*(3), 338–339. https://doi.org/10.1016/j.annemergmed.2013.10.035

Weick, K. E. (1990). The Vulnerable System: An Analysis of the Tenerife Air Disaster. *Journal of Management*. https://doi.org/10.1177/014920639001600304

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.

Wickens, C. D., Mavor, A. S., & McGee, J. P. (1997). *Flight to the Future*. *Human Factors in Air Traffic Control*. https://doi.org/10.17226/5493

Wiener, E. L. (1980). Midair collisions: The accidents, the systems, and the realpolitik. *Human Factors*, *22*(5), 521–533. https://doi.org/10.1177/001872088002200502

Wilson, J. R. (2014). Fundamentals of systems ergonomics/human factors. *Applied Ergonomics*, *45*(1), 5–13. https://doi.org/10.1016/j.apergo.2013.03.021

Woods, D. D. (2002). Chapter 2: Essential Characteristics of Resilience. *Resilience Engineering*, (2012), 21–34.

Woods, D. D. (2009). Escaping failures of foresight. *Safety Science*, *47*(4), 498–501. https://doi.org/10.1016/j.ssci.2008.07.030

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

Woods, D. D., & Cook, R. I. (2006). Incidents - Markers of Resilience or Brittleness? *Resilience Engineering: Concepts and Precepts*, 69–76.

Woods, D. D., Dekker, S., Cook, R., Johannesen, L., & Sarter, N. (2017). *Behind Human Error*. CRC Press. https://doi.org/10.1201/9781315568935