# What went right? An analysis of the protective factors in aviation near misses

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**Practitioner Statement:** The analysis of near misses is an important part of safety management activities. This paper demonstrates that Rasmussen's risk management framework can be used to identify networks of protective factors which prevent accidents. Safety practitioners can use the framework described to discover and support the system-wide networks of protective factors.

# What went right? An analysis of the protective factors in aviation near misses

Learning from successful safety outcomes, or what went right, is an important emerging component of maintaining safe systems. Accordingly, there are increasing calls to study normal performance in near misses as part of safety management activities. Despite this, there is limited guidance on how to accomplish this in practice. This article presents a study in which using Rasmussen's risk management framework to analyse sixteen serious incidents from the aviation domain. The findings show that a network of protective factors prevents accidents with factors identified across the sociotechnical system. These protective networks share many properties with those identified in accidents. The paper demonstrates that is possible to identify these networks of protective factors from incident investigation reports. The theoretical implications of these results and future research opportunities are discussed.

## Introduction

Aviation safety has reached unprecedented levels (ICAO 2017). One important contributor to this has been the approach of identifying the contributory factors involved in accidents and eliminating the perceived causes of failure (Aurino 2000). However, as aviation systems achieve ultra-safe levels (where the risk of a disastrous accident is below one per one million events), it has become difficult to identify further significant improvements through retrospective accident analysis (Amalberti 2001). One challenge in using reductionist retrospective accident analysis methods is the limited extent to which they can identify the multiple, interacting factors at play in complex, dynamic, non-linear environments, such as the aviation system (Dekker, 2008). With the amount of data which is collected by agents of the aviation system, there is an opportunity to learn more from incidents and normal performance rather than exclusively from accidents (Walker 2017).

When describing incidents, the International Civil Aviation Organization (ICAO) uses the term to identify; 'any occurrence, other than an accident, which could affect the safety of aircraft operation, whereas they define a 'serious incident' is one in which an accident nearly occurred' (ICAO, 1994). Examples of such serious incidents in aviation provided by the ICAO are; loss of separation (or near-collision), runway incursion, or landing on a closed or occupied runway. The Federal Aviation Administration (FAA) applies the same definition as the ICAO for the terms 'incident' and 'serious incident', and applies an additional term, 'occurrence' to identify an event, other than an accident or incident that requires investigation

for potential impacts on safety (FAA, 2012). Other terms such as near-accident, close calls, and near misses describe these types of event. Near misses have been formally defined as: a serious error that has potential to cause harm but does not due to chance or interception (WHO 2005); a potential significant event that could have consequences but did not due to the conditions at the time (IAEA 2007); and as an incident that could have caused serious injury or illness but did not (OSHA 2015). For this research, the term near miss (defined as, 'an outcome with a subjective potential negative (or more severe) consequence (e.g. damage, injury, loss)') is used throughout.

The study of factors leading to near misses rather than accidents is a promising direction for improving safety in the aviation industry. Hollnagel (2014) has repeatedly highlighted the need to understand how things go right (i.e. Safety II), as opposed to focussing only on why things go wrong (i.e. Safety I) (Hollnagel et al. 2013, Hollnagel 2013). Similarly, Carayon et al. (2015) has argued that a key question for safety scientists is how people act to prevent and avoid accidents rather than why an accident occurs. Resilience Engineering (Hollnagel, Woods, and Leveson (eds.) 2007) attempts to better understand the capacity of a system to adapt to changing conditions (Huber et al. 2009), including identifying how systems detect and recover from potential failures (Woods and Cook 2002). Near misses, which are routinely investigated in aviation, potentially provide objective information about the resilience of the system in response to threats, and the factors impacting on the success or failure of the controls in the system.

Despite this, it is apparent that the models of near misses may not be aligned with contemporary models of accident causation such as; Dekker's Drift into Failure model (Dekker 2012), Leveson's Systems Theoretic Accident Model and Process (Leveson 2004), or Rasmussen's Risk Management Framework (Rasmussen 1997). The analysis of near misses applies accident causation models that assume near misses are a type of accident (e.g. Heinrich, 1980, and Reason, 1990). There was only one standalone causation model of near misses found, the Eindhoven Model (Van der Schaaf 1992), which includes the possibility of error recovery as an added stage to the linear barrier model of accident causation developed by Reason (1990). This model of near misses is; over 20 years out of date with current research, focussed on the role of human error, treats near misses as a type of accident, and does not describe how systemic factors interact to prevent accidents. The addition of error-handing developed by the Eindhoven Model does include some of the concepts which underpin factors which prevent further harm in accidents.

Error-handling models describe the processes by which front line operators identify and address errors to generate near misses rather than accidents. Kontogiannis (1999) discusses the types of recovery made by operators at various stages of a work process. Similarly, research on error recovery (van der Schaaf 1995, Rizzo, Ferrante, and Bagnara 1995, Kanse et al. 2006) identifies the stages through which operators detect, explain, and correct errors. In aviation, the Threat and Error Management (TEM) model (Helmreich, 1999, Klinect, 2003) extends error-handling to the identification and management of threat and error within flight crews (Helmreich, 2001). The error-handling models do not, however, identify the system-wide factors which lead to the management of threats and errors.

The World Health Organization (WHO) has developed a taxonomy of mitigating factors, defined as an action or circumstance which prevents or moderates the progression of an incident towards harming a patient (WHO 2009). In TEM, four broad categories of factors (Communication, Situation Awareness, Task Management, and Decision Making) have been used to evaluate crew effectiveness in threat and error management (Thomas, 2004). These factors, as with the error-handling models, primarily focus attention onto the operator or operators performing the task, rather than a holistic view of the overall system. While the WHO taxonomy does include three factors directed to organizational level, this is only a starting point for understanding systematic influences on near misses. Therefore, current models have a significant gap in identifying systemic factors which generate near misses rather than accidents.

The systems approach is required to understand accident causation in complex sociotechnical systems (Underwood and Waterson 2013, Stanton, Rafferty, and Blane 2012, Salmon, Cornelissen, and Trotter 2012, Salmon et al. 2016). This approach views safety as an emergent phenomenon arising due to interactions among multiple contributing factors at multiple levels of a sociotechnical work system (Rasmussen 1997) and accidents as system-wide events (Leveson 2004, Reason 1997, Carayon et al. 2015). It is apparent that this theoretical understanding has not yet been fully translated to near misses. A first step to achieving this involves examining whether near misses align with the systems thinking approach.

To understand near misses from a systems perspective, two fundamental questions need to be addressed. First, the extent to which there is a network of systemic factors that interact to prevent the event from progressing to an adverse event requires investigation. This has important ramifications both for the study of near misses (i.e. whether it is important to examine the wider system for protective factors or not) and for accident prevention activities

(i.e. whether interventions should focus on human operators or on the wider organisational system). The second fundamental question, the answers to which have previously been assumed under previous models of system safety (Heinrich et al. 1980, Phimister, Bier, and Kunreuther 2004, Van der Schaaf, Lucas, and Hale 1991), is whether or not factors which prevent accidents are similar in nature and structure to the networks of contributory factors which cause accidents. This has important ramifications for the study of understanding factors (i.e. whether the same factor can be either contributory or protective, depending on context) and how their interaction affects performance (i.e. whether a factor must be optimal to contribute to accident prevention or can a sub-optimal factor support accident prevention through interactions).

The aim of this paper is to explore these questions by: 1) examining whether a network of systemic influences protect against accidents; and 2) whether the theory on accident causation in sociotechnical systems adequately describes the processes that protect systems from accidents. Rasmussen's (1997) framework has been found to effectively describe the systemic causes of accidents in multiple domains, and is applied here to accident prevention. To do this, the actors and network of factors that contribute to accident prevention will be examined in a sample of detailed aviation incident investigation reports.

### *Rasmussen's (1997) risk management framework and migration model*

Rasmussen's (1997) risk management framework, shown in Figure 1, describes sociotechnical systems as a hierarchy of multiple levels. The decisions and actions across these levels dynamically interact and contribute to the control of hazardous processes. In line with other systems accident causation models, safety is described as an emergent property of the system, as the outcome (positive or negative) of interactions between the components of the system cannot be predicted from examining the functioning or reliability of each component in isolation (Dekker, Cilliers, and Hofmeyr 2011, Leveson 2011).
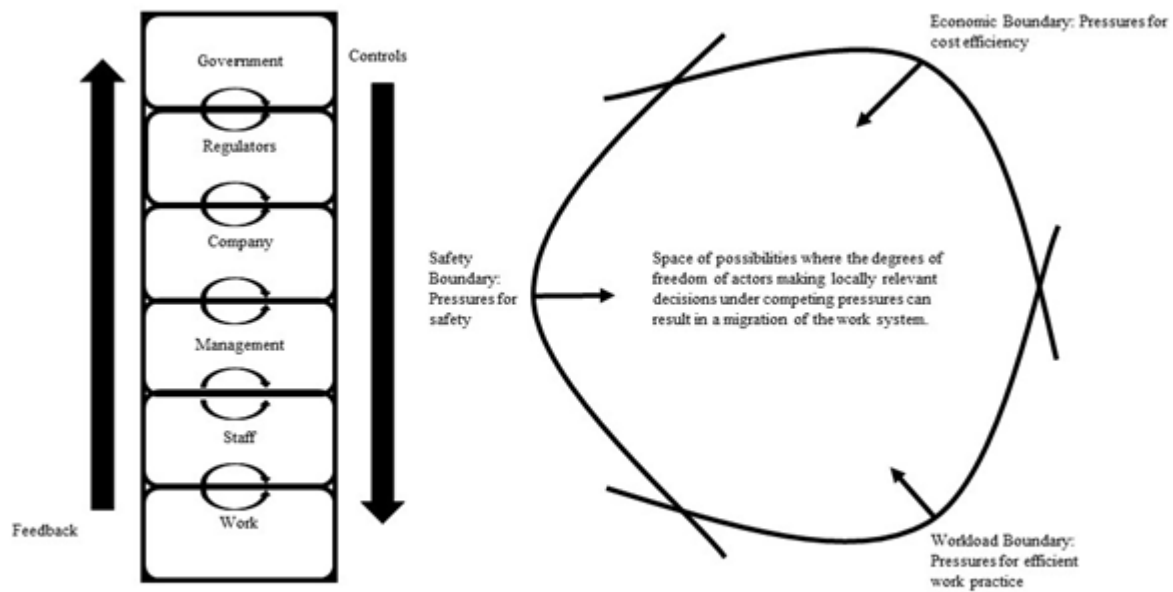
Figure 1: Rasmussen's risk management framework and system migration models

Rasmussen's framework and model (Rasmussen 1997) discusses several factors which contribute to accident causation in complex sociotechnical systems. These factors are often referred to as the "tenets" of accident causation and are summarised in table 1. These tenets have been validated in several domains, including: food safety, police action, road freight transportation, led outdoor activities, and bushfire response (Salmon et al. 2010, Salmon et al. 2014, Newnam et al. 2017, Jenkins et al. 2010, Cassano-Piche, Vicente, and Jamieson 2009). These previous applications of Rasmussen's model have focused on identifying how a network of contributory factors across a system lead to negative outcomes (i.e. accidents).

Table 1: Rasmussen's (1997) tenets of accident causation in sociotechnical systems (adapted from (Cassano-Piche, Vicente, and Jamieson 2009, Vicente and Christoffersen 2006))

| Rasmussen's Seven Tenets | |
|---|---|
| 1 | Safety is an emergent property of a complex sociotechnical system. It is impacted by the decisions of all the actors-politicians, managers, safety officers, and work planners-not just the front-line workers alone. |
| 2 | Threats to safety or accidents are usually caused by multiple contributing factors, not just a single catastrophic decision or action. |

| 3 | Threats to safety or accidents can result from a lack of vertical integration (i.e. mismatches) across levels of a complex sociotechnical system, not just from deficiencies at just one level. |
|---|---|
| 4 | The lack of vertical integration is caused, in part, by a lack of feedback across levels of a complex sociotechnical system. Actors at each level cannot see how their decisions interact with those made at other levels, so the threats to safety are far from obvious before an accident. |
| 5 | Work practices in a complex sociotechnical system are not static. They will migrate over time under the influence of a cost gradient driven by financial pressures in an aggressive competitive environment and under the influence of an effort gradient driven by the psychological pressure to follow the path of least resistance. |
| 6 | The migration of work practices can occur at multiple levels of a complex sociotechnical system, not just one level alone. |
| 7 | Migration of work practices can cause the systems' defences to degrade and erode gradually over time, not all at once. Accidents are released by a combination of this systematically-induced migration in work practices and a triggering event, not just by an unusual action or an entirely new, one-time threat to safety. |

Recently, the tenets have been validated in the context of identifying systemic factors leading to positive outcomes. Trotter, Salmon, and Lenné (2014) adapted the tenets to apply to sub-optimal performance to evaluate systemic influences on successful and unsuccessful improvisation. Similarly, Donovan et al. (2017) adapted the tenets to evaluate the positive systemic effects of safety leadership on an incident in the mining industry. While these examples differ from previous applications of Rasmussen's tenets, they are consistent with the Rasmussen's discussions of normal work and system migration (Rasmussen 1997).

In Rasmussen's model of system migration (Figure 1), three competing pressures affect a system (Economic, Workload, and Safety) each with a threshold boundary that, if exceeded, may lead to system failure (tenets 5 and 6). Multiple contributory factors across the system contribute to an accident (tenets 1 and 2) where decision makers cannot see how their actions affect the system holistically (tenets 3 and 4), and set the stage for a single act to initiate the release of an accident (tenet 7), indicating the safety boundary has been breached. In contrast, an incident indicates an outcome occurring at the edge of the safety performance boundary. Similarly, as has been found with accidents, it could be argued that during an incident, there are multiple protective factors (i.e. decisions, actions, and/or conditions across the work system which prevent or mitigate damage, injury, or loss) throughout the system, where vertically integrated decisions allow actors to see the current state of the system, and set the stage for a single act to initiate the prevention of an accident.

Many current incident models identify a linear causal trajectory in order to discover and correct errors (Van der Schaaf, Lucas, and Hale 1991, Phimister, Bier, and Kunreuther 2004, Heinrich et al. 1980). Rasmussen's model, instead, identifies the mechanisms by which networks of locally relevant decisions and actions made in the context of normal work can aggregate as system migration (Rasmussen 1997, Rasmussen and Svedung 2000). The authors argue that this same theoretical concept applies to accident prevention. As with accident causation, the authors suggest that a network of protective factors results from the decisions and actions of actors throughout the system. The purpose of this paper is it to validate these theoretical extensions using a sample of aviation incident investigation reports.

## Methods

The study was given an ethics exemption by the University of the Sunshine Coast's Human Ethics committee (E/17/0/78).

### *Data Source*

The analysis was based on all publicly available serious incident reports available in English from the Bureau d'Equetes et d'Analyses (BEA). The BEA is the French air accident investigation body for civil aviation safety ([www.bea.aero](www.bea.aero)). The authors selected this organisation to draw reports from as the BEA is the only investigative authority which was found that explicitly incorporated theoretical concepts from Rasmussen's approach to systems thinking (Boudou, 2002). The BEA also makes both their investigation process and reports publicly available. While there is another investigative body, the Australian Transport Safety Bureau (ATSB), which applies a systems method (AcciMap) for analysis (Walker, 2008), the underlying theory for this body is an adaptation of the Reason model (Reason, 1990) of organisational incidents. The search criteria from the BEA database included; all dates, all locations, all aircraft category, all flight class, all manufacturer, and all registration types under the 'serious incident' event category. Eighteen reports were found and downloaded. Two duplicate reports were then excluded. The BEA investigation process is initiated when an incident is declared and follows three phases: information gathering, examination and research, and analysis and conclusions (BEA 2017). Using the information gathered, the investigator reports on the circumstances, incident scenario, and contributing factors related to 'human factors' (e.g. communication, ergonomics, behaviour, and decision-making).

### *Data Coding and Analysis*

The reports were coded using Nvivo 11, a qualitative analysis software tool.

Actors were identified who contributed to a decision, action, or condition that interacted to prevent or mitigate damage, injury, or loss. These actors were then mapped onto the appropriate level of the risk management framework, based on their functional relationships. For example, automated systems were mapped onto the work level of the framework as these systems provide feedback to the staff level or actions at the work level.

Secondly, the protective factors, and the relationships between them, were identified from the reports. This involved one analyst reviewing each report to identify protective factors and their interrelations. Protective factors were defined as: decisions, actions, and/or conditions across the work system which prevent or mitigate damage, injury, or loss. This definition was developed to identify systemic factors of accident prevention based from the literature of conditioning factors from bow-tie analysis: 'barriers which mitigate or manage an accident pathway' (Markowski and Kotynia 2011), and failure compensation processes: 'error detection, explanation and correction' (Kontogiannis and Malakis 2009, Kanse and van der Schaaf 2001). For example, when Air Traffic Control (ATC) assigned a specific procedure to a flight crew to manage an issue, this was coded as a Procedure Assigned and mapped to the management level of the framework as ATC provided a control to the staff level in this context. Relationships between factors were identified where one factor had an explicitly stated causal link (e.g. factor 1 leads directly to factor 2). For example, an automated alert at the work level triggered the application of an emergency procedure by the flight crew at the staff level, "…since the red landing gear indicator light was still illuminated, they applied the emergency landing gear extension procedure and found the same symptoms as during the initial approach" (BEA, 2012d, p. 1).

In order to assess the reliability of the initial coding, an inter-rater coding reliability test was undertaken by a second analyst with extensive experience in accident investigation, using two incidents (12.5% of the sample). This sample size was selected as it falls within the 10-25% recommended to calculate overall intercoder reliability (Lacy, 1996). Three test runs of a single near miss were used for training of the second analyst. In the first two rounds, the second analyst initially found no protective factors and after further training, captured all protective factors but also included significant false positives (i.e. factors unrelated to the near miss). This required an update to the coding scheme to clarify the difference between factors related to accident prevention and those which represent normal work in the aviation domain, unrelated to the near miss. After the training and coding scheme update, the second coder identified protective factors for the two incidents used in the assessment. The agreement percentage (i.e. index of concordance) was calculated using the formula $(A/(A + D))*100$ where A is the number of agreements and D is number of disagreements (Ross, 2004). Results

were 100% for identification of protective factors, an 'almost perfect' level of agreement using % agreement or index of concordance (Olsen, 2013). The protective factors identified in the initial coding were then mapped onto the risk management framework.

Rasmussen's risk management framework (Rasmussen, 1997) is the basis for the development of a series of accident causation tenets (Vicente, 2006). The original tenets, shown in Table 1, describe how factors throughout a system can negatively affect safety (e.g. the migration of a system leading to a weakening of defences). This analysis focuses on identifying the factors related to accident preventions (e.g. how the migration of a system may lead to an increase in defences). Rasmussen's accident causation tenets were adapted to describe accident prevention, and evaluation criteria developed (Table 2). The first author drafted the adaptation of the tenets and evaluation criteria in alignment with previous approaches (Donovan, 2017; Goode, 2016). Using a workshop process, the second and third authors, who have extensive experience applying a systems approach in various domains, reviewed the tenets and criteria. Disagreements were resolved through discussion until a consensus was reached, consistent with other research applying the tenets (Donovan, 2017; Salmon, 2014). The factors identified in the reports were then evaluated against these criteria.

A tenet is supported where the evaluation of multiple reports matches the evaluation criteria. Previous research applying Rasumussen's tenets in multiple domains (Cassano-Piche, 2009; Jenkins, 2010; Vicente, 2006; Salmon, 2014) as well as in the application of adapted versions of the tenets (e.g. Donovan, 2017), take a binary approach to the tenets within single events (e.g. the event provides evidence for the tenet or not). While the BEA is influenced by Rasmussen's risk management framework, their investigative approach does not specifically set out to identify protective factors; therefore, the identification of any protective factor does provide evidence, consistent with what has been done in previous research. However, as this research is exploratory in nature, applying newly adapted tenets and identifying new types of factors across multiple events, it was decided that if a tenet was found in multiple reports, this represents a strong indicator supporting the tenet as a consistent influence on the prevention of harm. The first author aligned examples from specific reports with each tenet, these where then reviewed by the second and third authors, with disagreements resolved through discussion. For example, the experience of a unique weather event successfully managed by the flight crew influenced airport management to cancel flights until the weather system had passed, "At the request of ATC, the crew described the violent phenomenon they had encountered…take-offs were suspended and airplanes on arrival put in holding for about thirty minutes" (BEA, 2009, pg. 6) was evaluated as a report meeting the criteria for system migration away from the safety boundary (tenet 6).

Table 2: Rasmussen's tenets applied to accident prevention

| Accident Prevention Tenets | Evaluation Criteria |
|---|---|
| 1 – Protective trajectories result from decisions and actions throughout the system. | Protective factors are identified at three or more levels of the risk management framework |
| 2 – Protective trajectories are usually caused by multiple, interacting contributing factors. | Three or more protective factors are identified |
| 3 – Protective trajectories can result from vertical integration (i.e. matches) across levels of a sociotechnical system, not just from decisions at just one level. | Communication across levels identified as a protective factor |
| 4 – Protective trajectories are supported by feedback across levels of a sociotechnical system. Controls (propagated downwards) and feedback (propagated upwards) allow actors to see how their decisions interact with those made at other levels. | Feedback across levels identified as a protective factor |
| 5 - Practices leading to protective trajectories are not static. They migrate over time under the influence of a safety gradient driven by social pressures and individual psychological pressures to do no harm. | Internal and External influences on work practice at one level of the risk management framework identified |
| 6 - The migration of work practices leading to protective trajectories occur at multiple levels of a complex sociotechnical system, not just at one level alone. | Internal and External influences on work practices on two or more levels of the risk management framework identified |
| 7 – Migration of work practices can result in the introduction of new defences over time. Protective trajectories are released by identifying and evaluating potential accident trajectories and triggering protective factors. | Triggering event releasing the protective trajectory is identified |

**Results**

***Description of incidents***

In total, the study included sixteen reports, summarized in table 3. These covered a range of incident types including: loss of control, loss of separation, go-arounds, and maintenance issues.

Table 3: Summary of incidents included in the review

| Incident type | Description of incident type | Number of occurrences of incident type | Reports with incident type |
|---|---|---|---|
| Ground Maintenance | Incident occurring while aircraft on runway, related to ground maintenance tasks | 1 report – fire in avionics | BEA (2010b) |
| Loss of Control | Incident occurring during flight resulting in a loss of control of aircraft | 4 reports – 2 weather related, 2 mechanical failure | BEA (2010c, 2011c, 2012f), (BEA) |
| Go Around | Incident occurring during flight resulting in aborting a landing sequence | 7 reports – 3 procedure related, 2 mechanical failure, 1 loss of control, 1 other (approach on occupied runway) | BEA (2010a, 2011b, 2012d, 2012a, 2012b, 2012c, 2012e) |
| Emergency | Emergency declared during flight resulting in emergency landing | 2 reports – 1 smoke in cabin, 1 crew illness | BEA (2010d, 2011a) |
| Loss of Separation | Incident occurring during flight resulting in loss of separation (required distance) between aircraft | 1 report | BEA (2014) |
| Other | Unique incident outside normal category | 1 report – aircraft impacted runway construction during take-off | BEA (2008) |

### *Actors*

Figure 2 presents a summary of the actors identified in reports who contributed to accident prevention. On average, 4 actors were identified per report (SD = 1.3, Range = 2-8). Actors were identified who contributed to accident prevention at five of the six levels of the framework. Actors were most frequently identified at work and staff levels. No actors were identified at the regulatory/associations level.
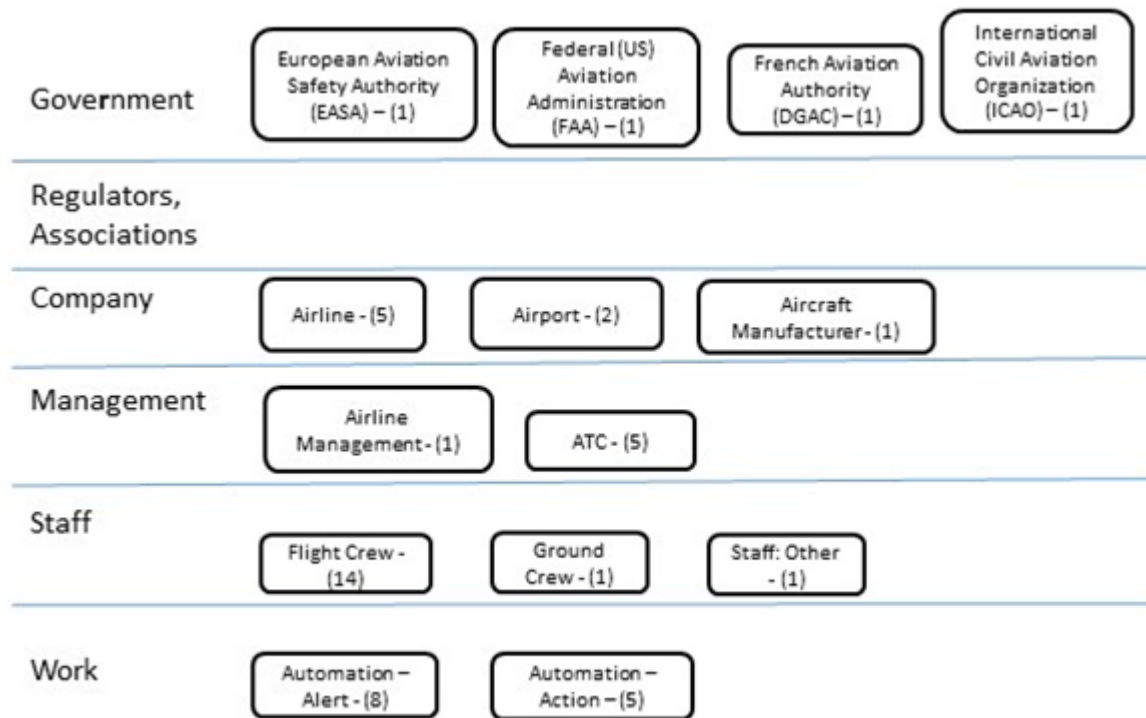
Figure 2: Actors who Contributed to Accident Prevention (n=16 reports). Number in brackets represents the number of reports where the actor was identified.
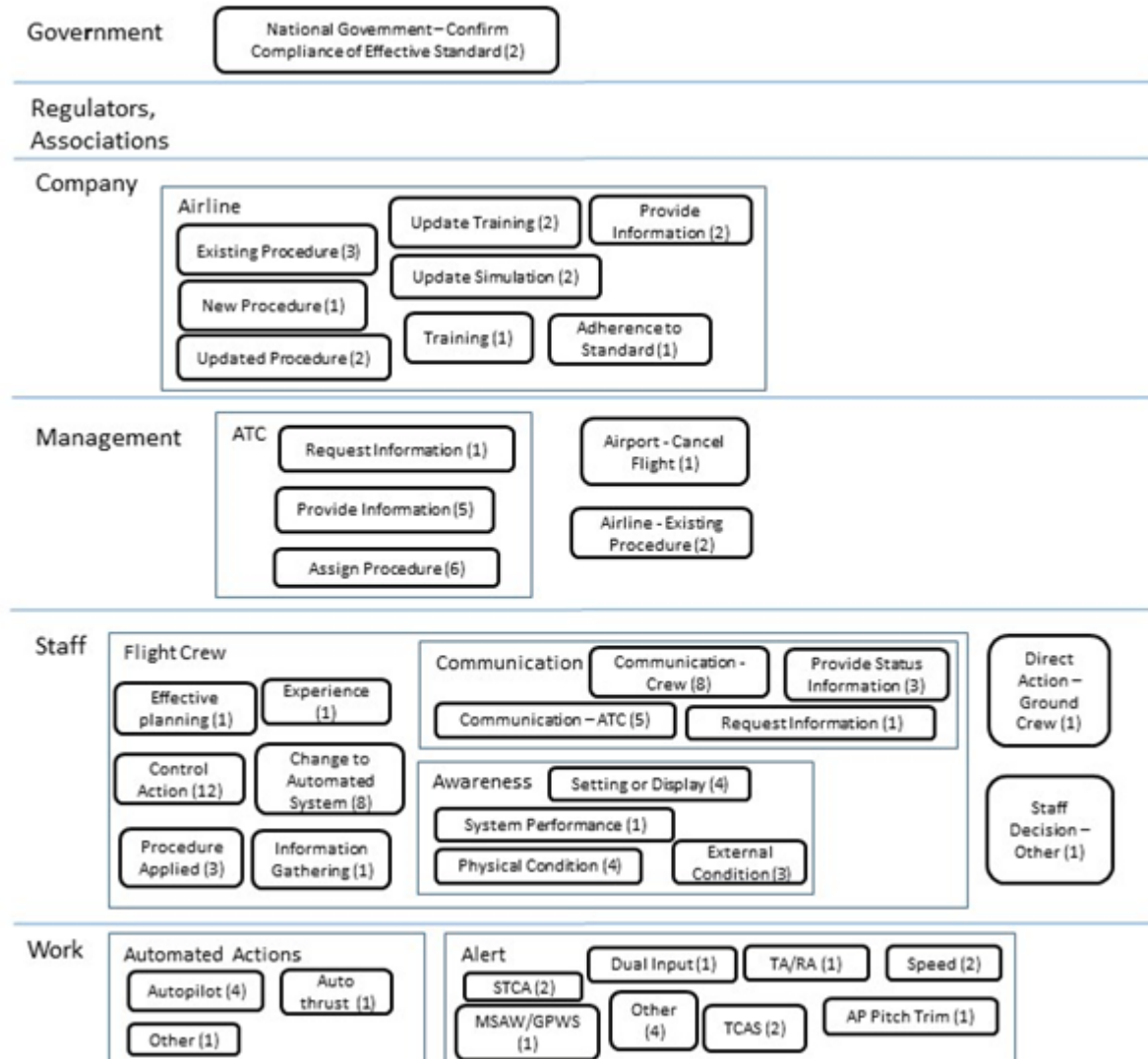
Figure 3: Protective Factors (n=16 reports). Numbers in parenthesis () indicate the number of reports in which the factor was identified.
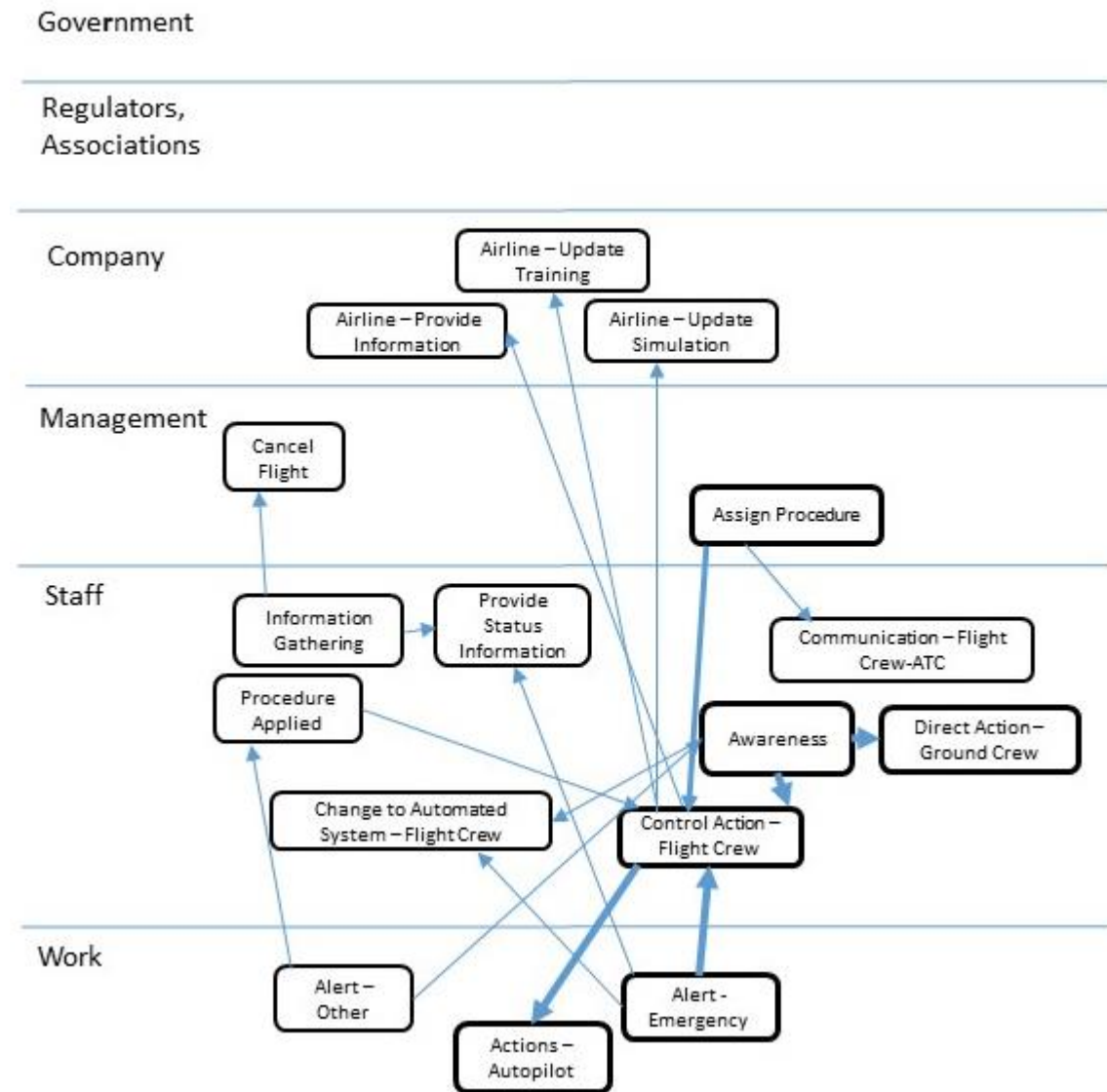
Figure 4: Protective Factor Relationships (n=16 reports). Bold arrows indicate relationships identified more than once. Bold borders identify factors identified in more than one relationship.

## *Protective factors and relationships*

A summary of the protective factors and relationships between them identified in the reports is presented in Figures 3 and 4, respectively. On average, 9.8 protective factors were identified per report (SD=5.6, Range 2-24). The most commonly identified protective factors were: Flight Crew-Control Action, ATC-Assign Procedure, and Flight Crew-Change to Automated System.

Protective factors were found at five of the six levels of the risk management framework. On average, 3 levels of the framework were represented in each report (SD=0.8, Range 1-4). The level most frequently represented was the staff level.

Ten reports identified relationships between protective factors; on average, 1.1 relationships were identified per report (SD=1.2, Range 0-4). Relationships were identified between the work, staff, management, and company levels with the highest number of relationships between protective factors occurring between the work and staff levels. The protective factors with the most relationships were: Work Level Alert-TCAS and Staff Level-Flight Control Action, Management Level-Assign Procedure and Staff Level-Flight Control Action, Staff Level-Flight Control Action and Work Level-Actions Autopilot, Staff Level-Awareness and Staff Level-Flight Control Action, and Staff Level-Awareness and Staff Level-Ground Crew Direct Action.

### *Evaluation of Rasmussen's tenets for accident prevention*

Each of the adapted tenets were identified within the reports. A summary of the results of the evaluation, with examples from the reports, appear in Table 4.

*Tenet 1: Protective trajectories result from decisions and actions throughout the system.*

The findings partially support tenet number one. As shown in the Figure 2, actors who contributed to the protective factors were identified at the work, staff, management, company, and government levels of the risk management framework. The tenet is only partially supported as the regulatory/associations level was not represented. However, as seen in Figure 3, decisions and actions (i.e. protective factors) were found at the work, staff, management, company, and government levels, with ten reports identifying factors at three or more levels.

*Tenet 2: Protective trajectories are usually caused by multiple, interacting contributing factors.*

The second tenet was supported as multiple protective factors (three or more) were identified in fifteen reports. No reports identified a single factor as the sole protective factor. As shown in the Figure 4, these factors interacted between the work, staff, management, and company levels, identified across ten reports. The relationships between: ATC-Assign Procedure and Flight Crew-Control Action, and Alert-TCAS and Flight Crew-Control Action were most prevalent at three and five instances respectively.

*Tenet 3: Protective trajectories can result from vertical integration (i.e. matches) across levels of a sociotechnical system, not just from decisions at just one level.*

The findings support tenet three, with communication providing a critical role in supporting protective trajectories. As shown in figure 3, seven instances of communication protective factors between the staff and management levels (Staff Level-Communication-ATC) were identified, from four reports. Additionally, communications were identified in four reports as being critical to maintaining awareness of flight status and task distribution among actors at the staff level.

*Tenet 4: Protective trajectories are supported by feedback across levels of a sociotechnical system. Controls (propagated downwards) and feedback (propagated upwards) allow actors to see how their decisions interact with those made at other levels.*

The findings support tenet number four, with protective feedback factors identified in eight reports. For example, the system feedback and control loop of: automation to flight crew to ATC to flight crew was found to be a key factor contributing to accident prevention in four reports.

*Tenet 5: Practices leading to protective trajectories are not static. They migrate over time under the influence of a safety gradient driven by social pressures and individual psychological pressures to do no harm.*

The findings support tenet five, showing the protective migration of safety practices. In two reports, individual pressures to do no harm at the staff level initiated new or adapted protective procedures leading to accident prevention. For example, a flight crew's use of a mobile phone to record the automated systems, providing diagnostic information to maintenance crews, allowed the maintenance crew to identify an issue with a flight control cable (BEA 2010). The flight crews' individual pressure to resolve the situation led to a unique work practice, one not covered by any existing procedure.

> One way in which systemic migration away from the safety boundary occurs is through the development and implementation of safety procedures. These procedures are developed as a systemic response to a previously identified threat, whether from a risk assessment, previous incident, or other event. These procedures are applied by operators in response to threats, to prevent accidents. In three reports, existing emergency procedures were applied at the staff level and in two reports, existing procedures were applied at the management level

*Tenet 6: The migration of work practices leading to protective trajectories occur at multiple levels of a complex sociotechnical system, not just at one level alone.*

The protective migration of safety practices occurs across multiple levels of the work system. Two reports identified how individual pressures to do no harm effected work practices at multiple levels of the framework. In these reports, successful accident prevention in novel conditions led to changes in organizational work practice. For example, after a previously unidentified significant weather event affected a flight, which was managed by the application of flight controls actions after automation systems were unable to address the issue, airport officials temporarily delayed take-offs and all arriving flights until the weather issue had abated (BEA 2009). In this case, the migration of work practices occurred at both the staff level (flight crew action to disengage autopilot) and the management level (decision to delay all flights until the hazard had abated).

*Tenet 7: Migration can result in the introduction of new defences over time. Protective trajectories are released by identifying and evaluating potential accident trajectories and triggering protective factors.*

The findings show the release of protective trajectories, with the triggering protective factor identified in eight reports. In these eight reports, automated monitoring and alerting processes triggered human operators to identify and evaluate hazardous system status. These triggers initiated a cascade of actions, resulting in an incident rather than an accident.

> The migration of the aviation system to introduce new defences over time has increased the number of defences throughout the system, including automated alerts, automated actions, procedures, and training. Automated alert systems (at the staff and management levels) and actor awareness (at the staff and management levels) often appear to provide these functions.

Table 4: Summary of validation findings

| Tenet | Findings for Protective Factors | Example |
|---|---|---|
| 1 | 10 of 16 reports identified decisions and actions contributing to the protective trajectory across 3 or more levels. | During a go around incident, factors were identified at the Work, Staff, and Management levels of the framework; automated systems, flight crew, and ATC decisions and actions led to accident prevention (BEA 2010a). |

| 2 | 15 of 16 reports identified 3 or more protective factors. | During a loss of separation incident, 10 automated alerts (at the staff and management levels), 7 communication factors (for flight crew and between flight crew and ATC), and 11 flight crew actions (flight control and changes to autopilot settings) were identified that prevented a worse outcome (BEA 2014). |
|---|---|---|
| 3 | 4 of 16 reports identified communication across levels as a protective factor. Additionally, 4 of 16 reports identified communication among levels as a protective factor. | Communication between flight crew and ATC as well as between ATC and the Airport were identified as a protective factor to resolve an emergency with smoke in the cabin (BEA 2010c). |
| 4 | 8 of 16 reports identified a feedback across system levels as a protective factor | During a loss of control incident, an automated system alerted the flight crew of a potentially dangerous system status, which allowed the flight crew to act and resolve the issue through flight control actions (BEA 2012). |
| 5 | 2 of 16 reports identified internal and external influences on work practices as contributing to the protective trajectory at 1 level. | During an equipment failure (flight control cable), the flight crew recorded the flight status in order to provide information to maintenance crews who were then able to identify the issue (BEA 2010b). |
| 6 | 2 of 16 reports identified internal and external influences on work practices at 2 or more levels. | Successful improvisation at the flight crew level during a novel type of loss of control incident due to a pilot's previous experience in the military was in turn developed into a new procedure, training, and simulation scheme for the airline (BEA 2011). |
| 7 | 8 of 16 reports identified the triggering events which released the protective trajectory. | A 'Stick Shaker' alert identified a potential stall and initiated required flight crew actions (BEA 2009). |

**Discussion**

The purpose of this study was to examine whether near misses are a systems phenomenon that involve networks of protective factors. This was achieved through determining whether the theory on accident causation in sociotechnical systems adequately describes the processes that protect systems from accidents. Rasmussen's (1997) framework was adapted to evaluate the actors and factors that contributed to accident preventions in sixteen investigation reports describing incidents from the BEA.

The key finding of the study is that Rasmussen's tenets apply to the analysis of accident prevention. As the protective factors fit onto Rasmussen's tenets, this provides a systems-thinking approach to the study of near misses. This study builds on the research applying Rasmussen's tenets to an understanding of positive systems attributes (Trotter et al. 2017, Trotter, Salmon, and Lenné 2014, Donovan et al. 2017). As with accident causation, a systems approach can analyse preventative factors of near misses.

The results indicate that near misses are, indeed, a systems phenomenon during which an accident is prevented from progressing to an adverse event through a network of protective factors. Fifteen reports identified multiple (i.e. three or more) factors leading to accident prevention. These multiple factors were identified at five of the six levels of Rasmussen's risk management framework, with the greatest number of factors found at the staff level, followed by the work, company, and management levels. As has been identified in applications of the framework to accident analysis (e.g. Vicente and Christoffersen (2006), Cassano-Piche, Vicente, and Jamieson (2009)), factors throughout the sociotechnical system interact in accident prevention.

The interactions of protective factors are a key element to accident prevention. Twelve reports showed how a relationship between factors links across and among levels of the framework. This vertical integration, as found between automated systems and staff, and staff and management, allows for actors throughout the framework to see the current state of the system. Contrary to the common belief that a single act can save the day (Reason 2008), it was found that communication (both within and across levels) and feedback and control loops develop a network of protective factors which can lead to accident prevention. Rather than only heroic moments of inspired action, the results suggest that factors throughout the aviation system interact to migrate the system away from the safety boundary and prevent accidents.

The aviation system is not static and simple, but complex and dynamic. Accordingly, work practices are constantly influenced by emerging contexts and competing pressures (Branford 2011). Two reports showed how actors across the system respond to these changing pressures and evolved work practices to accommodate them. Over time, these adaptations can become codified as new defences within the work system (Rasmussen 1997). In an accident, system migration erodes defences and allows for the release of a hazardous process by a single act (Rasmussen and Svedung 2000). As found in eleven reports, for accident prevention, system migration develops defences with the resolution of a hazard being initiated by a single act triggering a network of protective factors which prevented the progression toward an adverse event. These findings show how Rasmussen's accident causation tenets equally apply to accident prevention.

Near misses share many of the same properties of accidents, as they were found to result from: a network of multiple, interacting factors with influences from across the risk management framework, supported by vertically integrated feedback and control loops, and emerging from systemic migration away from a safety boundary. The protective networks appear to be similar in nature and structure to contributory networks found in accidents (e.g. Underwood and Waterson (2014), Debrincat, Bil, and Clark (2013), Newnam and Goode (2015)). For example, Salmon et al. (2010) identified how a network of factors among inadequate procedures, staff qualifications, and inadequate training contributed to a tragic drowning during a school camp. In three reports from the current study, the implementation of an existing procedure by qualified staff with appropriate training contributed to accident prevention. As both accidents and near misses seem to share comparable properties, what does this mean for future research into safety?

It appears that the same factor can be contributory or protective. It is unknown whether this is due to either; a factor being optimal versus degraded within the system, or to the interacting network associated with the factor, which leads to its protective or contributory impact. It may also be that factors themselves are less relevant and it is, in fact, the interactions which generate a protective or contributory impact. Several further research questions emerge from the idea that interactions determine which a factor is contributory or protective. With a network of protective factors now being identified in accident prevention, to what extent do the two networks (causation and prevention) interact? If these networks do interact, what is the nature of that interaction; are there specific network functions or structures that affect outcomes, a simple 'battle' between types of factors, or is something more sophisticated to discover? If factors are not either protective or contributory, how does context and migration affect the influence of a factor on an incident outcome? While these networks of protective

factors can be identified in reports focussing on contributory factors, there is an obvious gap in identifying a complete set of protective factors. Where common sense would infer that the normal training programs for pilots, operator experience, or hiring practices are components of accident prevention, these were not identified as relevant from the serious incident reports.

As near misses are, in fact, a systems phenomenon, much of the work done in the study of near misses is out of date with current accident models. Previous work has focussed on developing categories of errors within a linear accident model, underpinned primarily by the Swiss Cheese Model of accident causation (Reason, 1997) (e.g. MERS-TM (Battles, 1998), or HFACS-Ground (Mazaheri, 2015)). This approach of finding and blocking errors is unable to identify a network of factors which provide for accident prevention. The Human Factors Analysis and Classification System (HFACS), in broad use in the aviation domain, is an accident analysis method for investigating and analysing human error. The HFACS categorizes error contributing factors into: Unsafe Acts, Preconditions for Unsafe Acts, Unsafe Supervision, or Organizational Influences (Wiegmann, and Shappell 2001). This focus of HFACS, based on Reason's (1990) model of active and latent failures, would be unable to identify factors contributing to accident prevention. While some of the categories (such as communication within the Organizational Influences category) could potentially identify factors that provide for accident prevention; the vast majority are inappropriate for doing so as the method is underpinned by a linear accident causation model based on the assumption of human error. Comparatively, it was found that by applying a systems model, this network of protective factors becomes apparent.

There is a compelling argument of the need for a systems model of near misses. The findings show that Rasmussen's (1997) model appears to apply to near misses but there should be a model which provides a systems-thinking based approach to near misses that aligns with the Rasmussen model and incorporates the last twenty years of evolution in systems thinking and ergonomics. Currently, the analysis of near misses uses accident causation models, thus viewing them as a type of accident. This approach ignores one of the essential differences between accidents and near misses that has been discussed throughout this paper, specifically that a near miss can identify factors which protect from accidents. This is consistent with both the identified gap in the application of ergonomics methods towards understanding normal work (Salmon et al. 2016) and the issue of underlying assumptions such as the 'What you look for is what you find' principle (Hollnagel, 2008, Lundberg, Rollenhagen, and Hollnagel 2009).

While this research has been able to find protective factors from serious incident analysis reports, there is no way to know how much information about the effective components of accident prevention is left unidentified. Analysing current incident reporting systems (such as the Aviation Safety Reporting System) using this model is of course possible, however the results will likely identify fewer protective factors than exist as the focus of these reporting systems is to capture factors related to potential accident causation, rather than prevention factors or those related to normal work. It is unknown to what extent contributing or protective factors are represented in current data collection systems of normal work in the aviation domain (such as Flight Operations Quality Assurance or Flight Data Management), however the focus of the existing research into such systems is similar to those used in incident reporting systems (Chidester, 2003; Rosenthal, 2003). Moving forward, research into near misses and normal work should, as is known with investigations into accidents, look to identify protective 'human factors' as a point from which to look up and out at the system as a whole (Dekker 2014). Future investigations should treat all reports as a starting point to discover the entire network of protective factors which support accident prevention to understand what went right.

*Limitations*

This study does have some limitations. The major limitation is that the study relied on investigation reports, and the key point of these investigations was to identify failures. Therefore, they are not the ideal data source for identifying protective factors. Additionally, the only investigation reports analysed were those from the BEA and available in English. There are several other investigative bodies (e.g. NTSB, ATSB) which have publicly accessible reports.

## Conclusion

This study demonstrates that Rasmussen's theory of accident causation in sociotechnical systems also describes the processes involved in accident prevention. This was done through an analysis of sixteen serious incident reports from the aviation domain using Rasmussen's (1997) risk management framework and system migration model in the accident prevention context. Based on the study, it is concluded that protective factors occur in a network throughout the sociotechnical system which support accident prevention.  Near misses appear to share many of the same properties as accidents.

Rasmussen's tenets therefore provide a theoretical approach to the study of near misses. This application using a systems approach to the study of near misses draws out significant ongoing theoretical questions to address. The similarity between accident prevention and causation factors and networks call for further exploration. While it is possible to identify protective factors from current investigation reports, this limits the information available on

the influences of normal work. Practitioners are called to expand incident investigations by

applying systems-thinking based models, such as Rasmussen's tenets, to identify system wide

networks of protective factors.

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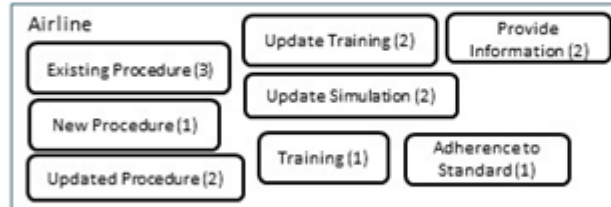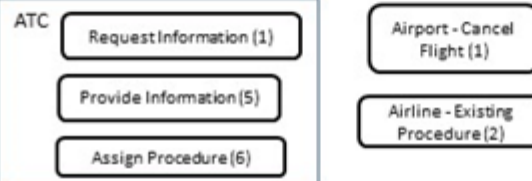Woods, David D, and Richard I Cook. 2002. "Nine steps to move forward from error." *Cognition, Technology & Work* 4 (2):137-144. doi: https://doi.org/10.1007/s101110200012.
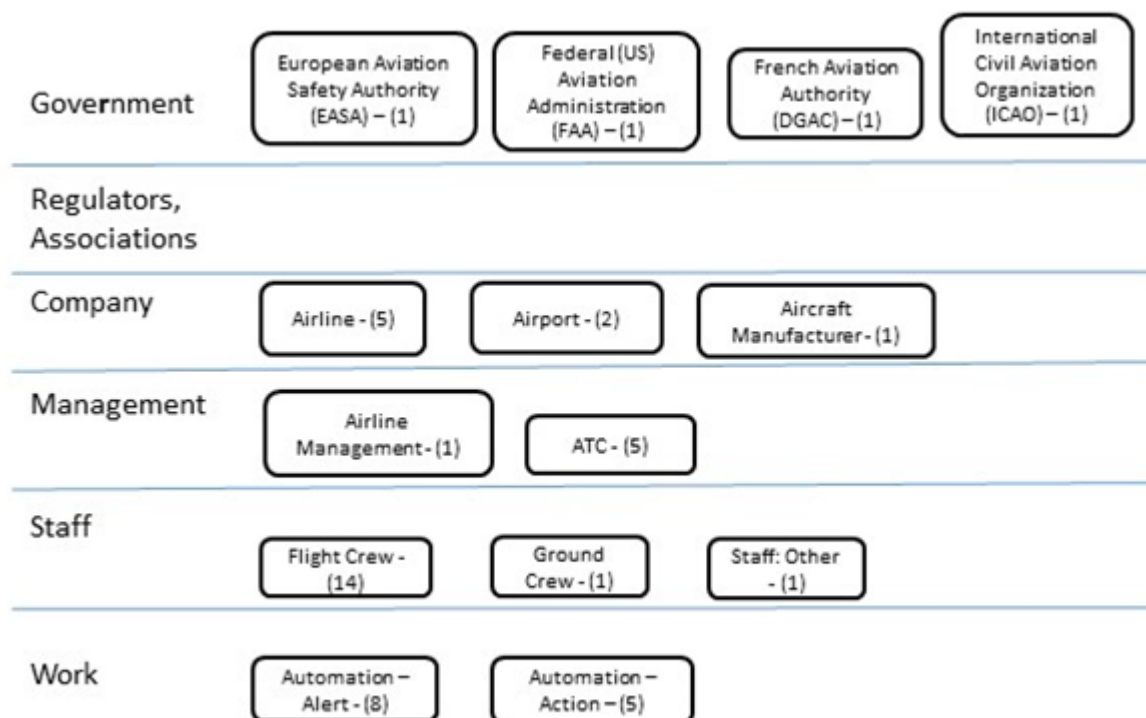
**Government**

National Government – Confirm Compliance of Effective Standard (2)

**Regulators, Associations**

**Company**

Airline

Existing Procedure (3)

New Procedure (1)

Updated Procedure (2)

Update Training (2)

Update Simulation (2)

Training (1)

Provide Information (2)

Adherence to Standard (1)

**Management**

ATC

Request Information (1)

Provide Information (5)

Assign Procedure (6)

Airport - Cancel Flight (1)

Airline - Existing Procedure (2)

**Staff**

Flight Crew

Effective planning (1)

Experience (1)

Control Action (12)

Change to Automated System (8)

Procedure Applied (3)

Information Gathering (1)

Communication

Communication - Crew (8)

Provide Status Information (3)

Communication – ATC (5)

Request Information (1)

Awareness

Setting or Display (4)

System Performance (1)

Physical Condition (4)

External Condition (3)

Direct Action – Ground Crew (1)

Staff Decision – Other (1)

**Work**

Automated Actions

Autopilot (4)

Auto thrust (1)

Other (1)

Alert

STCA (2)

MSAW/GPWS (1)

Dual Input (1)

TA/RA (1)

Speed (2)

Other (4)

TCAS (2)

AP Pitch Trim (1)
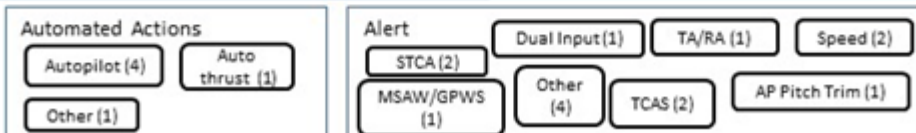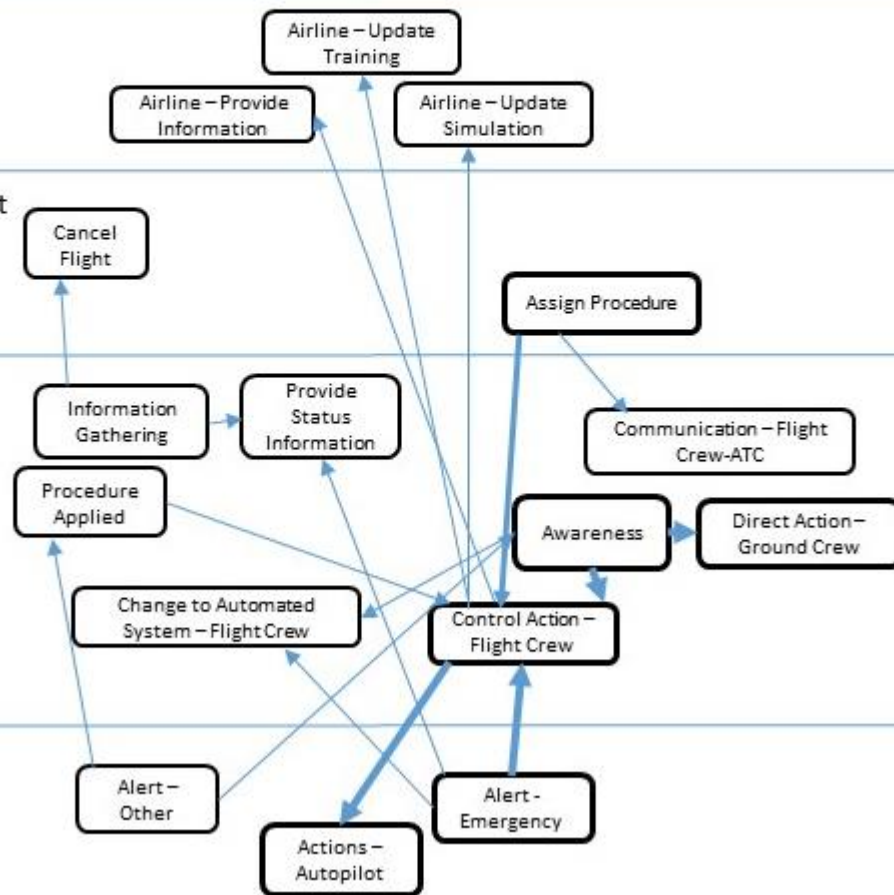
Government

Regulators, Associations

Company

Management

Staff

Work

| | Rasmussen's Seven Tenets |
|---|---|
| 1 | Safety is an emergent property of a complex sociotechnical system. It is impacted by the decisions of all the actors-politicians, managers, safety officers, and work planners-not just the front-line workers alone. |
| 2 | Threats to safety or accidents are usually caused by multiple contributing factors, not just a single catastrophic decision or action. |
| 3 | Threats to safety or accidents can result from a lack of vertical integration (i.e. mismatches) across levels of a complex sociotechnical system, not just from deficiencies at just one level. |
| 4 | The lack of vertical integration is caused, in part, by a lack of feedback across levels of a complex sociotechnical system. Actors at each level cannot see how their decisions interact with those made at other levels, so the threats to safety are far from obvious before an accident. |

| 5 | Work practices in a complex sociotechnical system are not static. They will migrate over time under the influence of a cost gradient driven by financial pressures in an aggressive competitive environment and under the influence of an effort gradient driven by the psychological pressure to follow the path of least resistance. |
|---|---|
| 6 | The migration of work practices can occur at multiple levels of a complex sociotechnical system, not just one level alone. |
| 7 | Migration of work practices can cause the systems' defences to degrade and erode gradually over time, not all at once. Accidents are released by a combination of this systematically-induced migration in work practices and a triggering event, not just by an unusual action or an entirely new, one-time threat to safety. |

| Accident Prevention Tenets | Evaluation Criteria |
|---|---|
| 1 – Protective trajectories result from decisions and actions throughout the system. | Protective factors are identified at three or more levels of the risk management framework |
| 2 – Protective trajectories are usually caused by multiple, interacting contributing factors. | Three or more protective factors are identified |
| 3 – Protective trajectories can result from vertical integration (i.e. matches) across levels of a sociotechnical system, not just from decisions at just one level. | Communication across levels identified as a protective factor |
| 4 – Protective trajectories are supported by feedback across levels of a sociotechnical system. Controls (propagated downwards) and feedback (propagated upwards) allow actors to see how their decisions interact with those made at other levels. | Feedback across levels identified as a protective factor |
| 5 - Practices leading to protective trajectories are not static. They migrate over time under the influence of a safety gradient driven by social pressures and individual psychological pressures to do no harm. | Internal and External influences on work practice at one level of the risk management framework identified |
| 6 - The migration of work practices leading to protective trajectories occur at multiple levels of a complex sociotechnical system, not just at one level alone. | Internal and External influences on work practices on two or more levels of the risk management framework identified |

| 7 – Migration of work practices can result in the introduction of new defences over time. Protective trajectories are released by identifying and evaluating potential accident trajectories and triggering protective factors. | Triggering event releasing the protective trajectory is identified |
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| Incident type | Description of incident type | Number of occurrences of incident type | Reports with incident type |
|---|---|---|---|
| Ground Maintenance | Incident occurring while aircraft on runway, related to ground maintenance tasks | 1 report – fire in avionics | BEA (2010b) |
| Loss of Control | Incident occurring during flight resulting in a loss of control of aircraft | 4 reports – 2 weather related, 2 mechanical failure | BEA (2010c, 2011c, 2012f), (BEA) |
| Go Around | Incident occurring during flight resulting in aborting a landing sequence | 7 reports – 3 procedure related, 2 mechanical failure, 1 loss of control, 1 other (approach on occupied runway) | BEA (2010a, 2011b, 2012d, 2012a, 2012b, 2012c, 2012e) |
| Emergency | Emergency declared during flight resulting in emergency landing | 2 reports – 1 smoke in cabin, 1 crew illness | BEA (2010d, 2011a) |
| Loss of Separation | Incident occurring during flight resulting in loss of separation (required distance) between aircraft | 1 report | BEA (2014) |
| Other | Unique incident outside normal category | 1 report – aircraft impacted runway construction during take-off | BEA (2008) |

| Tenet | Findings for Protective Factors | Example |
|---|---|---|
| 1 | 10 of 16 reports identified decisions and actions contributing to the | During a go around incident, factors were identified at the Work, Staff, and Management levels of the framework; automated systems, flight crew, and ATC decisions and actions led to accident prevention (BEA 2010a). |

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|---|---|---|
| | protective trajectory across 3 or more levels. | |
| 2 | 15 of 16 reports identified 3 or more protective factors. | During a loss of separation incident, 10 automated alerts (at the staff and management levels), 7 communication factors (for flight crew and between flight crew and ATC), and 11 flight crew actions (flight control and changes to autopilot settings) were identified that prevented a worse outcome (BEA 2014). |
| 3 | 4 of 16 reports identified communication across levels as a protective factor. Additionally, 4 of 16 reports identified communication among levels as a protective factor. | Communication between flight crew and ATC as well as between ATC and the Airport were identified as a protective factor to resolve an emergency with smoke in the cabin (BEA 2010c). |
| 4 | 8 of 16 reports identified a feedback across system levels as a protective factor | During a loss of control incident, an automated system alerted the flight crew of a potentially dangerous system status, which allowed the flight crew to act and resolve the issue through flight control actions (BEA 2012). |
| 5 | 2 of 16 reports identified internal and external influences on work practices as contributing to the protective trajectory at 1 level. | During an equipment failure (flight control cable), the flight crew recorded the flight status in order to provide information to maintenance crews who were then able to identify the issue (BEA 2010b). |
| 6 | 2 of 16 reports identified internal and external influences on work practices at 2 or more levels. | Successful improvisation at the flight crew level during a novel type of loss of control incident due to a pilot's previous experience in the military was in turn developed into a new procedure, training, and simulation scheme for the airline (BEA 2011). |
| 7 | 8 of 16 reports identified the triggering events which released the protective trajectory. | A 'Stick Shaker' alert identified a potential stall and initiated required flight crew actions (BEA 2009). |