Examining the Systemic Accident Analysis Research-Practice Gap

by

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Doctoral Thesis

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Abstract

In order to enhance safety and prevent the recurrence of major accidents it is necessary to understand why they occur. This understanding is gained by utilising accident causation theory to explain why a certain combination of events, conditions and actions led to a given outcome: the process of accident analysis.

At present, the systems approach to accident analysis is arguably the dominant research paradigm. Based on the concepts of systems theory, it views accidents as the result of unexpected and uncontrolled relationships between a system's components. Various researchers claim that use of the systems approach, via systemic accident analysis, provides a deeper understanding of accidents when compared with traditional theories. However, the systems approach and its analysis techniques are yet to be widely adopted by the practitioner community and, therefore, a research-practice gap exists. The implication of such a gap is that practitioners may be applying outdated accident causation theory and, consequently, producing ineffective safety recommendations.

The aim of this thesis was to develop the current understanding of the systemic accident analysis research-practice gap by providing a description of the gap, considering its extent and examining issues associated with bridging it. Four studies were conducted to achieve this aim. The first study involved an evaluation of the systemic accident analysis literature and techniques, in order to understand how their characteristics could influence the research-practice gap. The findings of the study revealed that the systems approach is not presented in a consistent or clear manner within the research literature and that this may hinder its acceptance by practitioners. In addition, a number of issues were identified (e.g. model validation, analyst bias and limited usage guidance) which may influence the use of systemic analysis methods within industry. The examination of how the analysis activities of practitioners may contribute to the gap motivated Study 2. This study involved conducting semi-structured interviews with 42 safety professionals and various factors, which affect the awareness, adoption and

usage of the systems approach and its analysis methods, were highlighted. The combined findings of Studies 1 and 2 demonstrate that the systemic accident analysis research-practice gap is multifaceted in nature. Study 3 investigated the extent of the gap by considering whether the most widely used analysis technique (the Swiss Cheese Model) can provide a systems approach to accident analysis. The analysis of a major rail accident was performed with a model based on the Swiss Cheese Model and two systemic analysis methods. The outputs and usage of the three analysis tools were compared and indicate that the Swiss Cheese Model does provide a means of conducting systemic accident analysis. Therefore, the extent of the research-practice gap may not be as considerable as some proponents of the systems approach suggest. The final study aimed to gain an insight into the application of a systemic accident analysis method by practitioners, in order to understand whether it meets their needs. Six trainee accident investigators took part in an accident investigation simulation and subsequently analysed the data collected during the exercise with the Systems Theoretic Accident Modelling and Processes model. The outputs of the participants' analyses were studied along with the evaluation feedback they provided via a questionnaire and focus group. The main findings of the study indicate that the analysis technique does not currently meet the usability or graphical output requirements of practitioners and, unless these issues are addressed, will struggle to gain acceptance within industry.

When considering the research findings as a whole a number of issues are highlighted. Firstly, given the benefits of adopting the systems approach, efforts to bridge the systemic accident analysis research-practice gap should be made. However, the systemic analysis methods may not be best suited to analyse every type of accident and, therefore, should be considered as one part of an investigator's 'analysis toolkit'. Adapting the systemic analysis methods to meet the needs of practitioners and communicating the systems approach more effectively represent two options for bridging the gap. However, due to the multidimensional nature of the gap and the wide variety of individuals, organisations and industries that perform accident analysis, it seems likely that tailored solutions will be required. Furthermore, due to the differing needs of the research and practice communities, efforts to bridge the gap should focus on collaboration between the two communities rather than attempting to close the gap entirely.

Statement of originality

The author (Peter J. Underwood) is solely responsible for the work submitted in this thesis with the exception of Study 3. The author designed Study 3 and performed the data collection and analysis. However, Dr. Patrick Waterson reanalysed the raw data with one of the three analysis methods used in the study. His analysis findings were incorporated into the Study 3 chapter (Chapter 5).

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This statement certifies that neither the submission nor the original work contained therein has been submitted for an award of this or any other degree awarding body.

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Publications

Journal publications

Underwood, P. and Waterson, P., 2013a. Systemic accident analysis: Examining the gap between research and practice. *Accident Analysis & Prevention,* 55, pp.154-164.

Underwood, P. and Waterson, P., 2013b. Systems thinking, the Swiss Cheese Model and accident analysis: A comparative systemic analysis of the Grayrigg train derailment using the ATSB, AcciMap and STAMP models. *Accident Analysis & Prevention*. DOI: dx.doi.org/10.1016/j.aap.2013.07.027

Conference publications

Underwood, P. and Waterson, P., 2012a. A critical review of the STAMP, FRAM and AcciMap systemic accident analysis models. In: ed. AHFE. *International Conference on Applied Human Factors and Ergonomics.* San Francisco, 21-25 July 2012. The Printing House: Stoughton, WI, USA. pp.1709-1718.

Underwood, P. and Waterson, P., 2012c. A Review of Systemic Accident Analysis Models. In: ed. M. Anderson. *Contemporary Ergonomics and Human Factors 2012.* Blackpool, UK, 16-19 April 2012. CRC Press: London, UK. pp.364-365.

Book chapters

Underwood, P. and Waterson, P., 2012b. A critical review of the STAMP, FRAM and AcciMap systemic accident analysis models. In: N.A. Stanton ed. *Advances in human aspects of road and rail transportation.* CRC Press: Boca Raton, FL, USA. pp. 385-394.

Poster presentations

Underwood, P., 2013. Systemic accident analysis: Examining the gap between research and practice. Poster session at: *CHI+MED Doctorial Consortium*. London, UK, 14 June 2013.

Underwood, P., 2011. Accident Analysis: The Industrial Divide. Poster session at: *IEHF Doctorial Consortium*. Uxbridge, UK, 7 June 2011.

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Abbreviations

AWS – Automatic Warning System

ATSB – Australian Transport Safety Bureau

CAST – Causal Analysis based on STAMP

COSS – Controller of Site Safety

CREAM – Cognitive Reliability and Error Analysis Method

ETA – Event Tree Analysis

FRAM – Functional Resonance Analysis Method

FTA – Fault Tree Analysis

GST – General System Theory

HAZOP – Hazard and Operability study

HFACS – Human Factors Analysis and Classification System

HFIT – Human Factors Investigation Tool

HRO – High reliability organisation

HRT – High reliability theory

IIC – Investigator In Charge

MMD – Man-made disasters

MORT – Management Oversight and Risk Tree

mph – miles per hour

NAT – Normal accident theory

NIA – National Investigation Agency

PWSB – Permanent way stretcher bar

RAIB – Rail Accident Investigation Branch

RCA – Root Cause Analysis

RE – Resilience engineering

RMF – Risk Management Framework

RPG – Research-practice gap

SAA – Systemic accident analysis

SBT – Scenario-based training

SCM – Swiss Cheese Model

SOAM – Systemic Occurrence Analysis Methodology

STAMP – Systems Theoretic Accident Modelling and Processes model

STPA – System-Theoretic Process Analysis

STS – Socio-technical system(s)

TSM – Track section manager

Chapter 1 – Thesis overview

1.1 Problem statement

The need to understand why accidents occur has existed in various forms for centuries, with major accidents often motivating interest in system safety and highlighting the dangers associated with safety-critical industries (Cooter and Luckin, 1997; Saleh et al., 2010). Indeed, demands to improve safety are usually made following accidents which involve a high number of casualties (e.g. Chernobyl and Bhopal), significant environmental damage (e.g. the Exxon Valdez and Deep Water Horizon oil spills) and/or destruction of symbolic technological assets (e.g. Concorde and space shuttle Columbia). Stakeholders in such events are found throughout various elements of society, e.g. governments, regulators, academic and industry experts, management teams, individual employees and the general public. Consequently, various incentives exist to prevent accident recurrence, e.g.: the moral and ethical imperative to prevent injuries and death; avoidance of the financial losses associated with replacing assets, damaged reputation and litigation; the legal requirements to meet regulatory standards.

Satisfying the demand to prevent accidents requires the determination of why certain combinations of events, conditions and actions led to specific outcomes, i.e. accident analysis (Hollnagel et al., 2008). At a fundamental level, accident analysis involves applying knowledge of accident causation to the data collected during an investigation in order to understand what happened and why. Accident analysis is an integral part of the larger accident investigation process, which involves other activities such as investigation planning and coordination, data collection and the production of recommendations (Hollnagel and Speziali, 2008). Furthermore, it can influence the collection of data (i.e. as information is analysed, new lines of enquiry can develop) and provide the basis for safety recommendations, as indicated by the generic accident analysis procedure described by Salmon et al. (2011 p.9) (see Figure 1).

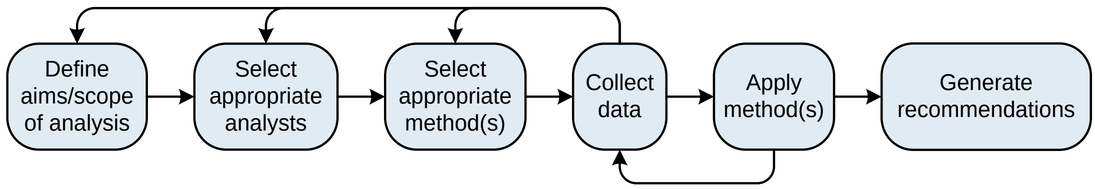

Figure 1 - Generic accident analysis process. From Salmon et al. (2011).

As detailed in Chapter 2, the nature and understanding of accident causation has changed dramatically over the last century. The systems approach to accident analysis is now, arguably, the dominant paradigm within safety research. Based on systems theory, it views accidents as emergent phenomena, which result from uncontrolled system component interactions, and necessitates a holistic examination of socio-technical systems (STS). Advocates of the systems approach (e.g. Dekker, 2011; Hollnagel, 2012; Leveson, 2012) propose that traditional theories of accident causation (which suggest that accidents are caused by linear sequences of cause-effect events) are no longer capable of accounting for the complexity of modern-day STS. To facilitate the application of the systems approach, a number of systemic accident analysis (SAA) models and methods have been produced.

As indicated in Figure 1, the use of analytical methods plays an important role in the analysis process, as they provide a structured means of applying accident causation theory. Various researchers (e.g. Leveson, 2001; Rasmussen, 1997) have been employing and recommending the use of SAA techniques for over a decade. However, these analysis tools are yet to be widely adopted by the practitioner community. This suggests that a research-practice gap (RPG) exists in the domain of SAA. The key implication of such a gap is that practitioners may be applying outdated knowledge of accident causation during their investigations and, therefore, producing ineffective safety recommendations.

It seems clear, therefore, that the SAA RPG needs to be addressed. However, there is no defined explanation for the presence of this gap, nor is there an understanding of the extent of the gap or how it could be bridged. Tackling these knowledge gaps provides the motivation for the studies presented in this thesis.

1.2 Research aims

This research aims to further the current understanding of the SAA RPG by meeting the following objectives:

- Provide a description of the SAA RPG by identifying and evaluating the factors which contribute to it
- Consider the extent of the RPG by comparing the analysis processes and methods used by the research and practitioner communities
- Examine issues associated with bridging the SAA RPG

1.3 Research approach

1.3.1 Research paradigm

Scientific research should be conducted systematically, with scepticism and an ethical approach, if it is to be considered as good quality (Robson, 2002 p.18). Clearly it is important to produce a high standard of research and adopting a suitable philosophical standpoint is a key element in achieving this, particularly as it can guide the choice of methods (Snape and Spencer, 2003). A wide range of ontological positions exist which have differing and, in some cases, extreme views of science (e.g. positivism and constructivism). A pragmatic approach to research can, however, be maintained by adopting a realist perspective (Robson, 2011). Various forms of realism exist, e.g. ‘critical realism’, ‘transcendental realism’ and ‘scientific realism’, with each brand emphasising different characteristics of the realism paradigm (Robson, 2011). However, the underlying concept of realism acknowledges the existence of both the real world that operates independently through natural necessity and the individual person with a personal perspective of the world (Bhaskar, 1975). Therefore, it aims to achieve a balance between the post-positivist and constructionist paradigms (Robson, 2002 p.42-43). Taking this ontological position allows the researcher to consider a wide range of methods, as described in Figure 2. Due to these advantages, the research presented in this thesis was conducted from the realist perspective.

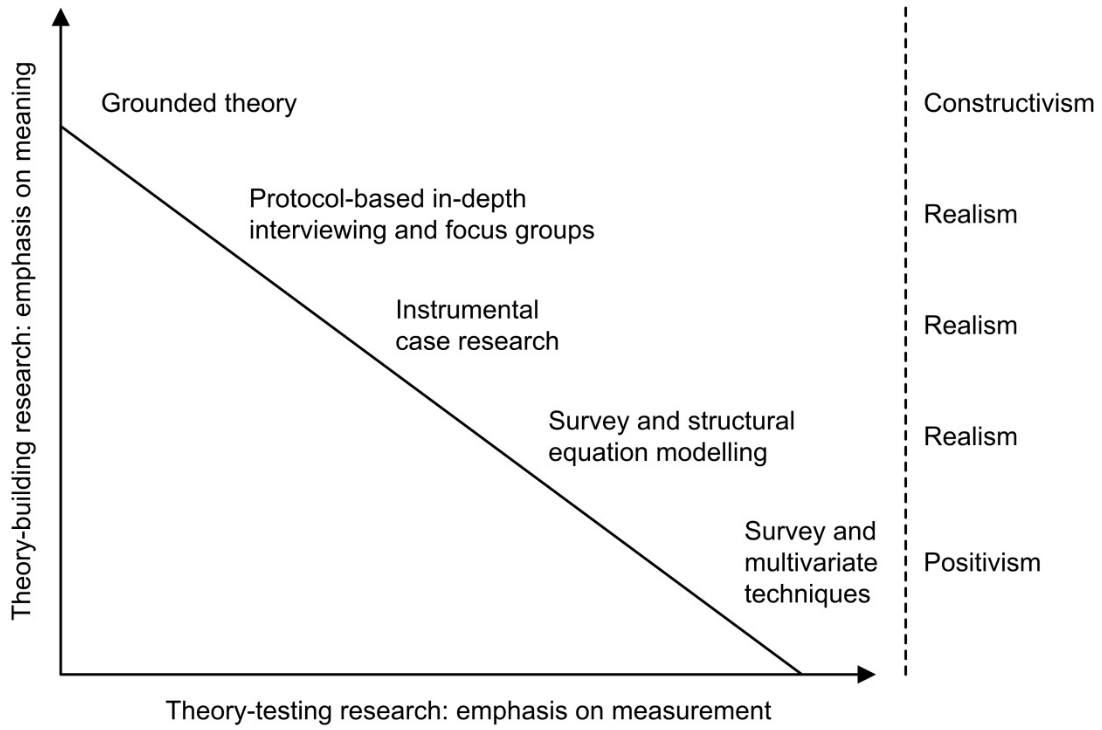

Figure 2 - A representative range of methods and their related research paradigms. From Healy and Perry (2000).

1.3.2 Mixed methods approach

The mixed methods approach to research combines quantitative and qualitative research techniques, approaches, concepts and/or language into a single study (Johnson and Onwuegbuzie, 2004). It has been described as the third research paradigm (e.g. Johnson et al., 2007) and offers an expansive and creative form of research which includes the use of inductive and deductive approaches (Johnson and Onwuegbuzie, 2004). The use of a mixed methods strategy precludes the adoption of a quantitative or qualitative purist research philosophy (e.g. positivism or constructivism) and is compatible with the realism approach adopted in this thesis (Healy and Perry, 2000).

Johnson and Onwuegbuzie (2004) recommend a pragmatic approach in order to combine the insights provided by qualitative and quantitative research into a workable solution. In other words, research approaches should be mixed in ways that offer the best opportunities for answering research questions (Johnson and Onwuegbuzie, 2004). Various benefits are provided by taking a mixed methods approach, such as: the improved validity of findings resulting from method triangulation, the weaknesses of one method can be overcome by the use of another technique and it provides a depth and breadth of research which is difficult to achieve with a single method (Johnson and Onwuegbuzie, 2004; Menon and Cowger, 2010; Royce et al., 2010). The drawbacks of a mixed methods approach include: the difficulty of integrating different types of data, an increased resource demand and the requirement to learn a wide range of methods (Brannen, 2005; Bronstein and Kovacs, 2013; Bryman, 2007). However, the benefits of performing mixed methods research were considered, in this instance, to outweigh the drawbacks and the decision was taken to utilise this approach.

Each study was performed sequentially, however, where necessary, different methods were used concurrently within the studies. The selection and usage of the various methods employed within this research are described in detail within the study-related chapters (Chapters 3-6). However, to illustrate the nature of the mixed-methods approach taken, Table 1 presents the methods utilised in this research.

Study	**Qualitative methods used**	**Quantitative methods used**
1	Document analysis	Document citation analysis
2	Semi-structured interviews	Analysis model awareness questionnaire
3	Application of accident analysis methods	n/a
4	Analysis workshop	Analysis method evaluation questionnaire
	Group interview	

Table 1 - Methods used during research

1.3.3 Ethical approval

This research was approved by the Loughborough University Ethics Committee. All study participants were provided with an information sheet (which detailed the purpose of the given study, the nature of their involvement and data protection information) and gave their written consent to take part.

1.4 Thesis structure

This thesis contains eight chapters which are briefly summarised below.

1.4.1 Chapter 1

This introductory chapter outlines the problem statement, the research aims and approach and the structure of the thesis.

1.4.2 Chapter 2

An overview of the literature that creates the context for the research contained in the thesis is presented in this chapter. The reviewed topics include: key accident causation theories, the systems approach to accident analysis, the evolution of accident analysis models and methods and the current evidence indicating the presence of an SAA RPG.

1.4.3 Chapter 3

In this chapter the SAA literature and analysis techniques are evaluated in order to understand how their characteristics contribute to the SAA RPG. Initially, the SAA literature is examined to determine how it incorporates and presents the core concepts of systems theory. The development process, systems approach characteristics and usage characteristics of the three most popular SAA techniques are then evaluated. The findings of the study are discussed to highlight a number of factors which may influence the SAA RPG.

The method evaluation component of this study was published in two conference proceedings and, subsequently, as a book chapter (see Underwood and Waterson, 2012a; 2012b; 2012c). Underwood and Waterson (2012a) can be seen in Appendix 1.1.

1.4.4 Chapter 4

This chapter follows on from the research presented in Chapter 3 and examines the SAA RPG from a different perspective. Safety experts were interviewed to understand the factors stemming from practice which contribute to the SAA RPG. In combination with the findings of Study 1, an overall description of the SAA RPG is provided and the factors which contribute to it are discussed.

The findings of this study were published in the Accident Analysis & Prevention journal: Underwood and Waterson (2013a) is presented in Appendix 1.2.

1.4.5 Chapter 5

The extent of the SAA RPG is investigated in this chapter. The academic debate on the ability of the most popular analysis technique, the Swiss Cheese Model (SCM), to conduct SAA is presented. A major accident case study is then analysed using a practitioner-developed SCM-based model and two SAA methods (AcciMap and the Systems Theoretic Accident Modelling and Processes model). The analysis outputs and usage of the techniques are compared and the issue of whether or not the SCM can offer a systems approach to accident analysis is discussed. An assessment of the extent of the SAA RPG is then presented.

The findings of this study were also published in the Accident Analysis & Prevention journal, as part of a special issue on 'systems thinking in workplace safety and health': Underwood and Waterson (2013b) is presented in Appendix 1.3.

1.4.6 Chapter 6

This chapter follows on from the findings of Study 2 (see Chapter 4), which indicate that SAA methods must meet the needs of practitioners if they are to be employed. A practitioner evaluation of the Systems Theoretic Accident Modelling and Processes model (STAMP) is presented in this chapter. Six trainee accident investigators performed a STAMP analysis on data collected during an accident investigation simulation and assessed the effectiveness and usability of the method. The findings of the study are discussed with regards to how the usage characteristics of STAMP may affects its use by practitioners.

1.4.7 Chapter 7

A discussion of the research contained in the thesis is provided in this chapter. Initially, a brief summary of the studies is presented. The overarching topics of whether the SAA RPG needs to be bridged, how this can be achieved and if it is possible to bridge the gap are then examined. Finally, the limitations of the research, as a whole, are discussed.

1.4.8 Chapter 8

This chapter presents the overall conclusions of the research and the contribution to knowledge provided by this thesis. Future work is then proposed which could follow on from this thesis along with suggestions for broader SAA RPG research. A graphical summary of the thesis is provided in Figure 3.

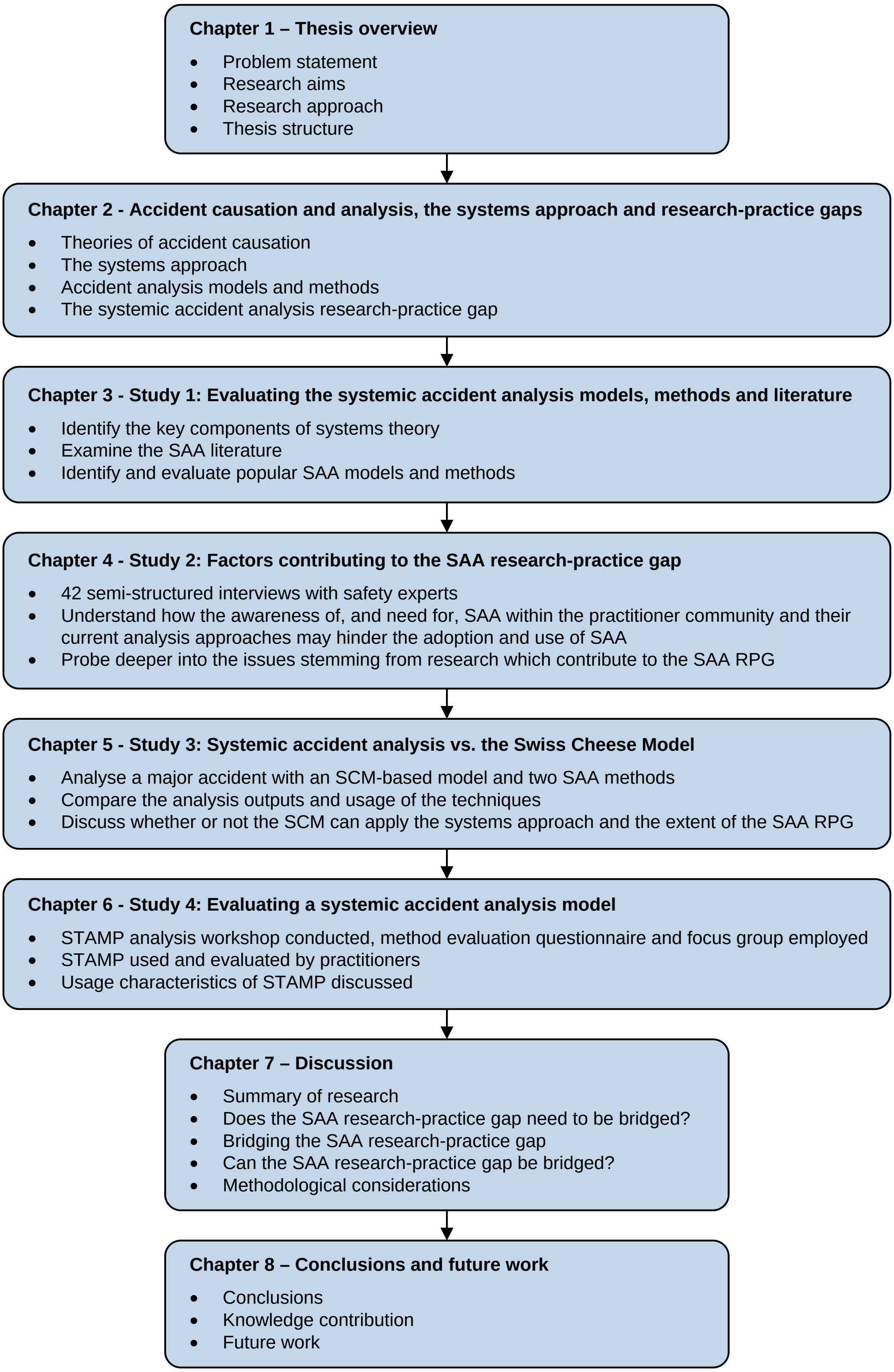

Figure 3 - Thesis structure

Chapter 2 – Accident causation and analysis, the systems approach and research-practice gaps

2.1 Chapter overview

This chapter provides an overview of the literature pertaining to four topics which create the context for the research presented in this thesis. Initially, some of the key accident causation theories are described, in order to highlight the changing perspectives on accidents which have occurred over the last century. This culminates with a detailed description of the systems approach to accident analysis, including the development and key components of systems theory. The evolution of accident analysis models and methods is subsequently presented to describe how accident causation theory has been applied by researchers and practitioners. This leads to the final topic: the current evidence indicating the presence of an SAA RPG.

2.2 Theories of accident causation

The literature on accident causation and system safety is extensive but fragmented (Le Coze, 2013b; Saleh et al., 2010). However, what can be discerned from studying the literature is that various theories, concepts and categorisations of accident causation have been created and developed over time. Why has this progression occurred? The answer lies in the continuously changing nature of accident causation. The mechanisms of accident causation have evolved due to the ever-increasing complexity of STS. This increased system complexity is a culmination of various factors, such as: the rapid pace of technological advances, competitiveness of the business environment and more complex relationships between humans and technology (Leveson, 2012; Rasmussen, 1997). The ability of humans to design technology, which is so complex that it is not fully understood, has been a reoccurring issue throughout history; the result being increased risk and accidents until scientific and engineering knowledge has caught up (Leveson, 2012 p.4). Therefore, the development of accident causation theory is a product of analysts identifying and going beyond the limitations of contemporary theories. An overview of the literature is presented in the remainder of this section, highlighting some of the important themes and ideas.

2.2.1 The three ages of safety

Until the nineteen century, the prevention of accidents was viewed from a practical, rather than scientific, perspective (Hale and Hovden, 1998). Three ages of scientific study followed, described by Hale and Hovden (1998) as the age of technology, human factors and safety management, respectively. This categorisation illustrates how the understanding of accidents has changed over time and provides a useful context for studying the development of other accident causation theories, as detailed in the rest of Section 2.2.

The age of technology, lasting until after World War 2, saw interest in accidents stem from a technical standpoint. For example, during most of the nineteenth century UK factory inspectors were only concerned with accidents resulting from inadequate/absent machinery guarding; other accidents were considered as unpreventable or the concern of the victim (Hale and Glendon, 1987). This suggests that accident causation was perceived as the result of a simple cause, i.e. a failure of something; a perspective Hollnagel (2012) describes as 'simple linear thinking'. The second (human factors) age originated from the post-World War 1 research conducted into personnel selection, training and motivation as accident prevention measures (Hale and Hovden, 1998). From the 1960's the rising influence of ergonomics and developments in probabilistic risk assessments revealed that technical prevention measures were no longer considered sufficient to prevent accidents. Accidents were no longer viewed as either purely technical or human in nature, i.e. human factors were seen as a major influence on accident causation. The dominance of the technical age of safety had come to an end and the human factors age came to the fore.

The age of safety management began in the 1980's when optimising the interface between individuals and technology was no longer considered adequate to maintain safety. Safety was seen as a management issue and research into the topic focused on issues such as quality assurance, selfregulation and safety culture (DeJoy et al., 2004; Kjellén and Hovden, 1993). As such, accidents were perceived as ‘organisational’ in nature and views of accident causation moved towards complex linear thinking and beyond to dynamic systems thinking (Hollnagel, 2012). Whilst the three ages of safety describe the changing perspectives of accident causation it is notable that they supplement, rather than substitute, each other, i.e. technical and human factors safety is still important (Hovden et al., 2010).

2.2.2 Man-made disasters

The man-made disasters (MMD) theory, devised by Turner (1978), was one of the first scholarly accounts which suggested that industrial accidents could be carefully analysed, rather than treated as sudden ‘Acts of God’ (Saleh et al., 2010). The overarching message of MMD theory is that the safe operation of technological systems can be subverted by ‘normal’ processes of organisational life, despite the best intentions of those involved (Pidgeon and O'Leary, 2000). Three key contributions to the understanding of accidents are provided by MMD theory: (1) MMD are a class of events which are underpinned by common patterns and can be analysed to improve system safety; (2) accidents develop over long incubation periods, during which a long chain of concealed errors and partially understood events increase system vulnerability; (3) accidents cannot be described as purely technical, i.e. they arise from interactions between the human and organisational elements of STS (Aini and Fakhrul-Razi, 2010; Pidgeon and O'Leary, 2000; Saleh et al., 2010). The theory of MMD was subsequently used as the foundation for an extensive amount of research into accident causation (e.g. Le Coze, 2013a; Pidgeon, 1997; Reason, 1990; Saleh et al., 2010).

2.2.3 Normal accident theory

In his work on normal accident theory (NAT), Perrow (1984 p.4) states that most high-risk systems exhibit special characteristics which make accidents in them inevitable. The two system characteristics which were deemed by Perrow (1984) to influence the causation of accidents were ‘interactive complexity’ and ‘coupling’. Interactive complexity refers to how system components interact with one another. Systems with a high degree of interactive complexity can have independent failures, each insignificant in itself, which interact in unexpected and even incomprehensible ways (Perrow, 1994). Factors which produce complex interactions include: the presence of multi-functional components, many control parameters with potential interaction and a limited understanding of processes (Hollnagel and Speziali, 2008; Shrivastava et al., 2009). Such systems are difficult to understand and are unstable due to their narrow limits of safe operation (Perrow, 1984). However, accidents in a highly complex system will only spread and become serious if the system is also tightly coupled. Coupling in a system essentially refers to the slack available to recover from an accident. Various issues contribute to a tightly coupled system, such as processes which occur rapidly and cannot be stopped, failed components that cannot be isolated and there being only one way to maintain safe operations (Perrow, 1984 p.5). The worst combination for accident potential that a system can have, therefore, is high interactive complexity and tight coupling (Hollnagel and Speziali, 2008). Perrow (1984) examined the characteristics of a number of systems, of which nuclear power plants were considered to be the most prone to accidents (see Figure 4).

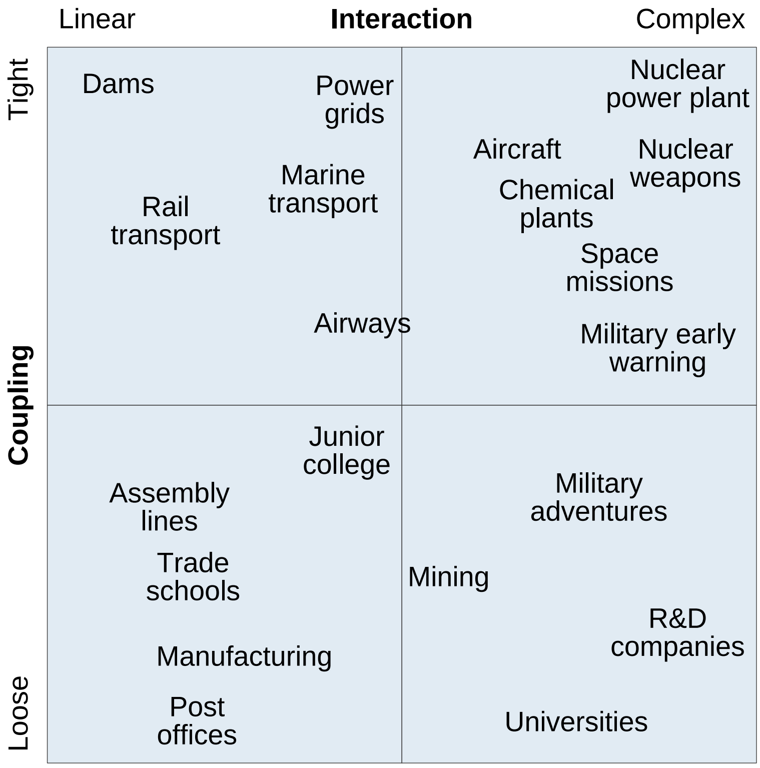

Figure 4 - System interaction-coupling matrix. From Perrow (1984).

Given that accidents in highly complex and tightly coupled systems are inevitable, according to NAT, Perrow (1984) suggests that such systems should be abandoned or radically redesigned to lower their level or complexity and/or coupling. Perrow (1984) also suggests that building technical redundancy into a system will only increase the level of complexity. Importantly, NAT describes major accidents as 'systems accidents', rather than the failure of system components (operators, equipment, procedures, environment etc.) where no significant unexpected interaction of failures occur (Perrow, 1994). In other words, it is how failures combine with each other which will affect the outcome of an accident, rather than the individual failures themselves. Notably, the idea that system complexity can create unexpected/incomprehensible component interactions is in contrast with MMD theory, which suggests that ‘warning sign’ events are present but either missed, overlooked or ignored before an accident happens (Hopkins, 2001).

2.2.4 High reliability theory

Despite its recognised importance, NAT has received criticism for its oversimplification of technical solutions to, and fatalistic view of, accidents which are of limited use to safety professionals (e.g. Marais et al., 2004; Saleh et al., 2010; Shrivastava et al., 2009). This led to the development of an alternative theory which, rather than focussing on how accidents occur, concentrates on what organisations do to successfully promote and ensure safety in complex systems. This high reliability theory (HRT) is based on the studies of various successful organisations, such as naval aircraft carriers (e.g. Rochlin et al., 1987), air traffic control systems (e.g. La Porte, 1988) and nuclear power plants (e.g. Bourrier, 1996). These types of organisations must not have major accidents as their work is too important and the effects of significant failures too disastrous, i.e. they must be highly reliable (LaPorte and Consolini, 1991). Although variation exists in the literature regarding the definition of a high reliability organisation (HRO), the characteristics of an HRO can be summarised as: (1) a preoccupation with failure and organisational learning; (2) a commitment to and consensus on production and safety as concomitant organisational goals; (3) centralised and decentralised operations (for normal and hazardous situations respectively) and deferring to experts when required; (4) organisational slack and redundancy (Saleh et al., 2010). According to HRT, organisations will remain safe if they are totally committed to high reliability practices (Rosa, 2005). Due to their differing theoretical standpoints, an extensive (and on-going) HRT-NAT debate exists within the scientific literature (e.g. Hopkins, 2013; Sagan, 1993; Shrivastava et al., 2009).

2.2.5 Drift into failure

The study of how people and organisations can, over time, incrementally adjust their perception of risk to the point where hazardous activities are considered normal has been studied (at least) since the 1970’s (e.g. Millman, 1977). The seminal work of Vaughan (1996) provides a detailed example of how such ‘normalisation of deviance’ can contribute to accidents. The historic ethnography presented by Vaughan (1996) describes how NASA’s decision to proceed with the final launch of space shuttle Challenger was not simply a result of managerial wrongdoing. Rather, NASA was exposed to numerous production pressures which became institutionalised and had a nuanced, unacknowledged and pervasive effect on decision making. Signals of danger were normalised so that they became aligned with organisational goals and were considered accepted behaviour. Vaughan (1996) suggests that these issues can apply to all types of organisations and that accidents result from the 'banality of organisational life' combined with a highly complex and competitive environment, rather than individual failures or intentional managerial misconduct.

The normalisation of deviance can, therefore, result in the 'drift' of an organisation towards (and beyond) the limits of safety, i.e. a drift into failure. This issue was also addressed by Rasmussen (1997), who remarks that there will be a natural migration of activities toward the boundary of acceptable performance due to the constraints and pressures placed on individuals and systems. This migration will occur as individuals vary their performance to increase their productivity and adapt to changes in local conditions. Whilst the local violations of an individual may not be visible in other parts of the system, they will re-shape the boundary of acceptable performance of other people and, ultimately, contribute to a systematic degradation of a system's defences (Rasmussen, 1997) (see Figure 5).

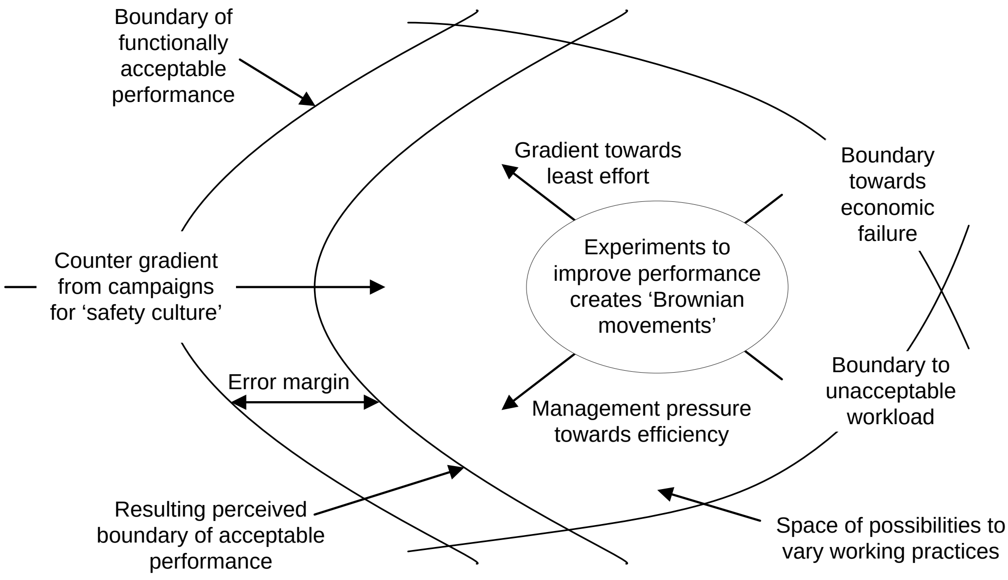

Figure 5 - Organisational drift mechanisms. From Rasmussen (1997).

The concept of 'drift into failure' was further elaborated on by Dekker (2011), who suggests that such a process is affected by five factors: (1) scarcity of and competition for resources; (2) decrementalism of operational practices, i.e. normalisation of deviance; (3) sensitive dependence on initial conditions, i.e. the butterfly effect; (4) unruly technology; (5) contribution of the protective structure (e.g. regulations, safety committees etc.) via poor knowledge, lack of access and information, conflicting goals and decisions that only make local sense. Research into organisational drift continues to take place across a number of industries, such as road transport (e.g. Salmon et al., 2012b), rail (e.g. Leach and Berman, 2012) and healthcare (e.g. Samaras, 2012).

2.2.6 Resilience engineering

It is usual and traditional for safety efforts to focus on reducing unwanted events, e.g. accidents (Hollnagel et al., 2011). However, proponents of resilience engineering (RE) (e.g. Hollnagel et al., 2006; Hollnagel et al., 2011) suggest that it is easier and more effective to improve safety by increasing the number of things that go right, rather than reducing the number of things that go wrong. Moving away from the common understanding of ‘freedom from unacceptable risk’, RE favours defining safety as the ability to succeed under varying conditions (Hollnagel et al., 2011). In order for a system to be resilient it must be able to respond to events, monitor on-going developments, anticipate future threats and opportunities and learn from past successes and failures. Whilst RE has become an established approach in the field of safety science it has drawn criticism on several issues, e.g. the introduction of a new vocabulary to safety research and a lack of analytical frameworks for investigating resilience (Le Coze, 2013a; Saurin and Carim Júnior, 2011). The development of the theories described in Section 2.2 is graphically represented in Figure 6.

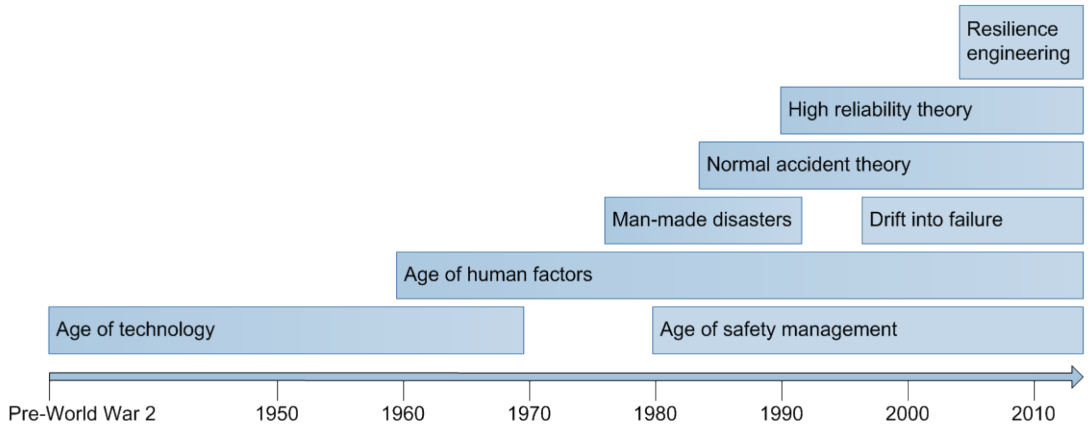

Figure 6 - Development of accident causation theories

2.3 The systems approach

Despite the advent of RE, significant effort is still directed towards the study of accidents and, at present, the systems approach to understanding major accidents is arguably the dominant research paradigm (e.g. Hollnagel, 2012; Leveson, 2012; Salmon et al., 2013; Stanton et al., 2012). Utilising concepts of system theory, it views accidents as the result of unexpected, uncontrolled relationships between a system's constituent parts. Systems must, therefore, be analysed holistically as whole entities, rather than considering their parts in isolation. Traditional theories of accident causation suggest that complex systems accidents are caused by sequences of causal events which are initiated by a single 'root cause' event, such as catastrophic equipment failure or an unsafe human action. However, as system complexity has increased over time, many accidents (e.g. space shuttle Columbia; Comair flight 5191) have not simply resulted from such trigger events. Instead these accidents emerge as complex phenomena within the normal operational variability of a system (de Carvalho, 2011).

Describing accidents in a sequential (cause-effect) fashion is, therefore, arguably inadequate. It can also lead to equipment or humans at the 'sharp end' of a system being incorrectly blamed for an accident. This represents a missed opportunity to learn important lessons about system safety and how to prevent accident recurrence. The use of the systems approach, via SAA, attempts to avoid these limitations and it has been used as the conceptual foundation for various SAA techniques, such as: AcciMap (Rasmussen, 1997), the Functional Resonance Analysis Method (FRAM) (Hollnagel, 2004; 2012) and STAMP (Leveson, 2004; 2012).

2.3.1 Development of systems theory

The origins of systems theory can be traced back to the theoretical biology studies of von Bertalanffy in the 1920's, in which he discussed the idea of organism-level behaviour (Seising, 2010). This research culminated in the publication of 'An outline of general system theory' in 1950, which proposed that the traditional reductionist view of science, i.e. examining separate elements in isolation, could not account for the behaviour of a system when considered as a whole (von Bertalanffy, 1950). Similar discoveries had been made in psychology, economics and philosophy and, along with scientists working in the fields of cybernetics and general semantics, von Bertalanffy identified a need for a 'general superstructure of science' (von Bertalanffy, 1950). This 'new basic scientific discipline', termed 'General System Theory' (GST) was established as a set of logico-mathematically underpinned principles designed to describe the behaviour of systems, regardless of the nature of their components (von Bertalanffy, 1950). From methodological and epistemological perspectives, GST represents a means of instigating and controlling the transfer of systems principles across scientific disciplines by using unambiguous, exact mathematical laws.

After the introduction of GST, other researchers elaborated mathematically-based systems theories (e.g. Klir, 1969; Mesarovic and Takahara, 1975) which have been incorporated into numerous disciplines, such as engineering, operations research, economics and ecology. Other non-mathematical theories have been developed in a variety of fields, such as sociology, political sciences, anthropology and psychology (Schwaninger, 2006). A notable application of GST, with regards to the understanding of systemic accident causation, is the concept of the STS. Pioneered by members of the Tavistock Institute (e.g. Emery, 1959; Trist, 1959), STS research considers the properties of complex systems consisting of interrelated human and technological components. Work in this field has primarily focused on the implications of organisational change (e.g. introducing new/re-designed technology and work practices) and STS are typically studied at the primary work, whole organisation and/or macrosocial system level (e.g. Geels, 2005; Kroes et al., 2006; Waterson, 2009b) (Davis et al., 2013; Trist, 1981). However, there is a clear link between STS and accident analysis research, as significant effort has been dedicated to examining the safety implications associated with STS (e.g. Salmon et al., 2012a; Stanton et al., 2012). Recent examples of systems theory application still cover a wide range of disciplines, such as plant systems biology (Lucas et al., 2011), project management (Kapsali, 2011), educational science (Nicolescu and Petrescu, 2013), sustainability (Xing et al., 2013) and tourism (Peeters, 2012).

2.3.2 Core components of systems theory

A wealth of literature regarding systems theory exists. Defining its core components, however, is a difficult task as there appears to be no firm agreement amongst researchers (Waterson, 2009a). Nevertheless, some broad interrelated themes can be identified within the literature.

2.3.2.1 System structure

Systems are generally based on a hierarchy of subsystems, which are formed in order to perform specific functions; a characteristic known as ‘differentiation’ or ‘division of labour’ (Skyttner, 2005). In order to understand a system, it is necessary to examine each relevant hierarchical level and its relationship with adjacent levels. Moving up the hierarchy provides a deeper understanding of a system’s goals, whereas examining lower levels reveals how a system functions to meet those objectives (Vicente, 1999). Furthermore, determining the boundary of a system, i.e. distinguishing between what is part of the system and part of the environment, is an important aspect of specifying its hierarchy (Jönsson, 2007 p.41).

2.3.2.2 System component relationships

When an isolated component is exposed to the system environment it becomes directly or indirectly connected to and, therefore, influenced by every other component (Skyttner, 2005). The resultant interaction of system components produces emergent, rather than resultant, behaviour. The main distinction between emergent and resultant behaviour is that the latter is predictable from the system's constituent parts, whereas the former is not (Reason, 2008 p.94). Therefore, STS will display characteristics and operate in ways not expected or planned for by their designers (Wilson, 2013). Such behaviour cannot be explained by studying system components in isolation: the whole is greater than the sum of its parts. Consequently, a system must be studied holistically, i.e. all components, human and technical, need to be considered as well as the relationships between them (Read et al., 2013).

2.3.2.3 System behaviour

Inputs are converted into outputs, via transformation processes, in order to achieve a system's goals, e.g. safe operations. If system goals are to be reached and safety maintained, a system's components must be controlled via regulatory feedback mechanisms when deviations in behaviour occur (Skyttner, 2005). Dynamic system behaviour means that a goal can be achieved from a variety of initial starting conditions (equifinality). Alternatively, systems can produce a range of outputs from an initial starting point (multifinality). This dynamic behaviour also means that systems can adapt over time to changing conditions and may migrate towards a state of increased risk and drift into failure (Dekker, 2011; Leveson, 2011). Furthermore, open systems (e.g. STS) interact with their environment and, consequently, their level of entropy (i.e. the amount of order within a system) can increase or decrease. The various elements of the systems approach are presented in Figure 7.

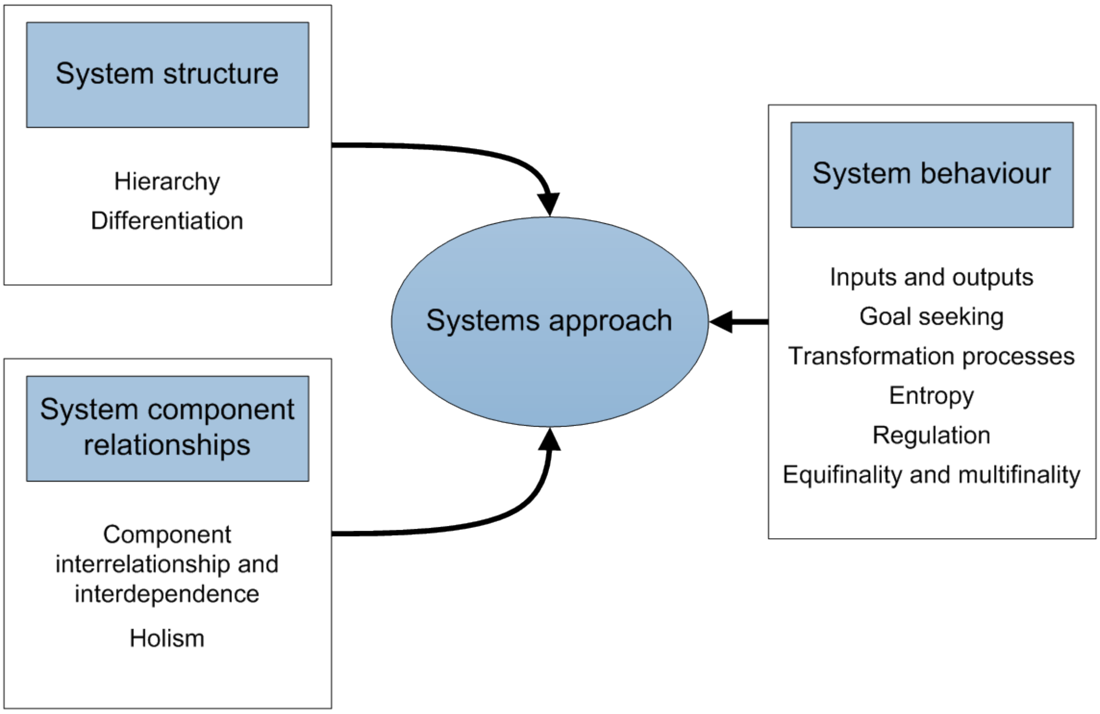

Figure 7 - The systems approach

2.4 Accident analysis models and methods

To facilitate the accident analysis process, a wide range of models and methods have been created. Analysis models provide a conceptual representation of accident causation whereas analysis methods provide a means of applying this theory. These tools enable the application of accident causation knowledge either retrospectively, as accident analysis, or prospectively, as risk assessments during system development and operation (Qureshi, 2007). Safety researchers have, over the last century, produced a large quantity of these models and methods, in order to determine how major accidents occur. Well known examples of retrospective techniques include:

- Domino model (Heinrich, 1931)
- Management Oversight and Risk Tree (MORT) (Johnson, 1973)
- Five Whys method (Ohno, 1988)
- SCM (Reason, 1990)
- Why-Because Analysis (Ladkin and Loer, 1998)
- Human Factors Analysis and Classification System (HFACS) (Wiegmann and Shappell, 2003)

Popular examples of tools used for prospective analysis include:

- Fault Tree Analysis (FTA) (Watson, 1961)
- Event Tree Analysis (ETA) (US Nuclear Regulatory Commission, 1975)
- Hazard and Operability study (HAZOP) (Kletz, 1983)
- Tripod Delta (Hudson et al., 1994)
- Cognitive Reliability and Error Analysis Method (CREAM) (Hollnagel, 1998)

The processes of accident analysis and risk assessment are closely linked, e.g. results of accidents investigations are often used to inform risk analyses (Goossens and Hale, 1997; Rasmussen and Grønberg, 1997). Indeed, Hollnagel (2008) suggests that they are two sides of the same coin, i.e. they consider the same events after or before they have happened. As such, some models and methods can be used for both retrospective and prospective purposes, such as FTA (e.g. Vestrucci, 2013; Yang et al., 2013), Failure Modes and Effects Analysis (e.g. Arendt and Lorenzo, 1991; Cicek and Celik, 2013) and ETA (e.g. Ronza et al., 2003; Zhang and Tang, 1993). However, they remain separate areas of study and, due to the resource constraints of this PhD, the scope of research contained in this thesis is limited to the topic of retrospective accident analysis.

Recent research demonstrates that, despite the array of available techniques, new tools are still being developed (e.g. Chen et al., 2013; Le Coze, 2013a; Mullai and Paulsson, 2011; Rathnayaka et al., 2011). A key driver for the continued rise in analysis model and method numbers is the changing nature of accident causation resulting from the ever-increasing complexity of STS (see Section 2.2). As researchers have sought to account for these changes (by devising new theories of accident causation and models to apply them), the ensuing development of analysis techniques can be described as having gone through three major phases, i.e. sequential, epidemiological and systemic; a categorisation that relates to the different underlying assumptions of accident causation (Hollnagel and Goteman, 2004). Katsakiori et al. (2009) suggest that this distinction is not obligatory, as other classification systems based on differing accident characteristics exist (e.g. Kjellén, 2000; Laflamme, 1990; Lehto and Salvendy, 1991). However, it aids in the understanding of researchers' desire to introduce systems theory concepts into accident analysis, as detailed in the following sections.

2.4.1 Sequential techniques

The sequential class of models and methods describe accidents as the result of time-ordered sequences of discrete events. They assume that an undesirable event, i.e. a 'root cause', initiates a sequence of events which leads to an accident and that the cause-effect relationship between consecutive events is linear and deterministic. This implies that the accident is the result of this root cause which, if identified and removed, will prevent a recurrence of the accident. Examples include the Domino model, FTA and the Five Whys method.

These methods work well for losses caused by physical component failures or the actions of humans in relatively simple systems and generally offer a good description of the events leading up to an accident (Leveson, 2004). However, the cause-effect relationship between the management, organisational and human elements in a system is poorly defined by these techniques and they are unable to depict how these causal factors triggered the accident (Le Coze, 2005; Rathnayaka et al., 2011). From the end of the 1970's it became apparent that the sequential tools were unable to adequately explain a number of major industrial accidents, e.g. Three Mile Island, Chernobyl and Bhopal (Hollnagel and Goteman, 2004). Consideration for the role that organisational influences play in accidents was required and resulted in the creation of the epidemiological class of analysis tools.

2.4.2 Epidemiological techniques

Epidemiological models and methods view accidents as a combination of 'latent' and 'active' failures within a system, analogous to the spreading of a disease (Qureshi, 2007). Latent conditions, e.g. management practices or organisational culture, are likened to resident pathogens and can lie dormant within a system for a long time (Reason et al., 2006). Such organisational factors can create conditions at a local level, i.e. where operational tasks are conducted, which negatively impact on an individual's performance (e.g.

fatigue or high workload). The scene is then set for 'unsafe acts', such as errors and violations, to occur. Therefore, the adverse consequences of latent failures only become evident when they combine with unsafe acts, i.e. active failures, to breach the defences of a system. The contribution of latent environmental factors has been acknowledged by researchers (e.g. Haddon, 1980; Perrow, 1984; Turner, 1978) since the work on military and domestic accidents conducted by Gordon (1949). However, the most well-known epidemiological technique is the SCM developed by Reason (1990; 1997), which has formed the conceptual basis for various analysis methods, e.g. HFACS, Tripod Delta and the Systemic Occurrence Analysis Methodology (SOAM) (EUROCONTROL, 2005).

The epidemiological class of techniques better represent the influence of organisational factors on accident causation, when compared with the sequential tools. Given that they require an individual to look beyond the proximal causes of an accident and examine the impact of a system's latent conditions, a more comprehensive understanding of an accident can be achieved. However, many are still based on the cause-effect principles of the sequential models, as they describe a linear direction of accident causation (Hollnagel, 2004). Leveson (2004) also observes that, besides preventing future losses, the basic reason for conducting accident analysis is the assignment of blame. This highlights a second important limitation of the sequential and epidemiological models: they guide analysts to search for the 'root cause' of an accident, whether it is at the 'sharp' or 'blunt' end of a system. Stopping an investigation when a suitable culprit is found may result in too superficial an explanation to correctly inform the development of safety recommendations (Leveson, 2004). For these reasons, a number of researchers (e.g. Leveson, 2001; Rasmussen, 1997; Svedung and Rasmussen, 2002) began to argue that the epidemiological techniques were no longer able to account for the increasingly complex nature of STS accidents.

2.4.3 Systemic techniques

Whilst the systems approach has been advocated in accident analysis research (at least) since the 1980's (e.g. Leplat, 1984), the identification of epidemiological model limitations renewed the interest in its application. As described in Section 2.3, systems theory describes accidents as whole-level, emergent system behaviour resulting from the interdependent relationships of its constituent parts (rather than sequences of cause-effect events). Proponents of the systems approach suggest that adopting this view of accident causation resolves the limitations of the previous generations of models by removing blame from individual components and looking at how the complex nature of the entire system resulted in an accident (e.g. Dekker, 2006 p.90-91; Holden, 2009; Leveson, 2004). A variety of models and methods were subsequently created to facilitate SAA, e.g. STAMP, FRAM and AcciMap.

A number of studies have been conducted to assess the benefits of using SAA methods in comparison with established non-systemic analysis techniques, e.g. FTA (Belmonte et al., 2011) and the Sequentially Timed Events Plotting method (Herrera and Woltjer, 2010). These studies and others like them (e.g. Arnold, 2009; Ferjencik, 2011; Hickey, 2012; Salmon et al., 2010a) suggest that, while the non-systemic methods are suitable for describing what happened in an accident, the SAA techniques provide a deeper understanding of how dynamic, complex system behaviour contributed to the event. This is further exemplified by studies which have used SAA methods to generate insights which go beyond the findings presented in official accident investigation reports (e.g. Jenkins et al., 2010; Johnson and de Almeida, 2008). This improved understanding of accident causation justifies the desire of researchers to perform SAA.

The development of accident analysis techniques is shown alongside the evolution of accident causation theory in Figure 8.

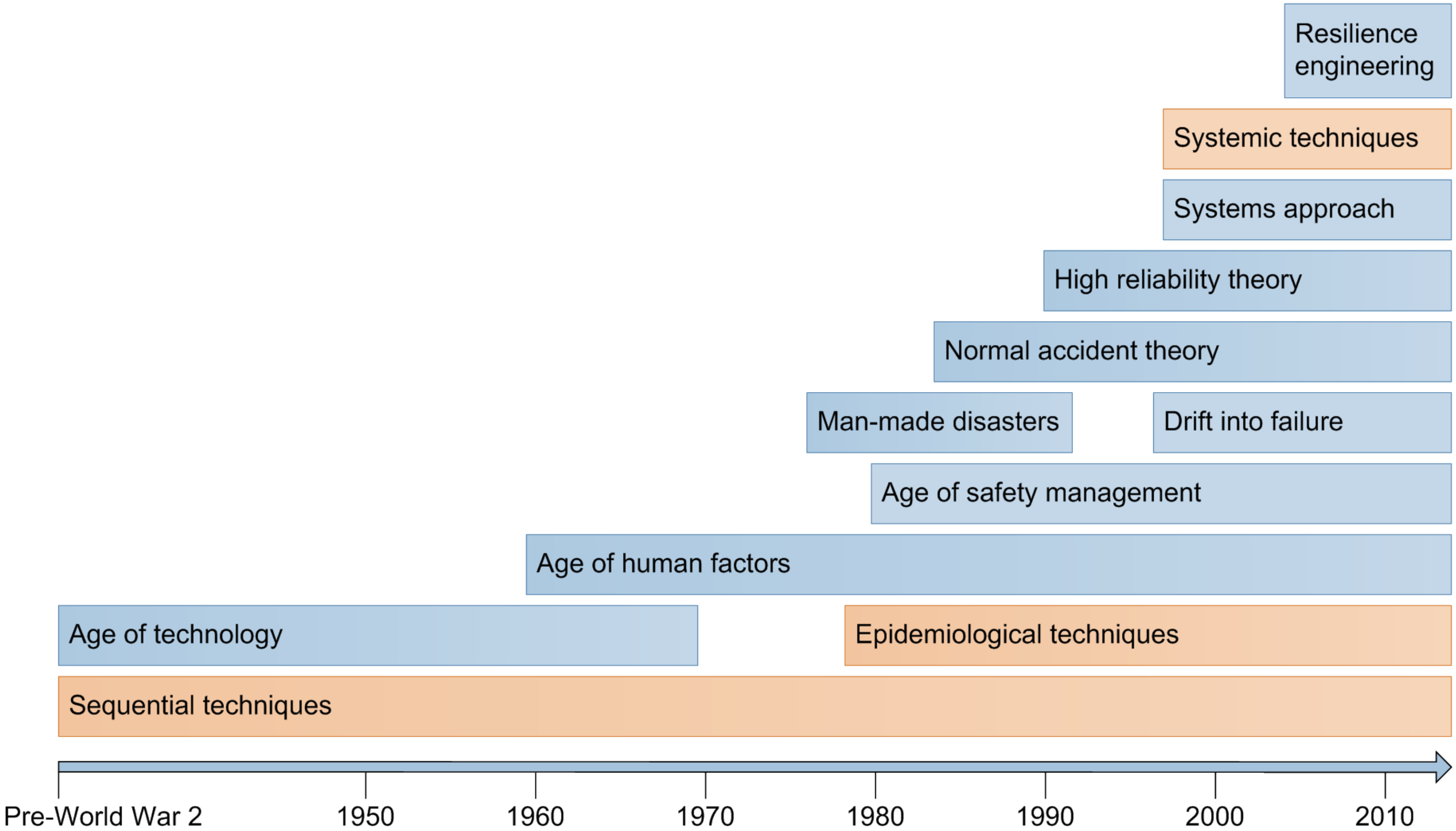

Figure 8 - Development of accident causation theories and analysis techniques

2.5 The systemic accident analysis research-practice gap

2.5.1 Existing evidence of a research-practice gap

Despite the proposed advantages of SAA, there is evidence within the scientific literature to suggest that methods and tools employing a systemic perspective are not being adopted in practice. Some researchers (e.g. Carhart and Yearworth, 2010; Dien et al., 2012; Leveson, 2012)[1] comment that the most commonly used tools for accident analysis are based on linear, reductionist models of systems and causality. Furthermore, other researchers note that SAA and its related techniques, e.g. STAMP, are yet to gain acceptance outside of the research community (e.g. Hollnagel et al., 2008; Okstad et al., 2012; Read et al., 2013; Salmon et al., 2012a; Salmon et al., 2012b). These observations are supported by the sequential understanding of accident causation presented within various elements of the practitioner-focused safety literature (e.g. Energy Institute, 2008; Health and Safety Executive, 2004; Rail Safety and Standards Board, 2011) and the focus on 'sharp end' factors within investigation reports (e.g. Cedergren and Petersen, 2011; Schröder-Hinrichs et al., 2011). The seemingly different analysis approaches taken by the researcher and practitioner communities suggest that an RPG exists in the domain of SAA. However, as noted in Section 1.1, there is no defined explanation for the presence of this gap, nor an understanding of its extent or how it could be bridged.

As described in Sections 2.3 and 2.4.3, the need for SAA has been widely acknowledged throughout the research community. There is also evidence to suggest that a desire to adopt SAA techniques exists within sections of the practitioner community. For example, accident investigators within aviation

[1] Since commencing the PhD in October 2010, a number of publications (e.g. Hollnagel, 2012; Leveson, 2012; Read et al., 2013; Stanton et al., 2012) have been released which relate to the research contained in this thesis. These recent publications are cited in this chapter, as they support the evidence that was available at the start of the PhD and which motivated the research contained in the thesis. However, had they been available at an earlier time, some of them would have also influenced the data collection process. Consequently, the impact of such publications on the studies presented in the thesis will be discussed, where relevant, in the study-based chapters (Chapters 3–6). This is done to demonstrate that, at the time the PhD studies were conducted, they were based on an up-to-date knowledge of the accident analysis literature and, therefore, that they provided an original contribution to knowledge (which is evidenced by the fact that three of the four studies presented in the thesis have been written as peer-reviewed publications).

have begun to recognise the need to look beyond sequential analysis methods (Martinez, 2011 p.8). Furthermore, Steele and Pariès (2006) suggest that many practitioners acknowledge the limitations of traditional models and are keen to apply new techniques. Given that a demand to apply SAA seems to exist in both the researcher and practitioner communities, the RPG needs to be examined in more depth.

2.5.2 Studying the research-practice gap

An RPG signifies the impairment of transferring a new idea, practice or object between the research and practice communities. The transference process itself, sometimes termed the ‘diffusion of innovation’, has been the focus of numerous studies across various domains for over 50 years, e.g. healthcare (Wolfe, 2012), sports medicine (Richardson, 2011), human factors (Waterson and Anderson, 2013), management science (Bansal et al., 2012) and human resource management (Aguinis and Lawal, 2013). A number of theories and models about the nature of innovation diffusion have also been produced (e.g. Bass, 1969; Greenhalgh et al., 2004; Rogers, 2003; Wandersman et al., 2008). Figure 9 shows Roger’s (2003) interpretation of the diffusion process.

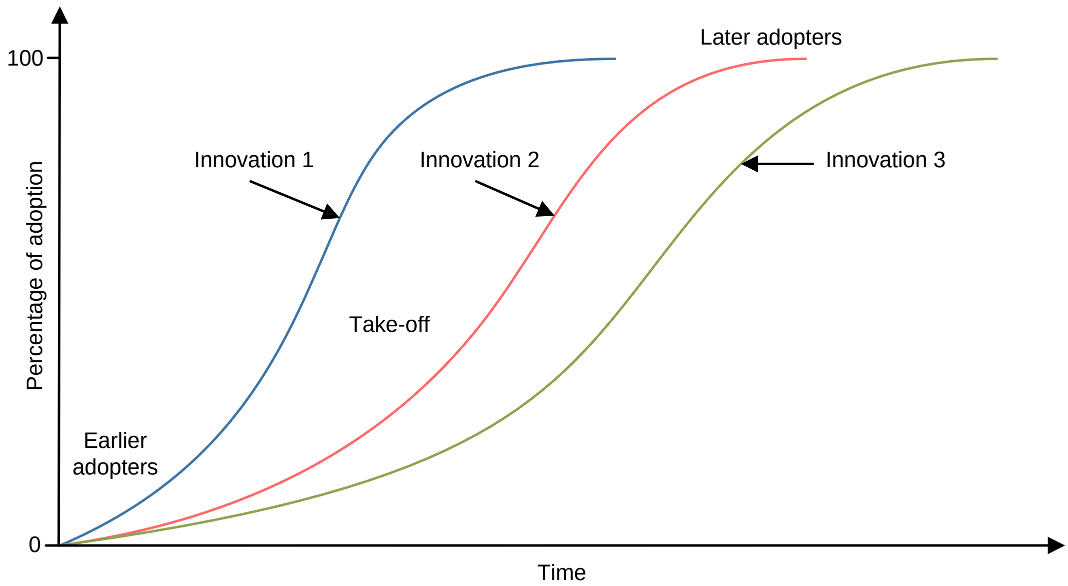

Figure 9 - Diffusion of innovation process. Adapted from Rogers (2003).

Researchers in different traditions have conceptualised, explained and investigated the diffusion of innovations in various different ways

(Greenhalgh et al., 2005). In addition to the diffusion of innovation literature, research concerned with the adoption and utilisation of innovations exists in well-established fields such as: technology adoption (e.g. Dercon and Christiaensen, 2011; Karahanna et al., 1999; Katz and Shapiro, 1986), STS research (e.g. Coiera, 2007; Eason, 2007; Luna-Reyes et al., 2005) and participatory-based research (Holmström et al., 2009; Kenny et al., 2012; Moore et al., 2012).

Although there is a wealth of innovation diffusion research to draw from when studying RPGs, it is important that the context in which the theory is applied matches the context in which it was developed (Fichman, 1992). Therefore, whilst aspects of this research were utilised when considered suitable (e.g. utilising a quasi-action research approach in Study 4), it was judged appropriate to base the work of this PhD within the context of the existing safety literature. Within the domain of safety, the study of factors which can impact on the adoption and usage of accident analysis techniques has mainly focused on two topics: (1) evaluating analysis methods and (2) examining issues which influence the analysis processes used by investigators.

Previous studies have developed methods to evaluate various theoretical and practical aspects of analysis tools (e.g. Benner, 1985; Harvey, 1985; Katsakiori et al., 2009; Lehto and Salvendy, 1991; Sklet, 2004; Wagenaar and van der Schrier, 1997). Other research has applied different analysis methods to accident case studies to examine whether they can provide additional safety insights (e.g. Herrera and Woltjer, 2010; Jenkins et al., 2010; Johnson and Holloway, 2003) and/or if they are suitable for use in a given industry (e.g. Salmon et al., 2010a; Woltjer et al., 2006). Collectively, this research examines the strengths and weaknesses of various techniques to inform their selection and usage. A wide range of analysis method characteristics are addressed in the literature which include issues such as validity and reliability, usability and resource requirements. Whilst various SAA methods have been used to perform accident case study analysis (e.g. Herrera and Woltjer, 2010; Jenkins et al., 2010; Salmon et al., 2010a), few studies have formally examined these techniques via defined, structured approaches (e.g. Branford, 2007; Sklet, 2004) or compared systemic techniques against each other (e.g. Johnson and de Almeida, 2008; Waterson and Jenkins, 2011). Moreover, none of these studies have examined the techniques to understand why they have not been accepted by the practitioner community. Therefore, an opportunity exists to develop a more detailed understanding of the SAA methods and how their characteristics may contribute to the RPG.

Generic factors which can influence a practitioner's approach to accident analysis have been identified, such as investigator bias, availability of data and resource constraints (e.g. Johnson, 2003; Kouabenan, 2009; Lundberg et al., 2010; Rollenhagen et al., 2010). These influences can arguably lead practitioners away from the theoretical ideal of accident investigation and therefore contribute to an RPG (Lundberg et al., 2010). However, the analysis processes of practitioners and the issues which affect them have yet to be examined with regards to how they may contribute to a gap. This represents another opportunity to establish the nature of the SAA RPG. The need to examine the characteristics of the SAA methods, the factors which influence the analysis activities of practitioners and the contribution they make to the SAA RPG provides the starting point for the research contained in this thesis. These issues are addressed in the following two chapters.

2.5.3 The wider research-practice gap context

Although the work contained in this thesis is placed within the context of the safety literature it is useful to understand how it relates to the RPG literature in general. Due to resource constraints, a comprehensive review of RPGs will not be given here. However, examining some of the recent literature (2011 onwards), which specifically addresses RPGs, highlights some important points (see Appendix 2.1 for search criteria and results). Firstly, as shown in Figure 10, RPGs in healthcare have received the majority of interest from researchers.

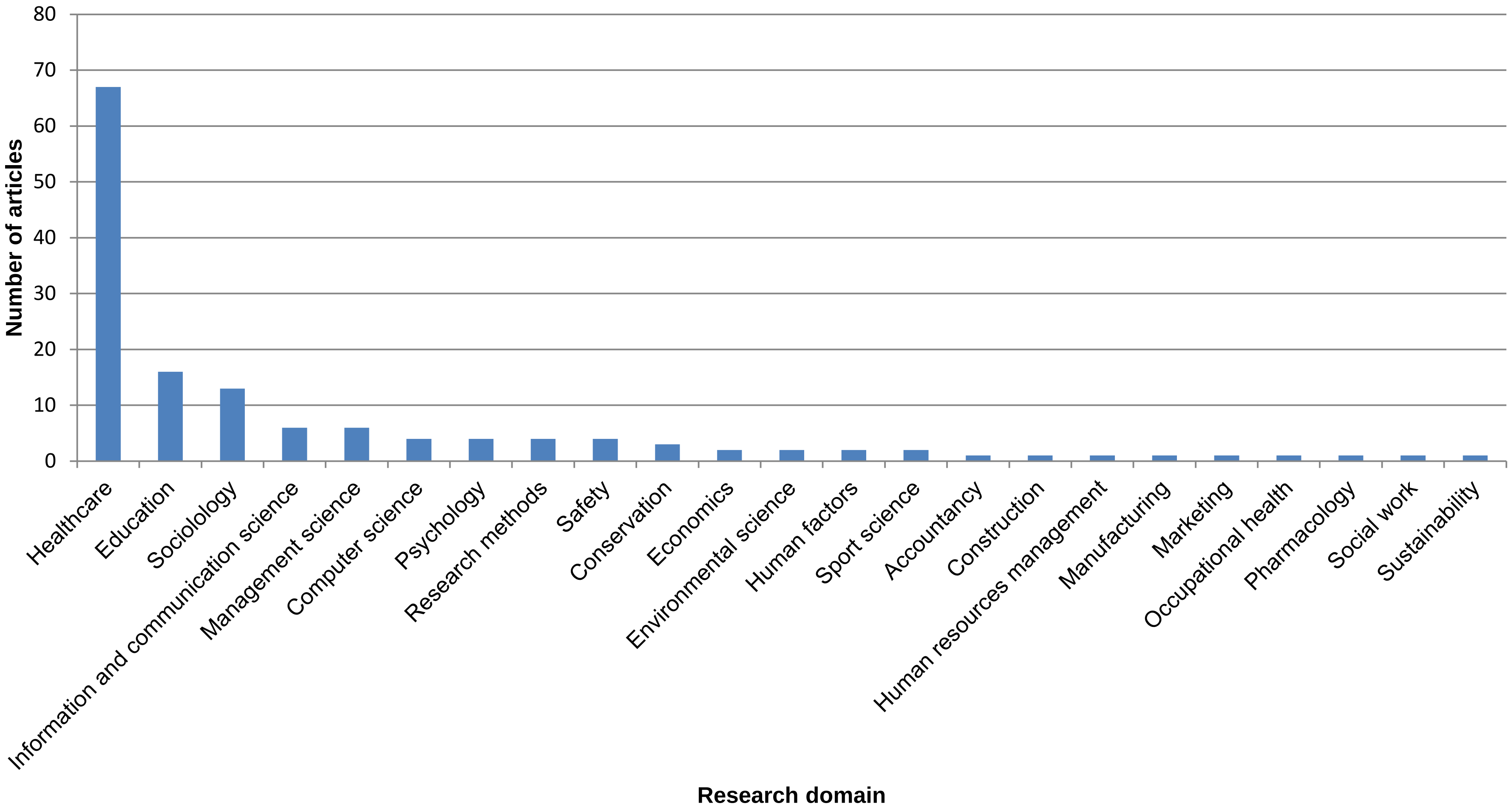

Figure 10 - Research-practice gap literature summary

Notably, only four articles (Groth and Swiler, 2013; Hanson et al., 2012; Lord et al., 2011; Noonan et al., 2011) were related to safety and none addressed the SAA RPG. In fact, a search of the Science Direct and Web of Science databases indicates that no research articles have been published on the overall nature of RPGs in accident analysis or investigation since 2000, apart from those associated with this thesis (Underwood and Waterson, 2013a; Underwood and Waterson, 2013b) (see Appendix 2.1 for search criteria and results). This suggests, therefore, that the knowledge presented in this thesis, as well as providing an original contribution to the field of accident analysis, adds to the existing RPG research.

Secondly, analysis of the recent literature reveals that a wide range of issues are cited as factors which contribute to the existence of RPGs (see Table 2). Furthermore, a number of solutions for bridging these gaps are provided (see Table 3).

Reasons for gap		% of articles citing reason	
Research not linked to practice	Inadequate research	6.9	25.3
	Theory is not empirically validated	6.9	
	Practitioner needs not considered	5.7	
	Historic lack of researcher interest in certain practice activities	3.4	
	Researchers lack practical experience	2.3	
Resources	Resource limitations	13.8	17.2
	Cost of implementing research too great	2.3	
	Guidance material not designed for practitioners	1.1	
Training	Inadequate training	5.7	17.2
	Lack of training	4.6	
	Insufficient theory in practitioner training	3.4	
	Practitioner training format	3.4	
Communication	Theory can be too complex	3.4	14.9
	Inadequate communication of research	2.3	
	Practitioner lack of awareness of research	2.3	
	Inadequate communication at organisational level	1.1	
	Lack of access to research information	1.1	
	Lack of communication networks	1.1	
	Lack of knowledge sharing	1.1	
	Researchers cannot decide what information to communicate	1.1	
	Too much research information available	1.1	
Practice not influenced by research	Insufficient practitioner knowledge	10.3	13.8
	Practitioners rely on experience rather than theory	2.3	
	"One size does not fit all" approach to applying research	1.1	
Practitioner biases	Cultural attitude of practitioners	4.6	6.9
	Learning style	1.1	
	Personal preference	1.1	
Industry influences	Nature of industry	2.3	4.6
	Practice affected by industry needs	1.1	
	Regulations do not reflect research	1.1	

Table 2 - Reasons cited for research-practice gaps

Methods of bridging the gap		% of times method cited	
Increase amount of research applied by practitioners	Improve practitioner training	23.3	31.7
	Organisational commitment to change	3.3	
	Base practice on research	1.7	
	Create research 'champions' in practice	1.7	
	Work systems and technologies based on research	1.7	
Improve communication of knowledge	Knowledge exchange meetings involving researchers and practitioners	6.7	25.0
	Increase dissemination of information	5.0	
	Literature developed for practitioners	5.0	
	Increase availability of research information	3.3	
	Create journal clubs for practitioners	1.7	
	Informal networks	1.7	
	Integrate research databases	1.7	
Researcher-practitioner engagement	Create research-practice partnerships	13.3	25.0
	Recruit practitioners into research	5.0	
	Researchers spend time in practitioner environment	3.3	
	Incentivise researchers to engage with practitioners	1.7	
	Job swaps	1.7	
Practice-focused research	Research designed around conditions experience in practice	6.7	18.3
	Set new research agendas	6.7	
	Models consider practitioner needs	3.3	
	Increase researcher awareness of subject	1.7	

Table 3 - Methods of bridging research-practice gaps

Given that the SAA RPG has not been examined in any great detail, it has yet to be determined whether all of the suggested reasons for RPGs existing listed in Table 2 will be present. Also, it is not known which of the methods for bridging the gap described in Table 3 will be relevant. However, as indicated by the research presented in Section 2.5.2, some of the contributing factors described in Table 2 are also observed in accident analysis, e.g. investigator bias and resource constraints. Therefore, it is possible that the SAA RPG shares other characteristics with gaps in different domains. Identifying areas of similarity via a more detailed examination of the SAA RPG may be able to provide insights into how the gap should be bridged, if indeed it needs to be; a topic which is addressed in Chapter 7.

Chapter 3 – Study 1: Evaluating the systemic accident analysis models, methods and literature

3.1 Chapter overview

This chapter provides an evaluation of the SAA literature and analysis techniques in order to understand how their characteristics contribute to the SAA RPG. This evaluation begins by examining how the SAA literature incorporates and presents the core concepts of systems theory. A systematic search is then conducted to identify examples of SAA models and methods. The three most popular techniques are assessed via an evaluation framework, which considers their development process as well as their systems approach and usage characteristics. The findings of the study are subsequently discussed to highlight a number of factors which may influence the SAA RPG.

3.2 Introduction

As described in Section 2.5.1, a need exists to examine the SAA RPG. As the gap has yet to be studied in any great detail what is needed to ascertain the factors that contribute to it? An appropriate starting point is the systematic evaluation of the SAA methods to examine how their theoretical and practical characteristics may hinder their adoption and usage (see Section 2.5.2). Indeed, the importance of understanding how an innovation's characteristics affects its integration into practice has been discussed at length within the RPG literature (e.g. Agarwal and Prasad, 1997; Damanpour and Schneider, 2009; Rogers, 2003; Smit et al., 2013; Tornatzky and Klein, 1982; Zaltman et al., 1973).

Previous studies (e.g. Salmon et al., 2010a; Sklet, 2004) have examined some characteristics of SAA models and methods, such as their training and usage resource requirements (see Section 2.5.2). Whilst these studies provide an insight into some of the characteristics which may influence the SAA RPG, they do not examine their contribution to the gap. Furthermore, the research conducted to date is far from extensive, e.g. it is not yet clear how many SAA techniques have been developed by the research community or how they compare with one another. Therefore, a more detailed investigation of the SAA technique characteristics is required to understand how they influence the SAA RPG.

Additionally, the SAA innovation is not just a range of analysis techniques. It also includes a body of literature which presents systems theory and its applicability to accident analysis. Therefore, examining the characteristics of the systemic methods only provides a partial description of the SAA innovation: it is also important to understand how much of the systems approach is incorporated within the SAA literature, how it is presented and how this may affect the RPG.

3.2.1 Study aim and objectives

The overall aim of the study was to evaluate the characteristics of the 'SAA innovation' to understand how they contribute to the SAA RPG. As the innovation consists of two key elements (the SAA literature and systemic analysis techniques), a number of objectives were established to achieve this aim:

- Identify the key components of systems theory
- Examine the SAA literature to identify which systems theory components are contained in the literature and how they are portrayed
- Review the scientific literature to identify the available systemic models and methods
- Conduct a citation analysis to assess the relative popularity of the SAA techniques within the research community
- Evaluate the most popular systemic analysis tools to identify factors which may influence their adoption and usage

3.3 Methods

3.3.1 System theory component identification

In order to understand how much systems theory is incorporated within the SAA literature and techniques, it was necessary to identify the core components of systems theory. This was achieved via electronic database searches, reference and citation tracking and personal knowledge of the relevant literature, in order to promote a systematic approach (Fink, 2010; Greenhalgh and Peacock, 2005; Hart, 1998). In order to understand the fundamental aspects of systems theory, the original article on 'General System Theory' (von Bertalanffy, 1950) was initially studied. Citation tracking of the article was subsequently employed using the ISI Web of Knowledge, Scopus and Google Scholar databases to gain an insight into the development and applications of the theory. This information was supplemented with electronic searching for systems theory related documents using the Science Direct, PsychINFO, MEDLINE and Google Scholar databases. The search was restricted to articles published in English since 1950. The bibliographies of seminal documents (e.g. Senge, 2006; Skyttner, 2005) were examined and references focused on systems theory were included in the search results. The literature gathered via these differing search methods was examined using an inductive thematic analysis approach, as described by Braun and Clarke (2006), in order to identify the core components of systems theory. The findings of this analysis are summarised in Section 2.3.2 in order to provide a context for the PhD research. However, the methods used to obtain this information are presented here to demonstrate the systematic nature of the approach taken.

3.3.2 SAA literature identification

The search for systems theory interpretation within the accident analysis literature was restricted to 22 safety, systems engineering and ergonomics related journals. This sample of journals was selected in order to generate pertinent results and was searchable within the ScienceDirect database[2]. The search string incorporated the terms 'accident', analysis', 'systems' and 'theory', as well as synonyms and truncated phrases (see Appendix 3.1 for details of the search criteria). To promote the creation of relevant results the search was restricted to the document title, abstract and key words list. The time span of the search commenced from the first available publication of each journal, to capture the highest number of relevant articles and enable a more comprehensive analysis of systems approach application. Review and

[2] The search was restricted to the use of the ScienceDirect website as other databases (e.g. Web of Science and Google Scholar) did not have the functionality required to effectively discriminate between safety and non-safety related articles.

model evaluation articles (e.g. Katsakiori et al., 2009; Qureshi, 2007; Sklet, 2004) were also used to identify key documents within the field. Reference and citation tracking was subsequently employed using the ISI Web of Knowledge, Scopus and Google Scholar databases to discover additional articles. Only documents printed in English were included in the search results. A theoretical (i.e. deductive) thematic analysis of the literature, as defined by Braun and Clarke (2006), was conducted using the core components of systems theory (see Section 2.3.2) as a coding template.

3.3.3 SAA model and method identification

A systematic electronic search for documents referencing SAA techniques was conducted in the 22 safety journals used to perform the SAA literature identification (see Section 3.3.2). All of the journals were examined within the ScienceDirect database in order to generate relevant results[2]. All available issues of the journals were interrogated with a search string which included synonyms and truncations of 'accident', 'analysis', 'model' and 'system' (see Appendix 3.1 for details of the search criteria). In order to increase the relevance of the results, the search was restricted to the document title, abstract and key words list. The results were combined with those gained from reference and citation tracking of key review and model evaluation articles (e.g. Sklet, 2004) and personal knowledge of the literature. A manual examination of the documents followed, in order to identify examples of systemic analysis tools.

Only models and methods explicitly described as being based on systems theory were considered for further analysis. Some methods purport to be systemic tools, however, in reality they are either sequential or epidemiological in nature, e.g. SOAM, which is underpinned by the SCM. This exclusion criterion was, therefore, set in order to ensure the shortlisted models were relevant to the study of the SAA RPG. In addition, only techniques that were specifically designed for use in accident analysis or risk assessment were included in the subsequent evaluation. Whilst some systemic models have been applied to accident research, e.g. causal loop diagrams (e.g. Goh et al., 2010; Goh et al., 2012), they are generic tools which have been utilised in other research fields. This exclusion criterion was, therefore, employed to maintain a focused scope to the study.

A search of the Science Direct, PsychINFO, MEDLINE and Google Scholar databases was subsequently conducted to identify the number of citations received by each SAA technique. The search terms ‘accident’, ‘disaster’ and ‘incident’ and their truncations were combined with the full name or known acronym of the model to reduce the likelihood of detecting articles unrelated to accident analysis (see Appendix 3.1 for details of the search criteria). The most frequently cited techniques were shortlisted for further analysis, via the evaluation framework described in Section 3.3.4. Other selection criteria have been used in previous studies, such as whether the tool was recently developed (e.g. Sklet, 2004). However, citation count ranking was chosen as it provides a measure of a model’s relative popularity and, therefore, the likelihood of its awareness within the practitioner community.

3.3.4 Model evaluation

As described in Section 2.5.2, a number of studies have developed methods to systematically evaluate various theoretical and practical aspects of accident analysis tools (e.g. Benner, 1985; Katsakiori et al., 2009). Some of these methods incorporate elements of the systems approach, such as the amount of the system hierarchy examined by the analysis technique (e.g. Sklet, 2004). None, however, consider the systems approach in its entirety. An evaluation framework, based on both theoretical and practical considerations, was designed to resolve this; the details of which are described in the remainder of Section 3.3.4.

3.3.4.1 Model development process

Consideration was given to the development of the analysis tools, which Bamber (2003 p.240) states involves four stages: (1) clearly define the analysis problem(s); (2) build a system diagram; (3) evaluate and test the system model using previously solved situations; (4) use the model on new problems. In addition, Wahlström (1988 p.163) comments that a modelling approach should be selected, a distinction made between the model and environment and that sub-models, variables and their relationships should be identified before the model is constructed. Cumulatively, these stages represent the general scheme that is followed when producing any system model (Wahlström, 1988 p.163). If the development of an SAA technique has not fulfilled a given stage of this process it may help to explain why it has not been accepted by the practitioner community. The following components were, therefore, included in the framework:

- Problem definition – is the reason for creating the model well defined, e.g. the need for a more detailed analysis of system control mechanisms?
- Modelling approach selection – what conceptual approach has been adopted?
- System model creation – how is the system graphically represented by the model?
- Model validation – how has the validity and reliability of the model been tested and demonstrated?
- Model usage – how has the model been used previously?

Based on the model development stages suggested by Wahlström (1988 p.163), it should also be determined whether an SAA technique has adequately examined the system's environmental boundary, hierarchy and component relationships. However, as these criteria are core elements of the systems approach they will be addressed in the following section of the evaluation framework.

3.3.4.2 Systems approach characteristics

The ability of an analysis model to employ the systems approach is governed by the number of the core systems theory concepts it incorporates (see Section 2.3.2). Therefore, the shortlisted techniques were analysed to identify how they address a system's structure, component relationships and behaviour:

- System structure – how does the model represent a system's hierarchy and component differentiation?
- System component relationships – how are the interactions between system components analysed?

- System behaviour – how does the model address the various factors which affect safety, e.g. controlling the transformation of system inputs?

3.3.4.3 Model usage characteristics

Establishing whether a given analysis technique is theoretically underpinned by systems theory concepts is only one factor that will determine if an individual can effectively perform SAA. A number of researchers have identified a range of other issues which can hinder the usage of analysis methods (e.g. usability and resource requirements) (Benner, 1985; Katsakiori et al., 2009) and the evaluation framework was designed to reflect this. This final section of the framework was developed in two stages. Initially, existing evaluation methods were reviewed (e.g. Benner, 1985; Katsakiori et al., 2009; Sgourou et al., 2010; Sklet, 2004) and the relevant usage-related components were selected. The second phase involved a review of these components after each model evaluation. Exclusion of criteria was determined by whether they received little or no coverage in the systemic model literature. This exclusion process does not in itself distinguish between relevant and irrelevant factors; rather it highlights the issues that have received the most attention from researchers. Consequently, the analysis models were examined with regards to:

- Timeline consideration – how does the model incorporate the concept of time in the accident development process?
- Avoidance of blame – does the model direct the analyst towards identifying a root cause?
- Model compatibility – can the model be used in conjunction with other analysis techniques?
- Recommendation production – Does the model aid the analyst in producing safety recommendations and provide generic insights into accident causation?
- Resources required – what resources and data does the analyst require in order to use the model?
- Usability – what features of the model affect the analysis efficiency and effectiveness?

The evaluation framework is graphically summarised in Figure 11.

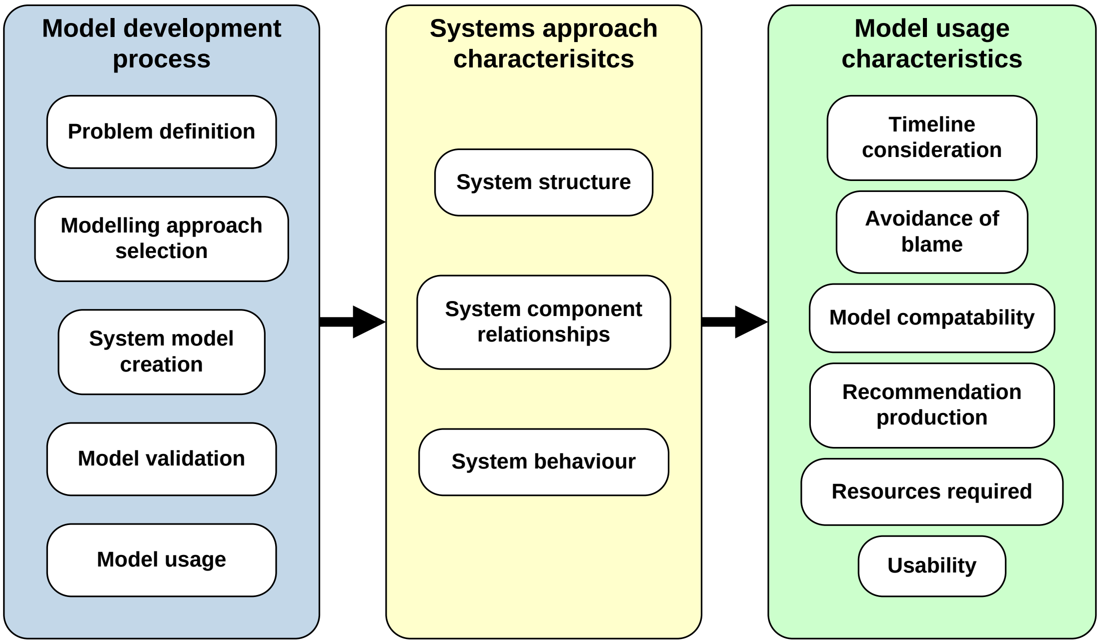

Figure 11 - Study 1 evaluation framework

The shortlisted SAA techniques were examined by performing a combined deductive and inductive thematic analysis of the literature pertaining to their development and usage, as described by Braun and Clarke (2006). The different evaluation framework criteria provided a coding template for the deductive analysis. An inductive approach was also taken to ensure that additional topics of interest would be recorded during the analysis. The analysis was conducted using NVivo 9.

3.4 Findings

3.4.1 Systems theory interpretation

This section provides details on the various aspects of systems theory discussed within the accident analysis literature.

3.4.1.1 System structure

Consideration of system structures within the literature is limited. The information that does exist focuses on defining the system hierarchy and its environmental boundary.

Defining the system hierarchy has been conducted at different levels of abstraction and from varying perspectives. For example, Abrahamsson et al. (2010) provide a general view by stating that real world systems can usually be modelled in a number of ways, depending on the purpose of the model and the requirements of the analyst, but will include a definition of the system's elements and its boundary. A general perspective is also provided by Lind (1988 p.273) who states that representing a system's hierarchy is achieved by studying its whole-part relationships. Other researchers offer a more safety-focused view of system hierarchies. For example, Leveson et al. (2009) propose that a primary characteristic of systemic analysis is the modelling and analysing of organisational safety structures. Furthermore, systems are modelled as a hierarchy of organisational levels, all of which contribute to accident causation and collectively define acceptable system performance and safety (Dekker, 2006; 2011 p.154; Leveson, 2011). A more detailed account of STS organisational hierarchies is provided by Rasmussen (1997) in the form of the Risk Management Framework (RMF) (see Figure 12). Rasmussen (1997) remarks that system models must be built using a system oriented approach based on control theoretic concepts. The RMF represents a control structure embedded within an STS and, as such, details six different organisational levels which affect the control of safety: (1) the system technology; (2) frontline staff; (3) management; (4) the company as a whole; (5) industry regulators; (6) the government.

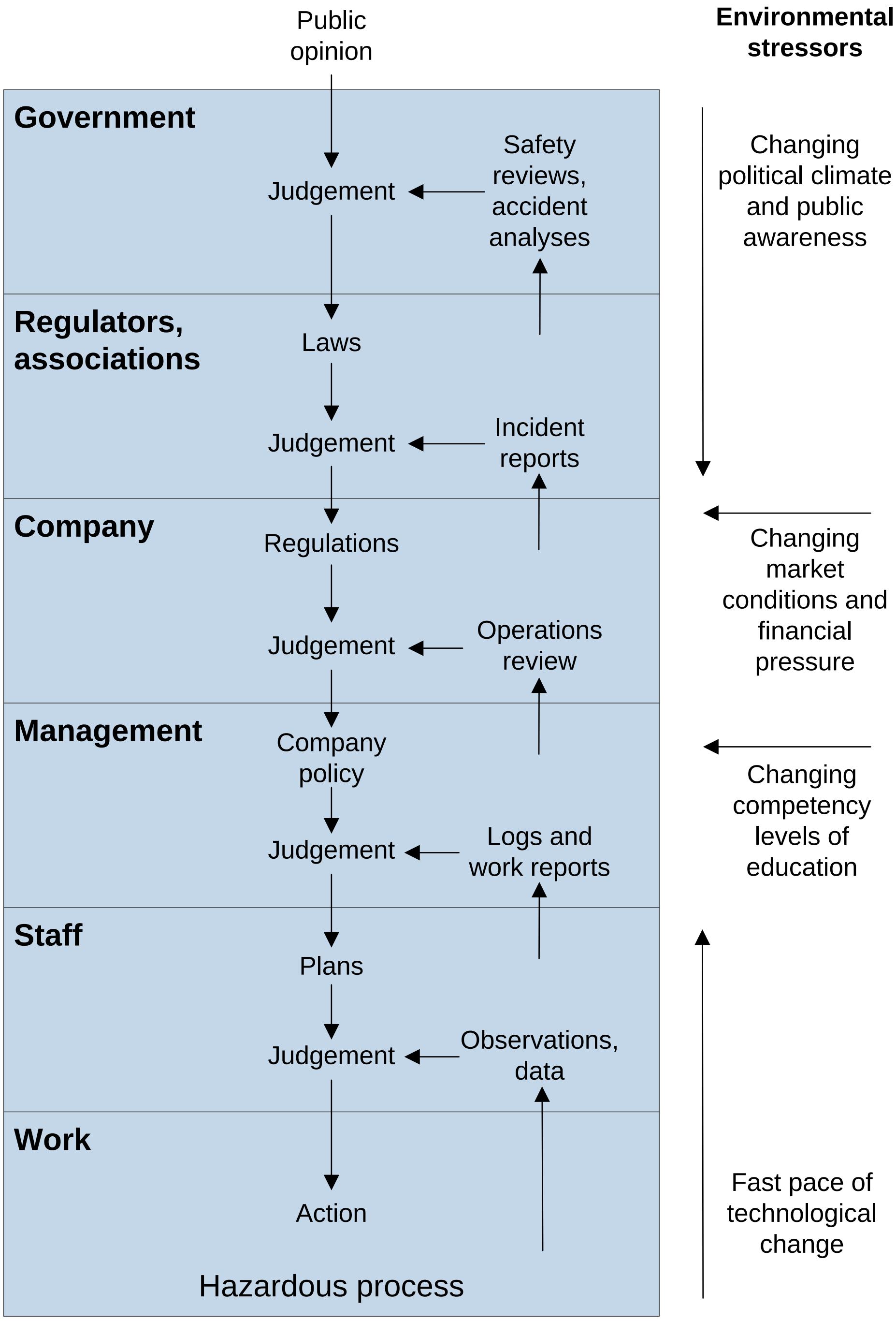

Figure 12 - Risk management framework. Adapted from Rasmussen (1997).

Defining the environmental boundary of a system is deemed as an important part of specifying the component hierarchy (Jönsson, 2007). This is a problematic process, however, as the boundary is unclear, inherently exclusionary and requires flexibility from the analyst (Dekker, 2011 p.136; Le Coze, 2005). Furthermore, the system 'environment' is generally referred to in a conceptual sense within the literature. However, in reality it has various facets. It is the physical landscape and climate, yet it also has political, societal, economic and technological dimensions. This is evidenced by researchers (e.g. Leveson, 2004; Rasmussen, 1997) who comment on issues such as the rapid pace of technological development, the aggressiveness of commercial markets and the changing regulatory and public views of safety.

Finally, the RMF, at a high level of abstraction, goes some way to addressing the differentiation, or specialisation, of the various system components. For example, company management is shown to be responsible for implementing organisational policy, whereas regulators are established to enforce governmental laws. There is, however, little specific attention given to the impact of differentiation on safety within the literature.

3.4.1.2 System component relationships

Considerably more attention has been paid to the concepts of holism and component relationships, when compared with the various aspects of system structure.

Various researchers, (e.g. Dekker, 2006 p.91; Leveson, 2011; Rasmussen, 1997), comment that systemic analysis concentrates on the whole system, rather than individual components. Indeed, Leveson et al. (2009) suggest that this is a primary characteristic of SAA. Only by considering the design and analysis of systems as whole entities can the emergent properties which give rise to accidents be studied (Dekker, 2006 p.96; Leveson, 2009 [cited in Leveson, 2011]). Consequently, the need to incorporate holism and, therefore, emergence into analysis tools has been made explicit by some researchers (e.g. Carhart and Yearworth, 2010; Dekker, 2006 p.91; Hollnagel and Goteman, 2004; Leveson, 2004).

The idea that safety and accidents are emergent phenomena of a system is widely acknowledged within the literature. Researchers (e.g. Cassano-Piche et al., 2009; Holden, 2009; Hollnagel et al., 2008; Leveson et al., 2009; Marais et al., 2004; Woo and Vicente, 2003; Woods and Cook, 2002), describe safety as such, whereas other authors (e.g. Hollnagel, 2004 p.59; Hollnagel and Goteman, 2004) refer specifically to accidents. The emergent properties of a system are a result of the relationships between its components and cannot, therefore, be understood by examining the components in isolation (Dekker, 2011 p138; Sinclair, 2007). Indeed, much of the meaning of system components arises from their relationships (Lind, 1988). As a result, the systems approach places a high importance on studying component interaction (Carhart and Yearworth, 2010). Accident analysis tools should, therefore, facilitate the study of interactions between all elements of the STS (Bamber, 2003; Leveson, 2004).

3.4.1.3 System behaviour

The majority of interest in system behaviour is centred on the nature and control of processes as well as the influence of the environment.

Various researchers (e.g. Carhart and Yearworth, 2010; Dekker, 2006 p.92; Hollnagel, 2004 p.62; Le Coze, 2005) comment that the processes and interactions of system components are non-linear in nature. This means that system inputs (causes) are not proportional to the outputs (effects) and that one cause can have numerous different effects (Hollnagel, 2004 p.62; Le Coze, 2005). This discussion within the literature, in a general sense, covers the issues of component inputs and outputs, their transformation processes and multifinality.

Consideration of system entropy is largely implicit within the literature, as a number of researchers refer to the fact that STS interact with their environment (e.g. Dekker et al., 2011 p.138; Le Coze, 2005; Mayntz, 1997 [cited in Choularton, 2001]). Due to this interaction, Jönsson (2007) states that it is insufficient to ignore the environmental context of a system. This is supported by the notion that environmental conditions can affect the goal seeking nature of systems. The environment places requirements for successful adaptation on the system and thereby interacts with the system goals, although requirements and goals are not always aligned (Dekker, 2011 p.154; Lind, 1988 p.275).

Alongside the idea that emergent system properties exist as a result of component interactions (see Section 3.4.1.2), the significance of feedback and control is the most frequently discussed systems approach issue. The feedback and control present in an organisation are deemed to be critical influences on system capability and failure (Mayntz, 1997; Sinclair, 2007; Woods and Cook, 2002). Goh et al. (2010) even describe feedback as the 'foundation of systems thinking'. Rasmussen (1997) takes the view that risk management is a control problem and must be conducted by taking a systems approach based around control theoretic concepts, e.g. the discrepancy-reducing feedback loop. The explicit need for analysis models to consider control, as well as emergence, is discussed by several researchers. For example, Dekker (2006 p.91) comments that the fundamental concepts underpinning systemic models are emergence and control. Considering safety as an emergent property necessitates analysis models treating accidents as examples of inadequate control; tools which do not do this are inherently limited (Carhart and Yearworth, 2010; Leveson, 2004).

The study of system behaviour dictates that consideration must be given to changes that occur over time. The fact that STS are influenced by their environment and internal processes means that their behaviour is dynamic and path dependent (Dekker, 2011 p.149). The constantly changing environment and the subsequent impact on system functions also cause hazards and their management to change (Woods and Cook, 2002). Although these new demands on system safety may be met, they may also stress the functioning of a system to the point of failure (Sinclair, 2007).

3.4.2 Model identification and evaluation

A total of 13 systemic models were identified within the 449 non-duplicated articles collected during the literature search described in Section 3.3.3. Performing a citation search for these techniques revealed a total of 476 documents[3], which were manually searched for explicit references to the models. The three most frequently cited models (STAMP, FRAM and AcciMap) accounted for 89.8 % of the 302 explicit references identified within the 476 documents and were selected for additional evaluation (see Table 4). The remaining models were discounted from further analysis. The rest of

[3] Document count excludes the articles in which the models and methods were first published in, duplicate articles and those unrelated to accident analysis

Section 3.4.2 provides details of the STAMP, FRAM and AcciMap evaluations.

Model	**Created by**	**Year**	**Explicit citations**	**% explicit citations**
STAMP	Leveson	2004	157	52.0
FRAM	Hollnagel	2004	60	19.9
AcciMap	Rasmussen and Svedung	1996	54	17.9
Deviation model/deviation concept	Kjellen	1984	17	5.6
Formal System Model	Watson	1984	8	2.6
Occupation Accident Genesis model	LaFlamme	1990	3	1.0
Delft Framework	Hale et al.	1997	2	0.7
Car-Driver Model	Rockwell	1972	1	0.3
Systems Model of Software Development Failure	McBride	2008	0	0.0
IPICA	Ferjencik	2011	0	0.0
WSR Model	Hall and Silva	2008	0	0.0
STAMP-VSM	Kontgiannis and Malakis	2011	0	0.0
Risk Management Systems Model	Bamber	2003	0	0.0

Table 4 - SAA model citation analysis

3.4.2.1 STAMP model development process

Problem definition

Accidents, from the systems approach perspective, occur due to the inadequate control of external disturbances, component failures or dysfunctional component interactions (Leveson, 2004). Therefore, understanding why accidents occur requires analysis of the control structure and its ineffectiveness, rather than individual element failure. STAMP is designed to meet this need.

Modelling approach

Three basic concepts are used by STAMP to analyse the breakdown of control structures: (1) constraints, (2) control loops and process models; (3) levels of control. Inclusion of these features allows the model to describe systems and accidents in terms of ‘a hierarchy of control based on adaptive feedback mechanisms’ (Leveson, 2004). A key element of the STAMP analysis approach is the idea that systems behave dynamically. The model, therefore, assesses why such changes in system state are present and how they could lead to conditions where an accident could occur (Ferjencik, 2011).

System model creation

No formalised procedure exists for creating a system model with STAMP and variation exists in the guidance that is provided (e.g. Ferjencik, 2011; Hollnagel, 2008; Johnson and de Almeida, 2008; Kontogiannis and Malakis, 2012; Qureshi, 2007)[4]. The typical graphical representation of the system is a tiered control structure, based on the RMF (see Figure 12), consisting of nodes (system components) linked by arrows, which symbolise feedback loops (see Figure 13). A STAMP analysis also involves examining control loop performance using a control flaw classification scheme (see Figure 14), which can result in the creation of multiple diagrams (e.g. Arnold, 2009; Ouyang et al., 2010). At present, a method for providing a structured presentation of STAMP’s analysis results is not available (Hollnagel and Speziali, 2008).

[4] Kontogiannis and Malakis (2012) was in press at the time of the STAMP evaluation

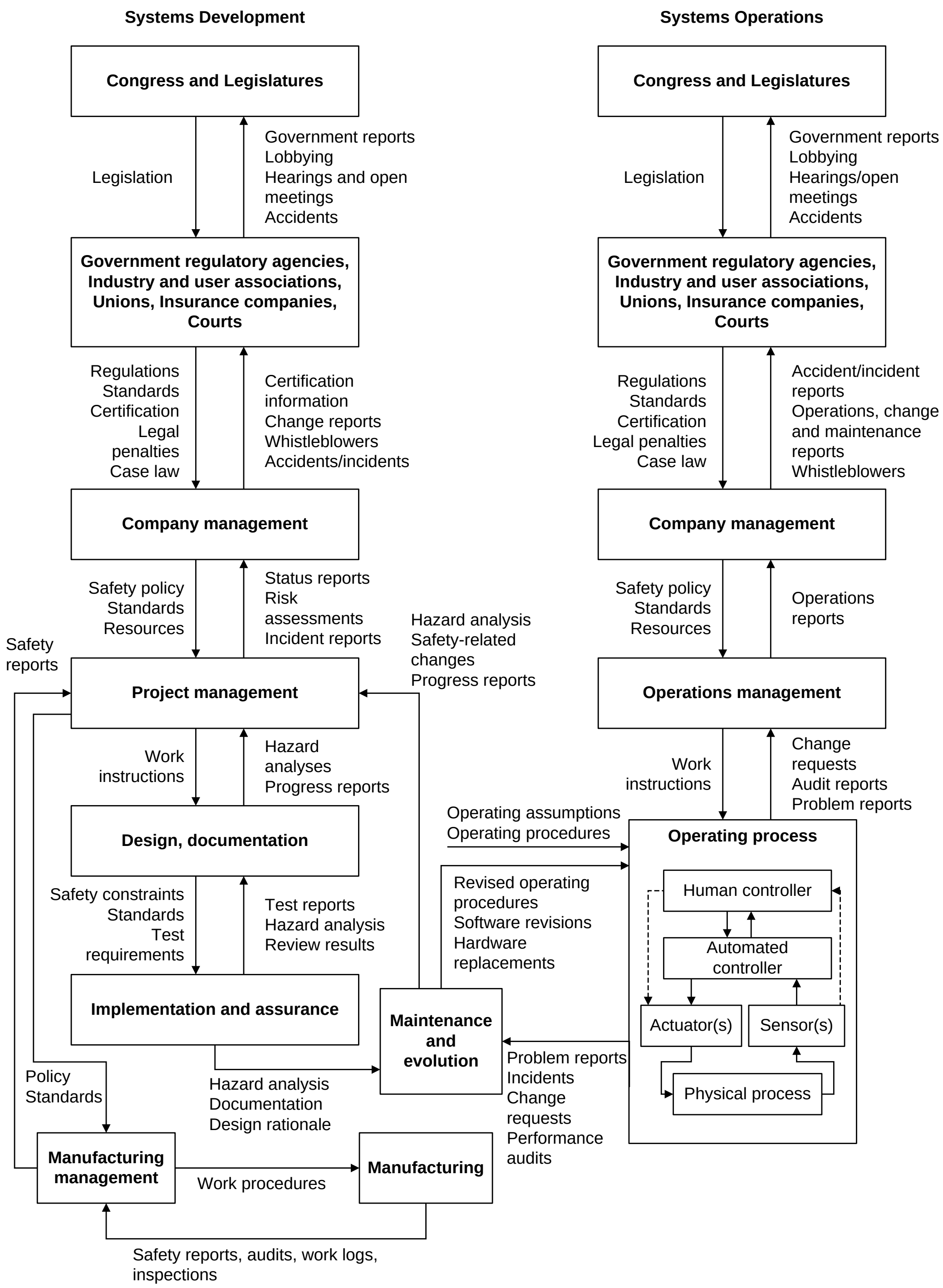

Figure 13 - General STS hierarchical safety control structure. Adapted from Leveson (2004).

Inadequate enforcement of constraints (control actions)

- Unidentified hazards
- Inappropriate, ineffective or missing control actions for identified hazards
  - Design of control algorithm (process) does not enforce constraints
    - Flaw(s) in creation process
    - Process changes without appropriate change in control algorithm (asynchronous evolution)
    - Incorrect modification or adaption
  - Process models inconsistent, incomplete or incorrect (lack of linkup)
  - Flaw(s) in creation
  - Flaw(s) in updating process (asynchronous evolution)
  - Time lags and measurement inaccuracies not accounted for
  - Inadequate coordination among controllers and decision makers (boundary and overlap areas)

Inadequate execution of control action

- Communication flaw
- Inadequate actuator operation
- Time lag

Inadequate or missing feedback

- Not provided in system design
- Communication flaw
- Time lag
- Inadequate sensor operation (incorrect or no information provided)

Figure 14 - STAMP control flaw classification. From Leveson (2004).

Model validation

Within the studies utilising STAMP, little work has been done to formally validate the model. Johnson and Holloway (2003) identified inter-rater reliability issues, as well as several validity and reliability related factors centred on the lack of structured analysis guidance. However, the authors state that their lack of prior experience in using STAMP may have influenced these findings and that the model was still under development at the time of testing. This developmental nature is still evident in subsequent studies (e.g. Ferjencik, 2011; Johnson and de Almeida, 2008; Kontogiannis and Malakis, 2012) and an evaluation of STAMP conducted by Hollnagel and Spezali

(2008) led the authors to declare that the model must still be considered as such.

Model usage

The generic approach to system analysis taken by STAMP makes it suitable for examining any type of STS and has resulted in its use in a variety of domains. Retrospective analysis has been conducted on aerospace (Johnson and Holloway, 2003; Johnson and de Almeida, 2008), water supply contamination (Leveson et al., 2003), train derailment (Ouyang et al., 2010) and military fratricide (Leveson et al., 2002) accidents. Leveson's (2004) notion that STAMP is also applicable for prospective risk assessment has been demonstrated by the development of the STAMP-based System-Theoretic Process Analysis (STPA) technique. This tool has been used, so far, to determine risk in aerospace operations (e.g. Ishimatsu et al., 2010; Owens et al., 2008; Stringfellow Herring et al., 2007).

3.4.2.2 STAMP systems approach characteristics

System structure

Consideration for system structure is a key feature of the STAMP approach. The system hierarchy is modelled as a control structure, based on the RMF, where each level represents a control process and control loop (see Figure 13) (Stringfellow Herring et al., 2007). Although Leveson (2004) makes various references to different environmental conditions, e.g. physical and operational, there is no explicit description of how STAMP represents the system boundary. Given that the model is based on the RMF it can be argued that the internal and external environments consist of the same elements considered by AcciMap (see Section 3.4.2.8). Consideration for component differentiation is implicitly addressed by STAMP, which analyses the varying contributions to safety made by the system components within the control structure.

System component relationships

STAMP places a clear emphasis on the interrelated nature of a system's components (Leveson, 2004). Such interactions are defined with respect to their impact on safety constraint control and are graphically represented by the feedback loop arrows connecting the system components (see Figure 13). Analysis of the whole system is encouraged by STAMP, as it focuses on the vertical relationships between groups at different levels in the hierarchy (Johnson and de Almeida, 2008). Indeed, Leveson (2004) comments that any analysis model which considers the entire STS must treat the system as a whole.

System behaviour

Examining system behaviour is a fundamental aspect of a STAMP analysis. The model treats a system as a dynamic process that continually adapts to achieve its ends and react to internal and external environmental changes (Leveson, 2004). Therefore, it deals with the inputs, outputs and transformation processes which influence the ability of the system to achieve its goals. This view of system behaviour, however, primarily focuses on how a system controls its processes. Entropy, via discussion of external environmental disturbances, is considered at a high level of abstraction by Leveson (2004). However, internal environmental conditions, such as company policies, have received the majority of attention from researchers (e.g. Johnson and de Almeida, 2008; Ouyang et al., 2010). STAMP analyses the control structure of a system at the time of an accident and, consequently, incorporation of equifinality and multifinality is not addressed by the model.

3.4.2.3 STAMP usage characteristics

Timeline consideration

A STAMP analysis does not incorporate a timeline: a control structure diagram represents a 'snapshot' of the system's dynamic control relationships and organisational constraints (Johnson and de Almeida, 2008). Creating a number of diagrams would, therefore, be necessary to show the changes in system state over time. Whilst not formally required by the STAMP analysis process, previous studies suggest that generating a sequence of events is a useful starting point prior to defining the control structure (see Johnson and Holloway, 2003; Johnson and de Almeida, 2008; Kontogiannis and Malakis, 2012).

Avoidance of blame

Leveson's (2004) comment that STAMP 'does not assign blame for the accident to a specific person or group' explicitly states the perspective of the model with regards to 'root cause' identification. Instead, the model views the cause of accidents as a lack of control of emergent behaviour throughout a system.

Model compatibility

STAMP was designed as a standalone accident analysis tool but Leveson (2004) suggests that it can be used as a basis for creating new hazard analysis and prevention techniques. However, besides STPA, it is unclear whether STAMP has been used to develop any hazard analysis tools. The ability to fuse STAMP with other models has been explored in retrospective analysis studies by Ferjencik (2011) and Kontogiannis and Malakis (2012). Ferjencik (2011) selected STAMP to augment the Root Cause Analysis (RCA) method, due to the inability of RCA to describe complex system relationships. Conversely, the Viable Systems Model was chosen by Kontogiannis and Malakis (2012) because of a perceived weakness of STAMP, i.e. a lack of consideration for general patterns of organisational breakdown. Both studies propose that combining STAMP with these other models produced greater safety insights than if the analysis tools had been used in isolation.

Recommendation production

STAMP does not automatically produce safety recommendations. Furthermore, although the model allows analysts to identify the flaws in the system control structure, it provides no means of prioritising them. However, STAMP was not designed to fulfil this need, as there is no scientific basis for such a prioritisation, and legitimate disagreements over the prioritisation process may exist due to the differing perspectives of stakeholders, e.g. regulators and line-management (Johnson and Holloway, 2003). STAMP has, however, been used by researchers to create general insights into different types of accidents (Johnson and de Almeida, 2008).

Resources required

Conflict exists within the literature regarding the training and expertise requirements of STAMP. It is claimed that the model requires considerable effort to use and is only suitable for experienced users with extensive theoretical and domain knowledge (Hollnagel and Speziali, 2008; Johansson and Lindgren, 2008). However, Johnson and Holloway (2003) comment that STAMP is simple, easy to follow and quick to learn. The data used in STAMP analyses, to date, has been based on secondary information garnered from accident reports. Leveson (2004) suggests that the use of comprehensive investigation reports is sufficient to build a STAMP model and its use during an investigation should help guide the analysis. This indicates that STAMP is compatible with primary as well as secondary sources of information, which typically provide quantitative and qualitative data.

Usability

The experience of using STAMP differs amongst analysts, as reflected by the various positive and negative comments found within the literature. The model has been classed as effective and easy to use as well as only suited to experienced users and part of the 'laborious' STAMP analysis process (Ferjencik, 2011; Hollnagel and Speziali, 2008; Johnson and Holloway, 2003; Ouyang et al., 2010). A number of specific limitations have been identified: an undefined model structure; a lack of detailed guidance on constraint flaw classification and identification of contextual factors affecting people at the regulatory and operational levels; presentation of results (Johnson and Holloway, 2003; Johnson and de Almeida, 2008; Kontogiannis and Malakis, 2012). The lack of formal guidance, however, provides flexibility for the analyst and encourages them to consider interactions across the whole system, look beyond the proximal accident events and consider the context of the actors involved (Hovden et al., 2011; Johnson and Holloway, 2003; Kontogiannis and Malakis, 2012). In addition, the ability to visually represent complex system structures and the constraints between actors is considered by Johnson and de Almeida (2008) to be a great benefit of STAMP.

3.4.2.4 FRAM model development process

Problem definition

The need to consider accidents as emergent phenomena resulting from dynamic, non-linear system behaviour led to the creation of FRAM. Hollnagel and Goteman (2004) argue that this perspective is required as searching a chain of events for a root cause results in an infinite regress, which is deemed practically and intellectually unacceptable. Given that sequential and epidemiological models are unable to meet this requirement, the preference for systemic tools is based on this reason alone (Hollnagel, 2004 p.159).

Modelling approach

The approach proposed by Hollnagel (2004 p.159-160) as a 'suitable candidate' for the basis of a systemic model is that of stochastic resonance (see Figure 15).

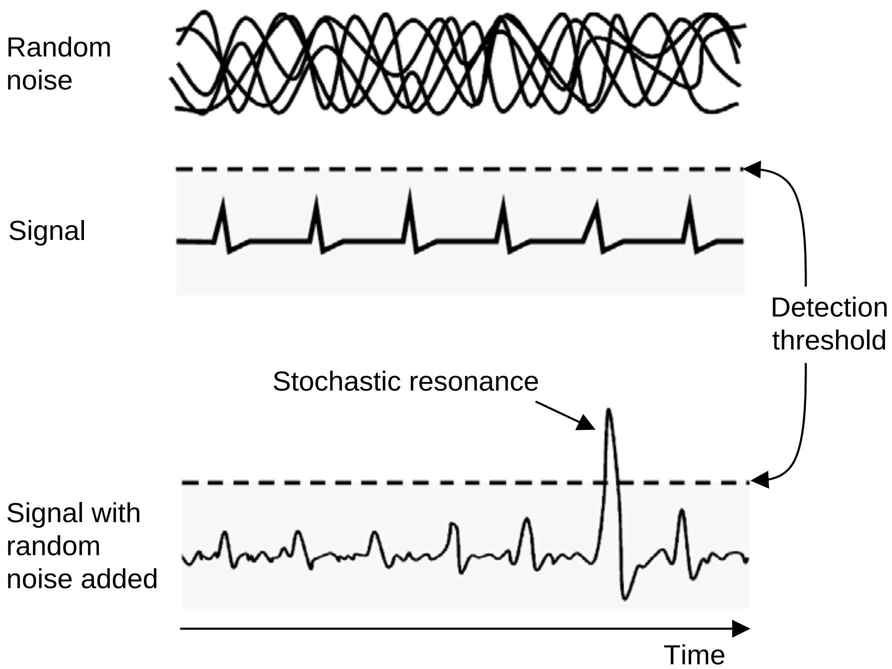

Figure 15 - Stochastic resonance. Adapted from Hollnagel and Goteman (2004).

STS are composed of sub-systems and functions which, although designed otherwise, will exhibit varying degrees of performance variation (represented by the 'signal' in Figure 15) (Hollnagel and Goteman, 2004). The performance variability of any given system component can 'resonate' with that of the remaining elements (represented as the ‘random noise’ in Figure 15) and produce emergent variation that is too high to control. Given that this performance variability resonance is not truly stochastic, as it is a consequence of functional coupling in the system, Hollnagel (2004) uses the term ‘functional resonance’ instead. FRAM, by considering accidents as the product of resonant system function variability, emphasises their dynamic, non-sequential nature (Hollnagel et al., 2008).

System model creation

The construction of a FRAM model follows a defined procedure, as described by Hollnagel (2004 p.186). Firstly, the relevant system functions are identified, labelled (according to their performance goal) and characterised by six basic parameters (input, output, time, control, preconditions, and resources). These functions and their features are graphically represented as hexagons with six sub-nodes respectively. The second stage involves determining the potential for performance variability by categorising each function (and labelling its hexagon) as either human, technological or organisational and assessing it via an 11-point common performance conditions checklist based on the CREAM method. This categorisation process is followed by the description of the dependencies between system functions in order to identify potential unwanted resonant connections. This is achieved by noting whether the variability of one function can affect any of the other functions. Graphically this means connecting the inputs and outputs of one function hexagon to the relevant inputs and outputs of the other functions, thereby producing a ‘FRAM network’ (Belmonte et al., 2011) (see Figure 16). The final part of the analysis involves determining the countermeasures required to dampen function variability. However, this process is conducted once the FRAM model has been completed in the previous stage.

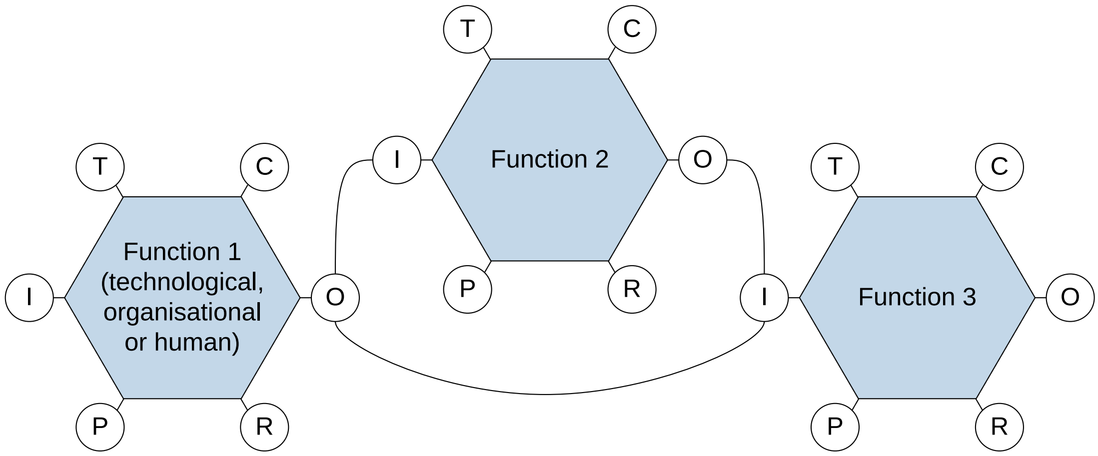

Figure 16 - FRAM diagram format (I = input, O = output, T = time, C = control, P = preconditions and R = resources)

Model validation

No formal evaluation of the validity and reliability of FRAM has been conducted to date and the developmental nature of the model has been highlighted in the literature (see Herrera and Woltjer, 2010; Stringfellow, 2010). Various issues have been raised, including: the need for a more structured approach to identifying performance variability and creating safety recommendations; the need to evaluate the suitability of FRAM for use during early stages of accident investigation; the need for guidance on how to address system migration to high risk operations. Research conducted by Belmonte et al. (2011) suggests that predictive FRAM models can be 'calibrated' by inputting data from real-world or simulated scenarios. This suggests that internal validity can be tested. However, no further studies have been conducted to demonstrate this. Despite the lack of formal testing, Woltjer (2006) suggests that FRAM provides a useful means of understanding current complex accidents and assessing risk.

Model usage

FRAM was developed to act as an accident analysis and risk assessment tool. Consequently there are number of examples for both methods of application. The generic nature of the technique has seen it utilised in a number of domains. Examples include aircraft collisions (de Carvalho, 2011; Herrera and Woltjer, 2010; Hollnagel et al., 2008; Sawaragi et al., 2006), financial services (Sundström and Hollnagel, 2011), emergency management (Woltjer et al., 2006), rail network control (Belmonte et al., 2011), patient safety (Alm and Woltjer, 2010) and air traffic control and navigation (Hollnagel and Goteman, 2004; Macchi et al., 2009).

3.4.2.5 FRAM systems approach characteristics

System structure

FRAM takes a different approach to defining the system structure, compared with STAMP and AcciMap, as it is not based on the RMF. The model provides a representation at the level of individual functions and, therefore, there is no explicit description of the overall system structure (Hollnagel and Goteman, 2004). The system boundary is also defined from a functional perspective. Hollnagel (2004 p.189) comments that the system boundary is relative to the chosen point of view, i.e. the functions contained in the model represent the internal environment. Consideration by FRAM for system element differentiation is clear. The functions included in an analysis are selected because of the specific role they play in the unwanted, i.e. unsafe, system operation. In addition, each function is defined by six standard characteristics, thereby facilitating comparisons throughout the system structure.

System component relationships

Component interrelationships and interdependence is explicitly addressed by the third stage of a FRAM analysis, i.e. establishing the dependencies between system functions. Indeed, Belmonte et al. (2011) comment that the main contribution of the model is that it highlights the complex interactions that arise in STS. Despite the lack of an overall system structure description, analysis of interactions across various system levels may occur depending on the functions under consideration. This allows for a holistic view of function variability and how their interactions can produce accidents (de Carvalho, 2011). Analysing the whole system for unexpected connections is also promoted by Hollnagel (2004 p.197).

System behaviour

The creation of a FRAM model, by definition, incorporates all facets of system behaviour. Indeed, the graphical nature of the model explicitly accounts for the inputs, outputs, goal and regulation of each system function. Transformation processes are also graphically accounted for, given that: (1) the system function labels help describe the processes and (2) the treatment of a system input requires certain resources and preconditions, which are represented as characteristic sub-nodes. System entropy is directly addressed by Hollnagel (2004 p.125), who comments that 'inputs are transformed into outputs, usually with increasing order or decreasing entropy as a result'. The concepts of equifinality and multifinality are also embodied in the notion of functional resonance, i.e. the performance variation in each system function can produce safe and unsafe outcomes.

3.4.2.6 FRAM usage characteristics

Timeline consideration

The graphical representation of system functions provided by a FRAM analysis does not include a sequence of events or timeline. The functions generally follow a left-right temporal relation but this is not always possible to apply and their relative position, therefore, carries no meaning (Hollnagel and Goteman, 2004). An analysis conducted by Herrera and Woltjer (2010) introduced instantiations of FRAM models to describe the change in system function interaction across different time periods; a process also advocated by de Carvalho and Ferreira (2012)[5]. This development goes some way to creating an accident timeline, albeit defined by changes in function performance rather than specific events.

Avoidance of blame

FRAM refrains from looking for 'root causes' by considering that accidents occur as a result of resonant variations in normal system function performance. This viewpoint is taken in order to contextualise the accident and understand why it happened, rather than simply determine what happened (Herrera and Woltjer, 2010).

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[5] de Carvalho and Ferreira (2012) was in press at the time of the FRAM evaluation

Model compatibility

Several studies have suggested that using FRAM alongside other analysis techniques could be beneficial. Belmonte et al. (2011) propose that sequential-based fault tree events can be thoroughly analysed with FRAM. Herrera and Woltjer (2010) comment that combining FRAM with other models during an analysis provides differing but complementary perspectives of an accident, which may enhance understanding of the incident. This idea is supported by de Carvalho (2011) and de Carvalho and Ferreira (2012), who suggest that using FRAM with cognitive analysis techniques can provide an understanding of how human performance is chosen to meet operational and personal objectives.

Recommendation production

FRAM does not automatically produce recommendations for safety interventions. The model does highlight which parts of a system require remedial action, however, it is the responsibility of the analyst to determine what types of interventions are necessary. The model has been used in various studies to identify general safety insights into various types of system by considering specific accidents, e.g. air traffic management (de Carvalho, 2011; Herrera and Woltjer, 2010) and financial services (Sundström and Hollnagel, 2011). Belmonte et al. (2011) also suggest that hypothesised FRAM networks can be tested by inputting real-world or experimental data, thereby allowing knowledge of different types of accident to be developed.

Resources required

The application of FRAM is structurally simple but, due its different theoretical grounding, requires an initial learning period coupled with extensive domain and human factors knowledge (Hollnagel and Speziali, 2008). Due to the time consuming nature of a FRAM analysis a prototype software tool (the FRAM visualizer) was developed, although it appears the development of the tool has been discontinued (see http://code.google.com/p/framvisualizer/). It is understood that FRAM has not been used in active investigations and hence its compatibility with primary data has not been tested, although it seems it would be compatible with such information. Previous studies have, however, used investigation reports as data sources (e.g. de Carvalho, 2011; Herrera and Woltjer, 2010) which suggests that acceptably comprehensive analyses can be performed solely with secondary data.

Usability

No formal usability assessment has been conducted on the FRAM model, however various researchers have highlighted both benefits and drawbacks of using the technique. Herrera and Woltjer (2010) remark that the model guides the analyst towards explicitly identifying the systemic factors associated with the accident and why they occurred. The authors also mention, however, that there is a need for a structured approach to generate the subsequent safety recommendations. A lack of guidance is also highlighted by Stringfellow (2010), who suggests that FRAM does not support the analyst in discovering resonance modes within the system. Hollnagel et al. (2008) state that the technique is easy to learn and use but, given that development of the supporting analysis software has ceased, use of FRAM can be time consuming. In addition, Johansson and Lindgren (2008) comment that analyst requires extensive theoretical and domain knowledge.

3.4.2.7 AcciMap model development process

Problem definition

Svedung and Rasmussen (2002) state that the limitations of the traditional cause-consequence chart are the reasons for creating the AcciMap method. The various purposes of the technique are: to aid accident analysis; identify decision makers who can potentially improve safety; act as a communications aid for cross-disciplinary research and design; provide a visual representation of complex system accidents (Svedung and Rasmussen, 2002).

Modelling approach

The approach to modelling taken by AcciMap is based on the idea that safety is impacted by decisions taken at every level of the system hierarchy. The tool is, therefore, designed to perform a vertical analysis of an STS for a particular accident case. This includes studying the events, acts and decisions that contributed to the accident.

System model creation

An AcciMap diagram is generated by mapping nodes and arrows on to the organisational hierarchy defined by the RMF. These nodes and arrows represent the causal flow of events and system states (Ladkin, 2005) (see Figure 17).

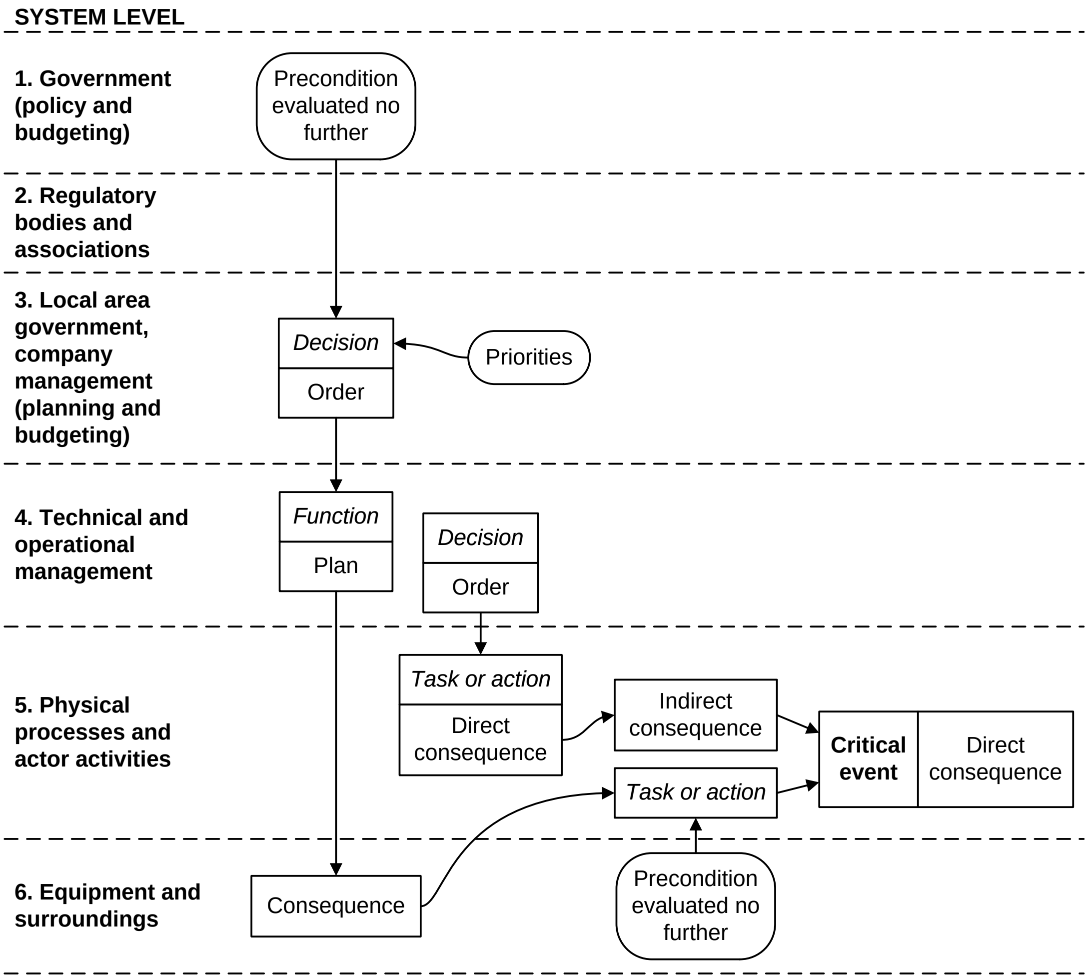

Figure 17 - AcciMap diagram format. Adapted from Svedung and Rasmussen (2002).

Consideration for particular levels of the system hierarchy depends on the system being analysed but generally incorporates all the sections identified by the RMF (Salmon et al., 2010a; Stringfellow, 2010). The use of the RMF structure is for the purposes of clarity and analysts can add extra notations, which refer to detailed narratives in an accident report, to justify their depiction of the accident scenario. This is exemplified by the AcciMaps presented by Rasmussen and Svedung (2000) and Svedung and Rasmussen (2002).

Model validation

The AcciMap concept was not originally presented as a fully developed and tested model and few efforts have subsequently been made to formally validate the tool (Svedung and Rasmussen, 2002). The most thorough attempt was conducted by Branford (2007), who standardised the use of the model and tested its validity and reliability through a series of controlled experiments. Branford's (2007) findings highlight the subjective nature of AcciMap analysis and the resulting need to capture the underlying processes of its use. Various other criticisms have been levelled at the technique, such as its susceptibility to hindsight bias (Salmon et al., 2010a). However, Waterson and Jenkins (2011) comment that extensive validation may not be necessary if AcciMap is used as an exploratory tool.

Model usage

The generic nature of AcciMap makes it applicable for analysis in any industry (Salmon et al., 2010a). This is evidenced by the variety of domains considered in previous studies utilising the method, e.g. food production (Cassano-Piche et al., 2009), oil and gas (Hopkins, 2000), emergency services (Jenkins et al., 2010), aerospace (Johnson and de Almeida, 2008) and outdoor activities (Salmon et al., 2010a). Use of AcciMap has been almost entirely retrospective in nature. One example of prospective use was identified, in which a 'generic AcciMap' was developed to study the transportation of dangerous goods (see Svedung and Rasmussen, 2002).

3.4.2.8 AcciMap systems approach characteristics

System structure

The system hierarchy is addressed by graphically incorporating all levels of the RMF (see Figure 12). This results in the system structure being described from an organisational perspective, with the different levels being defined by their influence on the control of safety. The model also accounts for the physical, technological, regulatory and commercial internal environments. A key system boundary seems to exist within the societal environment, where the general public represent the ‘external’ environment and the various decision makers involved in safety exist in the ‘internal’ environment. Consideration for system component differentiation is given, at a high level of abstraction, by the various characteristics of the hierarchical levels and the elements which exist in each tier.

System component relationships

Analysis of the whole system and the component interactions which lead to accidents is inherently promoted by the model, given that it considers safety as an emergent property (Salmon et al., 2010a). The nature of the AcciMap graphical representation requires the analyst to consider component interaction within and across all levels of the system hierarchy (see Figure 17). The directional nature of the arrows connecting the nodes implies a counterfactual interpretation of cause-effect relationships (Ladkin, 2005).

System behaviour

The creation of an AcciMap necessitates that the analyst considers the behaviour of the system and its components. The causal links between nodes show that outputs of one system element act as inputs to other components (see Figure 17). The nodes themselves represent processes, internal environmental conditions and regulation mechanisms that contributed to the accident.

System entropy is implicitly accounted for by enabling analysts to consider the influence of various internal environmental factors. The influence of the external social environment, i.e. that of public opinion, is indirectly accounted for via the inclusion of regulatory/governmental bodies in the system hierarchy. Public opinion, according to the RMF, influences the policies created at this level of the system (see Figure 12). AcciMap does not explicitly consider the multi- and equifinality aspects of system behaviour. However, as the model is focused on specific issues relating to a given accident scenario, this is a moot point.

3.4.2.9 AcciMap usage characteristics

Timeline consideration

AcciMap does acknowledge the chronology of accident events, however, it is only possible to preserve the strict time dimension within one system level during a given phase of the model creation (Hale, 2009). Svedung and Rasmussen (2002) state that this event sequence is established in the 'physical process and actor activities' level in the system hierarchy. This sequence is similar to a timeline, in that it describes how accidents develop over time (Johnson and de Almeida, 2008).

Avoidance of blame

Through inclusion of an event sequence, the analyst is directed towards an 'initiating event' of an accident. However, the AcciMap approach places these events into a context which enables an understanding of why they happened. This contextual detail helps to avoid unfairly blaming front-line operators by providing the background of how their actions came about (Branford, 2011). Indeed, Svedung and Rasmussen (2002) comment that the focus of AcciMap analysis is not the search for management errors 'and the like'. Rather, it is aimed at identifying the causal flow of events and the management and regulatory bodies that may have contributed, in order to improve system design and safety.

Model compatibility

AcciMap can operate as a standalone analysis technique or part of a suite of risk management methods (see Svedung and Rasmussen, 2002). However, it is understood that no research has attempted to incorporate it with other models in order to conceptually enhance either tool.

Recommendation production

AcciMap does not automatically produce safety recommendations, nor does it provide guidance on how to generate them (Branford et al., 2009; Salmon et al., 2010). However, the way causal effects are graphically represented means analysts can systematically identify factors that, if corrected, could prevent a range of potentially hazardous situations from arising (Branford et al., 2009). Furthermore, the 'big picture' approach provided by AcciMap can be useful for determining where safety improvements can be made (Branford, 2011). Beyond looking at the causes of a specific accident, Johnson and de Almeida (2008) note that researchers have used AcciMap to identify more generic insights into wider classes of failure. This can be achieved by developing a ‘Generic AcciMap’, i.e. an amalgamation of accident scenarios which forms a basis for generalisation (Svedung and Rasmussen, 2002).

Resources required

Use of AcciMap requires significant resources for data collection and analysis activities, as well as formal education and training (Salmon et al., 2010a; Sklet, 2004). Although Svedung and Rasmussen (2002) detail the structure of an AcciMap, there is no specific guidance regarding how accident data should be selected and manipulated to contribute to the diagram. The vast majority of studies have been based on secondary data extracted from existing official accident investigation reports (e.g. Branford, 2011; Cassano-Piche et al., 2009; Salmon et al., 2010a). Such information typically includes witness testimonies, technical engineering data and expert opinions and suggests that AcciMap would be compatible with primary data of this nature.

Usability

No formal usability testing has been conducted for the AcciMap. However, several features of the method are highlighted in the literature as improving the ease of accident analysis. The model provides a clear and concise summary of the accident, which can act as a useful ‘conversation piece’ to support discussion (Branford, 2011; Svedung and Rasmussen, 2002). AcciMap also enables the analyst to visualise the entire system structure and propagation of events across its hierarchy (Johnson and de Almeida, 2008). This, in turn, facilitates a better understanding of political and organisational influences and the devising of high-level safety interventions (Branford et al., 2009; Kirwan, 2001). The lack of usage guidance and standardised error classification have been raised as issues which reduce the accessibility of the model and produce inconsistent application across studies (Branford et al., 2009; Salmon et al., 2010a). However, this also means that analysts have a large range of options for configuring an AcciMap diagram (Waterson and Jenkins, 2011).

A summary of the STAMP, FRAM and AcciMap evaluations is presented in Tables 5-7.

Model development process				
Evaluation criteria		Model		
		STAMP	FRAM	AcciMap
Problem definition		Analysis of control structure deficiencies	Need to analyse emergent behaviour	Aid accident analysis, identify relevant decision makers, act as a communications aid, graphically represent system accidents
Modelling approach selection		Analysis of feedback mechanisms within control hierarchy	Analysis of resonant performance variability of system functions	Vertical system analysis of events, acts and decisions
System model creation	Format	Nodes (control structure components) linked by directional feedback loops	Nodes (system functions) linked by lines representing function dependencies	Nodes (events etc.) linked by causal arrows mapped on to RMF
	Procedure	Not defined	Defined procedure	Not defined
Model validation	Validation process	Minimal formal testing (inter-analyst reliability tested)	No formal testing	Validity and reliability formally tested
	State of validation	Validity and reliability problems caused by subjective nature of analysis		
Model usage	Type of use	Retrospective and prospective	Retrospective and prospective	Retrospective
	Domain application	Aerospace, public water supply, rail transport	Aerospace, financial services, emergency management, rail networks, patient safety	Construction, food production, oil and gas, emergency services, aerospace, outdoor activities

Table 5 - Model development process evaluation summary

Systems approach characteristics				
Evaluation criteria		Model		
		STAMP	FRAM	AcciMap
System structure	System hierarchy	Defined by system control structure, based on RMF	Defined by individual accident-related system functions	Organisational perspective defined by influence on control, based on RMF
	Environmental boundary	Implicitly defined by society external to system, i.e. general public	Implicitly defined by functions selected for analysis	Implicitly defined by society external to system, i.e. general public
	Component differentiation	Abstract definition based on position within control structure	Explicitly defined by functional role in accident	Abstract definition based on differing impacts on safety
System component relationships	Component relationships	Explicitly represented by feedback loops	Explicitly represented by function dependency links	Explicitly represented with causal arrows
	Holism	Addressed by analysis across system levels	Addressed by analysis across system levels (depending on functions included in analysis)	Addressed by analysis across system levels
System behaviour	Inputs and outputs	Implicitly represented by feedback loops	Explicitly represented by nodes	Explicitly represented by nodes
	Goal seeking	Implicitly represented by feedback loops	Explicitly represented by nodes	Not represented
	Transformation processes	Implicitly represented by nodes	Explicitly represented by nodes	Explicitly represented by nodes
	Entropy	Implicitly represented by feedback loops	Implicitly represented by nodes	Implicitly represented by nodes
	Regulation	Explicitly represented by feedback loops	Explicitly represented by nodes	Explicitly represented by nodes
	Equi- and multifinality	Not represented	Implicitly represented by considering both normal and resonant performance	Not represented

Table 6 - Systems approach characteristics evaluation summary

Model usage characteristics				
Evaluation criteria		Model		
		STAMP	FRAM	AcciMap
Model compatibility		Used with other models in retrospective analysis	Not tested (but suggested by researchers)	Not tested (although forms part of risk management toolset)
Safety recommendations	Automatic generation	No	No	No
	Provides general insights	Yes	Yes	Yes, via 'Generic Accimap'
Resources	Training required	Unclear (conflict in the literature)	Yes	Yes
	Level of analyst expertise required	Extensive domain and theoretical knowledge		Formal education
	Input data compatibility	Secondary quantitative and qualitative data (possibly compatible with primary data)		
Usability	Formally tested	No	No	No
	Pros	Effective and easy to use, visual representation of system structure and constraints, applicable to any domain, flexibility of model creation	Explicit identification of systemic factors, easy to learn and use	Clear and concise visual summary, helps high-level intervention design, applicable to any domain, flexibility of model creation
	Cons	Time consuming, lack of guidance, undefined model structure	Lack of guidance, time consuming	Lack of usage and error classification guidance

Table 7 – Model usage characteristics evaluation summary

3.5 Discussion

3.5.1 Systems theory interpretation in the SAA literature

The SAA literature does, on a general level, provide information about the various features of the systems approach. However, the coverage of these topics is varied and is, in some instances (e.g. environmental boundaries), predominantly conceptual and/or generalised in nature. For example, relatively little attention is paid to system hierarchies and there are differing views of how system structures are defined. This contrasts with the focus given to holism and the more consistent views surrounding safety and accidents as emergent properties of system behaviour. There is also extensive use of abstract language to describe the various elements of the systems approach. This varied and, at times, highly theoretical presentation exemplifies a lack of clarity regarding SAA that exists within accident analysis research. Indeed, no single definition of the systems approach has been adopted by the SAA research community.

Therefore, any practitioner wishing to utilise the literature to gain an overall understanding of SAA would need to consult a range of documents. This may not be possible due to the time and cost constraints associated with accessing and studying the literature (Chung and Shorrock, 2011). Also, the varying levels of conceptualisation within the literature may limit its applicability and, therefore, its relevance to practitioners; an issue which is reflected in other research disciplines such as human factors (e.g. Salas, 2008) (see Table 2). It is arguable that these issues may restrict the adoption of SAA within industry.

The different interpretations of the system theory components are, however, unsurprising. The lack of clarity in the SAA literature may well be affected by the variation within the existing systems theory research (see Section 2.3.2), i.e. different SAA researchers basing their systems theory interpretations on different elements of the literature. In addition, the individual experiences and biases of SAA researchers would be expected to affect their interpretations. For example, Nancy Leveson's computer science and engineering background (see http://sunnyday.mit.edu/) may help account for the substantial use of technical language associated with STAMP (see Figure 14). Nonetheless, the varied presentation of SAA represents a possible barrier to its acceptance within the practitioner community.

3.5.2 SAA model evaluation

The evaluation summary provided in Tables 5-7 highlights both common and disparate features of the STAMP, FRAM and AcciMap models. The remainder of Section 3.5.2 discusses how these similarities and differences may impact on the adoption and usage of these techniques.

3.5.2.1 Model validation

A lack of validation seems the most likely aspect of model development which would affect the selection of the three SAA techniques by practitioners. Indeed, the other development criteria have been met: the creators of the models have explained the objectives and analysis approaches of the techniques, provided a means of modelling any system and have seen their tools applied across multiple domains. Although all three models explicitly incorporate several systemic concepts and, therefore, provide a degree of face, content and construct validity, as described by Branford (2007 p.97-98), these forms of validity cannot be proven. Despite this, the research community is still advocating the use of systemic models, based on the assumption that they are conceptually valid.

However, Reason (2008 p.95) comments that there is no single right view of accidents and finding the ‘truth’ is less important than practical utility. In this context, it is arguable that empirical, rather than theoretical, validity is the dominant influence on practitioners’ model selection. Whilst empirical validation of systemic tools has occurred within research, via a number of accident analysis case studies (e.g. de Carvalho, 2011; Salmon et al., 2010a), it is far from extensive. As most practitioners in safety-oriented businesses tend to prefer well established methods and concepts, it is unlikely that they would use a relatively unproven systemic technique unless a business case could be produced to justify otherwise (Johansson and Lindgren, 2008).

3.5.2.2 Systems approach characteristics and analyst bias

Whilst all three techniques are based on systemic concepts, they all have different aims and approaches to modelling accidents. Differences are also observable in the way they incorporate the various aspects of systems theory. They all explicitly address the concepts of system component relationships, holism and regulation. This indicates these system theory elements are considered most relevant for analysing STS accidents and is consistent with their level of coverage within the literature (see Section 3.4.1). The remaining aspects of systems theory are, however, given varying degrees of consideration by the models, ranging from explicit, graphical representation to exclusion. The differing characteristics of the models demonstrate that, along with the variation in the SAA and wider systems theory literature, there is a lack of consistency regarding the application of the systems approach. The differences in the analysis models are, however, to be expected. It is doubtful that Nancy Leveson or Erik Hollnagel would have developed STAMP and FRAM, respectively, if they thought that AcciMap provided the ideal method for SAA. So, how would these differences affect the adoption and usage of SAA techniques by practitioners?

There is little information available concerning the relative benefits of the SAA tools. Therefore, it is arguable that selection of one model over another will depend on the analyst's personal preference, i.e. how well the method suits their way of thinking with respect to accident causation and analysis. This may (at least partly) explain the relative popularity of the SAA methods within the research community and also suggests that SAA concepts and methods will not be suited to every practitioner, thus contributing to an RPG. In addition, an individual's previous experience will also affect their analysis approach and, arguably, their choice of model (Svenson et al., 1999). For example, an analyst who is experienced in the use of sequential techniques may resist employing the SAA models.

3.5.2.3 Usage guidelines

The perceived benefits and drawbacks of the limited model application guidance provided in the literature (see Sections 3.4.2.3, 3.4.2.6, and 3.4.2.9) are indicative of the varying usability needs of researchers who used the techniques. It is arguable that individuals who prefer the flexibility offered by a lack of usage guidance are more likely to adopt a systemic technique, as opposed to methods employing a more structured and/or taxonomic approach (e.g. HFACS). However, greater analysis flexibility is likely to decrease the inter-rater reliability of the methods. Therefore, for practitioners who work as part of an investigation team and/or need to conduct accident trend analysis, a lack of usage guidance and detailed causal taxonomies may hamper their analysis efforts. Consequently, they may be discouraged from adopting the SAA models.

3.5.2.4 Resource constraints

Practitioners working in any industry will be faced with various resource constraints, e.g. time and financial budgets. Given that effective use of systemic tools requires a substantial amount of theoretical and multi-disciplinary knowledge, the time and cost required to train an individual (or a team) to conduct SAA may be unjustifiable. In addition, the use of systemic models is comparatively time-demanding in relation to other methods used in industry, which creates an extra barrier to their application (Johansson and Lindgren, 2008).

3.5.2.5 Assignment of blame

The systems approach actively promotes the avoidance of blaming a single individual for causing an accident. Each of the three SAA models embodies this notion by looking for safety deficiencies throughout a system, rather than search a for ‘root cause’. However, one of the principle reasons for conducting accident analysis is the assignment of blame and searching for a human error makes it easier to find out who should be held accountable (Leveson, 2004; Reiman and Rollenhagen, 2011). Given that the financial and legal implications of apportioning blame can be vast, analysts may be incentivised to use non-systemic techniques to ease the identification of culpable personnel.

3.5.3 Developments in the literature

Since the literature and model evaluations were performed for this initial study a number of SAA-related articles and books have been published. It is important to discuss the findings of this study within the context of these newer publications, as they help inform the understanding of the SAA RPG.

Various studies have been conducted which utilise the SAA methods to retrospectively analyse accidents in various domains, e.g. rail (Salmon et al., 2013), military aviation (Stanton et al., 2012), led outdoor activities (Salmon et al., 2012a) and maritime aviation (Hickey, 2012). All of the studies support the notion that SAA provides deeper insights into accidents and that systemic techniques are, therefore, appropriate tools for accident analysis. This does not offer any new information with regards to how the characteristics of the SAA innovation may contribute to the SAA RPG. It does, however, demonstrate a continued interest from researchers to conduct SAA which, in itself, is a factor that influences the gap.

The nature of accident analysis and the systems approach has continued to be studied by various researchers, e.g. Read et al. (2013), Le Coze (2013a; 2013b) and Wilson (2013). Examining this literature reveals that the systems approach is still presented in a varied manner. For example, Wilson (2013) suggests that there are six key components to the systems approach, compared to the four proposed by Read et al. (2013). Hollnagel (2013) states that the term ‘system’ is rarely defined in an explicit manner and there are often considerable differences in how it is interpreted and applied. Indeed, Le Coze (2013b) states that the safety literature is fragmented and that there is no dedicated framework and synthesis of the research to facilitate learning from accidents. This is exemplified by the research of Read et al. (2013), who discovered that none of the rail level-crossing behaviour literature they reviewed embodied the core concepts of the systems approach. This observation is consistent with the findings of Salmon et al. (2012b), who state that road safety research is primarily focused on individual system components. Furthermore, as the understanding of STS continues to evolve (e.g. Davis et al., 2013; Klein, 2013; Siemieniuch and Sinclair, 2013), the variation in systems approach perspectives seems likely to increase. Therefore, the more recent literature contributes to the issues described in Section 3.5.1 which may influence the SAA RPG.

Two key documents which contribute to the SAA literature and, in particular, the usage of STAMP and FRAM are the books written by Leveson (2012) and Hollnagel (2012). Detailed information on systems theory and the conceptual foundations of STAMP is provided by Leveson (2012). An updated and more structured approach to applying the method is also described, i.e. the nine-stage Causal Analysis based on STAMP (CAST) process. Similarly, Hollnagel provides the underlying concepts of FRAM and an updated application process for the method. Although both techniques still offer a flexible analysis approach, i.e. they are not constrained by detailed taxonomies, the improved guidance partly addresses the inter-rater reliability issues discussed in Section 3.5.2.3. Therefore, this new literature may reduce the extent of the SAA RPG.

Two important studies, conducted by Stanton et al. (2012) and Salmon et al. (2012a), have compared the STAMP and AcciMap methods against one another (and other analysis techniques) by using them to analyse accident case studies. Stanton et al. (2012) used a structured evaluation framework to assess and compare the methods, similar in nature to the framework utilised in this study. Conversely, Salmon et al. (2012a) adopted a less defined approach. However, both studies provide similar findings. For example, Stanton et al. (2012) show that whilst STAMP and AcciMap apply the majority of the systems approach, they do so in different ways. Salmon et al. (2012a) also state that both techniques provide comprehensive analyses of the entire STS structure albeit that they achieve this in different manners, i.e. STAMP requires additional data and analysis to create the control structure diagram. The studies also comment on the limited reliability of the two methods resulting from their lack of guidance material and detailed taxonomies. The significant resource demands associated with learning and using the techniques is noted in both articles. Stanton et al. (2012) also comment on the limited validation that STAMP and AcciMap have received. In summary, Salmon et al. (2012a) suggest that AcciMap, due to its greater analysis flexibility, is the method best suited for single case analysis (they recommend that taxonomies be developed for the method in order to facilitate trend analysis). Stanton et al. (2012) do not state a preference for either technique. The findings of these two studies (in terms of the method characteristics they identified and their impact on method adoption and usage) support those contained in this chapter and help to confirm which aspects of the systemic analysis tools may contribute to the SAA RPG.

Finally, research has now been conducted which suggests that combining AcciMap with other techniques can provide insights beyond those produced by a single method (see Debrincat et al., 2013; Salmon et al., 2013). This indicates that analysts may now be equally likely to select STAMP, FRAM or AcciMap based on their compatibility with other methods and, therefore, that any contribution to the SAA RPG from this characteristic will be consistent amongst the three techniques. However, it is unclear whether this compatibility will, overall, increase or decrease the extent of the gap. For example, the deeper analysis insights provided by the use of multiple methods may cause some practitioners to utilise the SAA techniques, thereby reducing the RPG. Conversely, the resultant increase in resource demands may dissuade other individuals from employing the systemic methods and increase the extent of the gap.

3.6 Study limitations

Whilst this chapter presents a systematic evaluation of the SAA literature and popular models and highlights a range of factors which can affect the SAA RPG, two key limitations exist. Firstly, it is not possible to discern the relative impact of the different issues discussed in Sections 3.5.1 and 3.5.2. However, this was beyond the scope of the study. Furthermore, as some of the identified themes are subjective in nature, e.g. the benefits/drawbacks of the limited usage guidance (see Section 3.5.2.3), ranking the influence of the SAA characteristics with the available data is arguably inappropriate. Secondly, the evaluation of STAMP, FRAM and AcciMap was based on an analysis of the literature, rather than applying the techniques to an accident case study in order to gain a first-hand perspective on how the techniques perform SAA. Whilst it is considered that this study provides useful information regarding the three methods, it also believed that additional insights can be gained by performing such an analysis. This need is addressed by the research conducted in Study 3 (see Chapter 5).

3.7 Conclusion

Whilst the systems approach is being promoted within the research literature as the conceptually preferred means of analysing major accidents, systemic techniques developed to perform SAA are not being used widely within industry. This study examined various characteristics of the SAA literature and the three most popular SAA models (STAMP, FRAM and AcciMap) to ascertain their contribution to the RPG.

The findings of this study show that the research literature has not presented a consistent or clear approach to applying systems theory within accident analysis. This may be an influential factor in the lack of SAA performed by practitioners. A lack of model validation, analyst bias, limited usage guidance, high resource requirements and the implications of not apportioning blame for an accident were identified as the key issues which may influence the use of the SAA techniques within industry.

3.7.1 Future work

Whilst this chapter provides an insight into the SAA innovation characteristics and how they affect the SAA RPG, as described in Section 2.5.2, the analysis processes of practitioners have yet to be examined with regards to how they may contribute to a gap. This forms the motivation for Study 2.

Chapter 4 – Study 2: Factors contributing to the SAA research-practice gap

4.1 Chapter overview

This chapter follows on from the research presented in Chapter 2 and examines the SAA RPG from a different perspective. Semi-structured interviews were conducted with 42 safety experts to understand which factors stemming from practice contribute to the SAA RPG. In combination with the findings from Study 1, an overall description of the SAA RPG is provided. The factors which contribute to the gap are subsequently discussed, thereby highlighting their impact on the RPG.

4.2 Introduction

The findings of Study 1 revealed that SAA is not presented consistently or clearly via the research literature and that there are a number of factors which may affect the adoption and usage of SAA methods. A question that naturally follows is: are these issues relevant to practitioners? Also, what other issues might affect the awareness, adoption and usage of SAA and its methods? Indeed, the use of an analysis technique is affected not only by its features but also by the characteristics of the users, the tasks they carry out and the technical, organisational and physical environments in which the method is used (Thomas and Bevan, 1996). Given that the analysis processes of practitioners (and the issues which affect them) have yet to be examined, with regards to their contribution to the SAA RPG, an opportunity exists to answer these questions (see Section 2.5.2). By doing so, a more comprehensive understanding of the SAA RPG can be obtained.

4.2.1 Study aims and objectives

The overall aims of the study were to identify and examine the factors stemming from practice which contribute to the SAA RPG and, in combination with the findings of Study 1, present a general description of the gap. The following objectives were established to achieve this:

- Understand how the awareness of, and need for, SAA within the practitioner community could inhibit its adoption and usage

- Understand how the factors influencing current analysis approaches may hinder the adoption and usage of SAA
- Probe deeper into the issues stemming from research (see Chapter 3) which may contribute to the SAA RPG

4.3 Methods

4.3.1 Method selection

The use of semi-structured interviews was selected as the most appropriate method to achieve the aims of the study for a number of reasons. Firstly, the lack of information regarding SAA within the practitioner literature prevented the use of document analysis alone. Secondly, Study 1 included a thematic analysis of the scientific literature and other SAA research has centred on user evaluations of SAA methods (e.g. Salmon et al., 2012a; Stanton et al., 2012). Consequently, interview data was viewed as the most suitable form of information to supplement the existing findings. Finally, semi-structured interviews provide the ability to examine topics of interest in varying degrees of depth; an approach which suited the exploratory nature of this study (Robson, 2002).

4.3.2 Sampling strategy

Due to the study resource constraints, it was not possible to create a statistically representative sample. Therefore a convenience sample, considered to be indicative of the accident investigation community, was created. The sample included participants employed as full-time accident investigators, health and safety professionals (e.g. company safety managers), human factors specialists and accident analysis researchers. However, these participant categories were not mutually exclusive, e.g. some practitioners had research experience. Therefore, participants were allocated to the category associated with their current role as it was felt that their role would have the most influence on their analysis approach, e.g. due to resource constraints. Also, gaining a detailed understanding of how a participant's background influenced their analysis approach was beyond the study scope. Human factors experts were recruited as they are often employed on a consultancy basis to provide input into accident investigations or safety-critical system design. The views of researchers were also sought to enable a comparison with the practitioners' perspectives and further explore the research-based factors that may influence the SAA research–practice gap. Participants were required to have experience of investigating accidents and/or performing risk assessments within at least one safety-critical industry. No specific inclusion criteria were set regarding the level of their experience. Participant recruitment was halted when an appropriate level of thematic data saturation was judged to have been achieved.

4.3.3 Participants

Interviews were conducted with 42 participants (age range: 28–79 years; mean age: 46.4 years) based in ten countries. The nine full time accident investigators, 17 health and safety professionals, ten human factors specialists and six researchers had experience of working in at least one of 25 industries (see Appendix 4.1 for a more detailed description of the participants' location and experience). Of these industries, those that had been worked in by at least five participants included: rail, aviation, maritime, oil and gas, defence, healthcare, nuclear power and manufacturing. The interviews lasted between 28 and 128 min (mean interview length: 70 min).

4.3.4 Interview question design

The interview questions were designed to understand the following topics: (1) the participants' knowledge of SAA and accident causation; (2) the analysis methods and processes they currently use; (3) the barriers they feel prevent information flowing between the research and practice communities. In order to provide a comprehensive examination of these topics, the question list was informed by the interview study of Lundberg et al. (2010) and the findings of Study 1 and other SAA studies (e.g. Salmon et al., 2012a; Stanton et al., 2012) (see Appendix 4.2 for interview questions). The questions were reviewed by a senior human factors researcher prior to the start of data collection and no amendments were suggested.

In addition to the interview questions, participants were asked to complete an analysis model awareness table (see Appendix 4.3) which was specifically designed to assess their level of awareness and usage of well-known systemic and non-systemic techniques. The STAMP, FRAM and AcciMap methods were included as they were identified as the most frequently cited systemic analysis tools (see Section 3.4.2). The SCM, MORT, FTA and Domino model were also included as they are examples of traditional techniques commonly mentioned in the scientific literature (e.g. Katsakiori et al., 2009; Qureshi, 2007; Sklet, 2004).

4.3.5 Data collection and analysis

Five pilot interviews were conducted and analysed. The interview questions were reviewed and amended, where necessary, after each interview. The main interview study was subsequently performed with a minor iteration of the question list performed halfway through the process (the wording of two questions was changed). Upon the conclusion of the data collection phase a deductive and inductive thematic analysis, as described by Braun and Clarke (2006), was performed on the interview transcriptions using NVivo 9.

4.3.6 Research–practice gap evaluation framework

As described in Chapter 2 (see Section 2.5.2), RPGs signify the impairment of transferring new information between the research and practice communities. Rohrbach et al. (1993) summarised the stages involved in achieving long-term commitment to new ideas, which arguably relate to transferring SAA knowledge and techniques from research into practice. The first stage involves creating awareness of an innovation, e.g. SAA, within the practitioner community. The second and third steps involve practitioners committing to adopt and subsequently using the innovation. These stages were used as a framework to evaluate whether issues discovered in the data could affect a given stage and, therefore, contribute to the formation of a gap.

4.4 Findings

4.4.1 Key themes

The themes which were considered to be key issues, i.e. topics that were mentioned by at least 20% of the participants, are presented in Table 8. The majority of these themes focus on two aspects: ensuring that the SAA methods meet the needs of the practitioners (themes 2–4, 8); communicating SAA research in a more effective manner (themes 5, 7, 9–12). Whilst the number of participant comments indicates the importance of a given theme, the non-representative nature of the sample means that this cannot be meaningfully tested (see Section 4.6 for more information). Therefore, the key themes listed in Table 8 are described alongside others that were deemed to influence SAA awareness, adoption and usage and contribute to the RPG.

Theme (relevant chapter section)	Percentage of participants				
	Accident investigator	**Health and safety professional**	**Human factors expert**	**Researcher**	**Total**
1. Requirement for accountability influences analysis approach (4.4.3.3)	56	41	30	67	45
2. Model not practitioner focused (4.4.3.1)	33	24	80	50	43
3. Empirical validation requirements (4.4.3.4)	11	35	60	50	38
4. Analyst chooses a technique that suits the situation (4.4.4.1 and 4.4.6.2)	56	35	30	17	36
5. Previous experience and training affects analysis approach (4.4.4.2)	67	18	30	50	36
6. Model suits user's way of thinking (4.4.3.2)	22	24	30	67	31
7. Research considered too conceptual (4.4.2.5)	56	12	30	17	26
8. Analysis time requirements (4.4.4.1)	44	6	40	33	26
9. Company policy affects analysis (4.4.5.1)	22	18	50	17	26
10. Amount of training given (4.4.2.3)	33	24	30	0	24
11. Previous training and experience affects model preference (4.4.3.2)	11	24	20	50	24
12. Lack of communication between researcher and practitioner communities (4.4.2.5)	56	18	10	0	21

Table 8 - Key themes

4.4.2 SAA awareness

4.4.2.1 Current level of SAA awareness

The scientific literature presented in Section 2.5 describes a general lack of systemic analysis model usage with industry. This situation does not necessarily stem from low levels of SAA awareness and comments from several senior practitioners indicate that awareness is growing within industry:

"*Lots and lots of people talk about this [systemic analysis approach] and it's very current in a lot of the safety and high-hazard industry community.*" (Health and safety professional)

Furthermore, notable remarks from two participants provide evidence that systemic models are currently employed in certain industry sectors. One individual commented that both AcciMap and FRAM are used within their national transport accident investigation agency. A second participant with a background in human factors described the AcciMap training provided by their organisation to accident investigators within the rail industry. However, the analysis model awareness table responses obtained from the participants suggest that the majority of practitioners remain unaware of the most frequently cited systemic analysis models, i.e. STAMP, FRAM and AcciMap (see Figure 18).

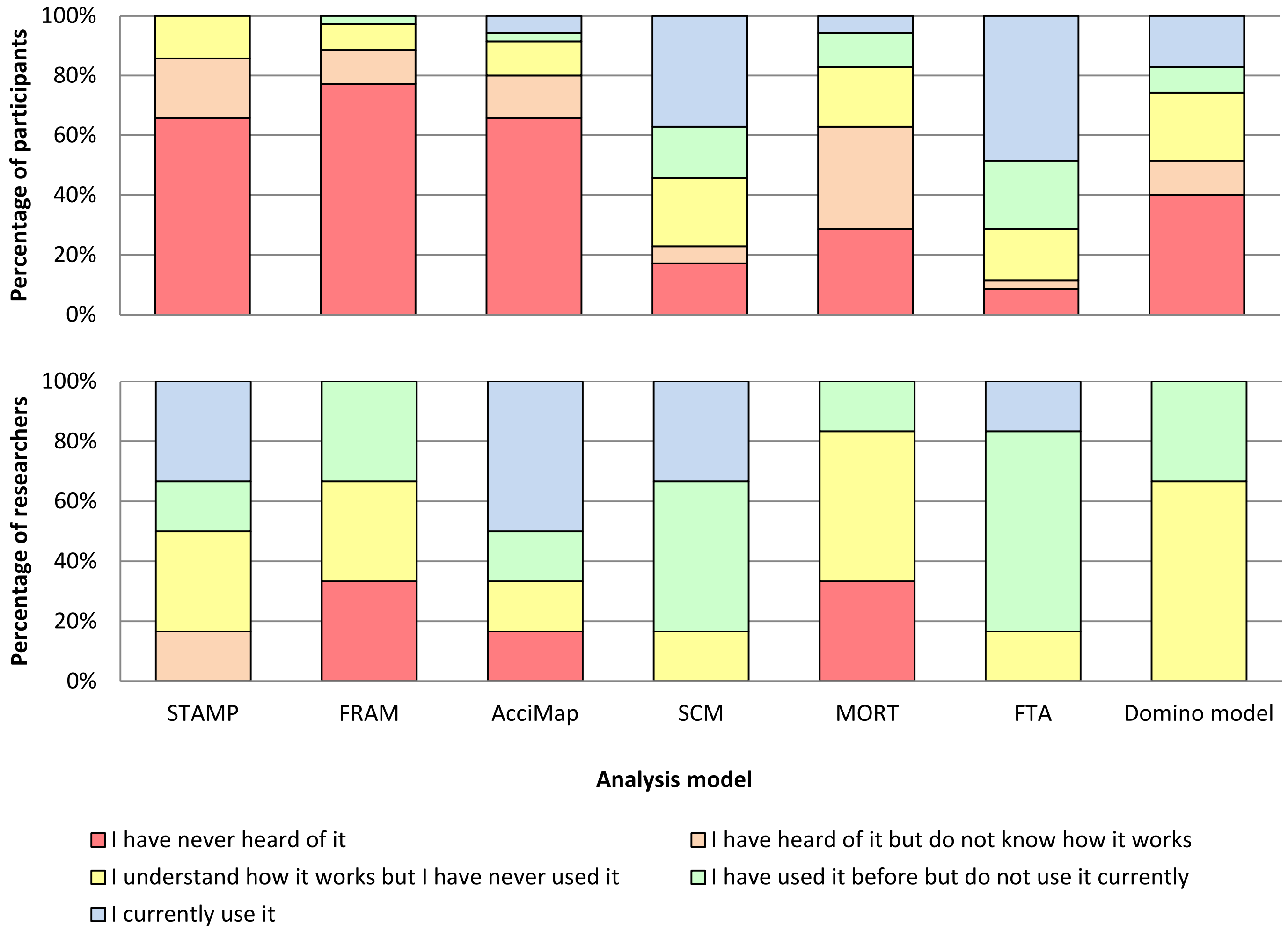

Figure 18 - Analysis model awareness

This is in contrast to the responses of the researchers who were interviewed and indicates that knowledge and use of these models is greater within the scientific community. The research-based participants only accounted for 14% of the sample and, therefore, this comparison must be made tentatively. However, it is indicative of the lack of SAA model usage within industry portrayed in the scientific literature and provides further evidence that an RPG exists.

In addition, a different understanding of SAA seems to exist between the two communities. When asked to provide a description of the 'systems approach to accident analysis', the two most common characteristics mentioned by participants referred to 'component interactions' and 'analysing the whole system', which are key elements of SAA. However, relatively fewer practitioners referred to these characteristics when compared with the researchers (see Table 9).

Systems approach characteristic	**Percentage of participants**			
	Accident investigator	**Health and safety professional**	**Human factors specialist**	**Researcher**
Component interactions	22	27	30	67
Analysing the whole system	22	20	40	50

Table 9 - Participant understanding of SAA

Five practitioners described SAA as a 'systematic' approach, rather than providing examples of 'systemic' analysis characteristics, which suggests a degree of confusion may exist regarding SAA terminology. Furthermore, five practitioners were unable to provide a definition.

4.4.2.2 The demand for SAA information

Whilst there is a clear theoretical argument for the use of SAA (see Sections 2.3 and 2.4.3), various factors exist which may negate the need or opportunity for a practitioner to seek out a systemic analysis tool. Some practitioners simply have no desire to change their current approach and therefore have no need for new information:

"*I can't say that I've actively gone and looked at the new techniques that are out there as the ones I've always used have worked.*" (Health and safety professional)

Additionally, day-to-day workload demands were considered by some individuals to restrict their learning opportunities:

"*I don't have nearly enough time to keep up with the [research] paperwork in this area; hardly any at all. That's a problem that most practitioners have; they're so busy doing investigations it's very difficult to keep up with the theoretical side.*" (Accident investigator)

These comments highlight factors which inhibit the search for SAA-related information. However, should a practitioner decide to use a systemic analysis technique, they are still faced with obstacles associated with accessing and utilising the relevant research.

4.4.2.3 Extent of training impacts awareness

An individual's awareness of analysis methods is dictated, at least in part, by the level of training they receive. The extent of training received has clear implications with regards to the opportunity to increase SAA awareness and comments from participants indicate that levels of training are role-dependent. Full-time investigators, for example, sometimes receive extensive training via university-level courses:

"*After you join, the first two years is spent doing a diploma, through a university here, in accident investigation.*" (Accident investigator)

However, it may also be the case that other practitioners with varying degrees of involvement with accident investigation receive less training:

"*We had analytical investigation methods training which was a week-long course. The course started as a week but latterly I think it went down to one and a half days.*" (Human factors expert)

Several participants with experience in the rail and nuclear sectors remarked that individuals with lower levels of responsibility for accident investigation may not have received any relevant training.

4.4.2.4 Accessibility of SAA information

Individuals who are not provided with SAA training can find gaining access to the relevant information problematic, which may limit their awareness. The time and costs associated with acquiring the necessary training, for example, may be excessive:

"*A lot of the time, when you hear about courses, it costs a lot of money to go, which dissuaded me from going.*" (Health and safety professional)

Furthermore, an accident investigator, a health and safety professional and a human factors expert all remarked that the cost of purchasing scientific journal articles and attending conferences may prohibit access to SAA information. As well as cost, intellectual property rights can form another barrier to acquiring scientific research information:

"*The academic community is very competitive. There's intellectual property rights problems in industry too but normally if there's a buck in it, or a common benefit, you'll collaborate and create an alliance. I find it very hard to get an alliance of academics.*" (Health and safety professional)

4.4.2.5 Communication of SAA information

Each participant was asked to list the sources of information they utilise in order to keep their knowledge up-to-date. 40 participants provided answers, which are summarised in Table 10.

Source of information	Percentage of participants				
	Accident investigator (n = 9)	Health and safety professional (n = 16)	Human factors expert (n=10)	Practitioner total	Researcher (n = 5)
Colleagues and network contacts	56	44	60	51	60
Conferences	33	50	40	43	20
Internet searches	22	13	10	14	0
Investigation reports	11	19	0	11	0
Online forums and networks	11	19	0	11	0
Practitioner literature and organisations	33	44	70	49	20
Research literature	22	6	50	23	100
Research projects	0	19	10	11	60
Textbooks	22	6	10	11	0
Training and experience	44	31	20	31	20
Does not search for information	0	6	0	3	0

Table 10 - Sources of information

Table 10 indicates that the three most popular sources of new information for practitioners, in general, are: (1) speaking with colleagues and members of their extended networks; (2) attending conferences; (3) consulting industry literature and professional institutes. In comparison, Table 10 suggests that the majority of researchers tend to gain new knowledge via the scientific literature and by conducting research projects, as well as consulting colleagues. The data in Table 10 also suggests that most practitioners do not consult the scientific literature. Moreover, some of the practitioners specifically remarked on a general lack of communication between the research and practice communities:

"*I'm not aware of any real liaison between the two [communities].*" (Human factors expert)

"*We hardly ever meet people on the theoretical side; it's once in a blue moon.*" (Accident investigator)

When practitioners do engage with the research community the information presented is considered by some to be too conceptual and provides little or no practical benefit:

"*I know some accident investigators that have been to international conferences where there were lots of academics putting forward papers on approaches to accident investigation. The practitioners in the audience said 'this is actually meaningless and we don't use it.'*" (Accident investigator)

Consequently practitioners can develop a sense of disregard for researchers which could further influence the apparent lack of SAA communication:

"*There is a mentality within practitioners where academics are seen as people sitting in an ivory tower and haven't had any real experience of accident investigation so [practitioners think] 'how can they comment on investigations?'*" (Accident investigator)

4.4.3 SAA adoption

4.4.3.1 Practicality of analysis method

Even if sufficient awareness of research is obtained, barriers to its adoption may arise from a lack of consideration for practitioner requirements. The features of an analysis method desired most by participants referred to aspects of usability, such as the simplicity of using a method (see Figure 19).

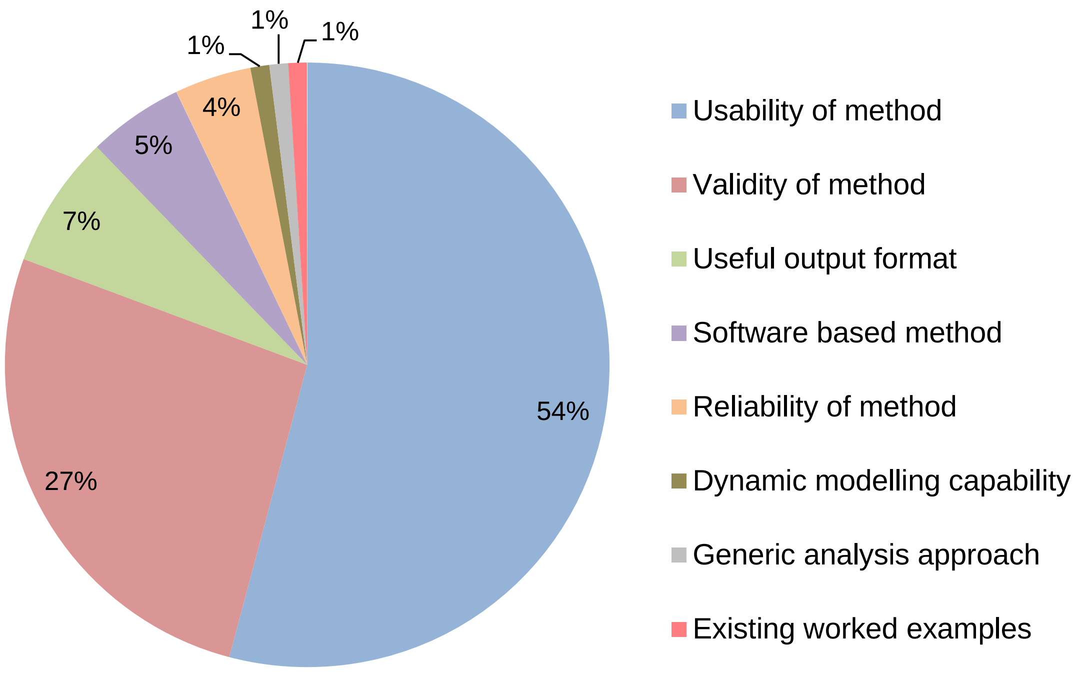

Figure 19 - Preferred features of an anaysis method (% values = percentage of participants referring to a given feature)

The importance of designing a usable technique was reflected in the comments of several individuals:

"*I think if you make it simple, people will use it. If it's complicated, they won't and it becomes another job that's too difficult to do and it gets put on the shelf.*" (Health and safety professional)

Other practicality-related issues which may inhibit the adoption of research were also referred to by participants. Several accident investigators, for example, commented on a possible lack of appreciation for the practicalities of their role in the design of analysis methods. The potentially excessive cost of implementing research was also highlighted by a human factors expert.

4.4.3.2 Personal adoption criteria

In addition to the practicalities of using an analysis technique, adoption may also be influenced by a number of factors based on an individual's personal preference and experience. A person's decision to adopt a method may be, for example, based on how well it suits their way of thinking:

"*When I think of the SCM, I can really think of those barriers being broken and trying to find out why they have been broken. For me it's a very natural way of investigating. Some people really hate it but for me it works.*" (Accident investigator)

The preference for a given model can also be influenced by an individual's previous experience and training:

"*If I had trained with other people I would probably have a very different default model that I use. I think it's mostly my [educational] upbringing that makes it very difficult to think of anything else.*" (Researcher)

Experience gained by analysis method usage was specifically highlighted by several participants who remarked that their decision to adopt a technique was based upon the outcome of an initial trial period.

4.4.3.3 Accountability influences analysis approach

The analysis approach taken by a practitioner can be influenced by their need to assign liability for an accident. Some individuals remarked that they prefer, or are mandated, to avoid seeking blame in favour of focusing on safety improvements, as per the systems approach. However, other practitioners who are more concerned with the commercial and legal implications of accidents may seek to apportion blame:

"*The way the analysis was set up was really to assist with legal proceedings. That was the main driver... [it was] not always to find out what the root cause was. It would be more to do with whether a prosecution was likely to be successful or not.*" (Human factors expert)

This is particularly evident when those who are conducting an investigation may be deemed culpable and are incentivised to apportion liability elsewhere:

"*Because it's the manager that carries out the industry's own investigation they're not really going to look at themselves and they're certainly not going to look at their own management chain because that puts them in a threatening position.*" (Accident investigator)

In addition to the influence on SAA adoption, the need to demonstrate liability can also influence the use of an analysis technique. One health and safety professional, for example, referred to the occasions where he was instructed by clients to use their analysis tools in particular ways in order to avoid ‘black spots’ on their safety records.

4.4.3.4 Model validation

The extent of an analysis model’s empirical validation was considered by many practitioners to be a key influence on their adoption decision. Several participants commented on the need for extensive validation to demonstrate that a method has been ‘proven’ and can be ‘trusted’:

“*Has it been tried and tested? Does it add value? We have to ask these questions when we implement something.*” (Health and safety professional)

A number of individuals who provide consultancy services in accident investigation and risk analysis specifically commented on the importance of a method’s track record when attempting to establish the credibility of their work with clients. However, less consideration was given to the extent of a method’s theoretical validity:

“*Validity comes very much down the line. I think it’s very much about quickness and whether the technique is understood in the community, if I’m brutally honest.*” (Health and safety professional)

4.4.4 SAA usage

4.4.4.1 Usage resource constraints

The level of effort given to an investigation will be based, at least in part, by the resources available to the investigation team:

“*There’s a 14 out of 15 chance that we’re not going to do a field-based investigation that we should do and that’s simply because of funding.*” (Accident investigator)

Consequently, this can affect whether an individual employs more complex analysis techniques, such as those based on the systems approach:

"*[Name of method] is something that I've been trained in but I'd only use it if there had been a major incident, whereas the Five Whys method is probably a starting point for a nice and simple easy one. I think the more complex the incident, you'd pull in more of the techniques to give you the answer.*" (Health and safety professional)

In addition to whether or not an analysis method is used, the time and financial constraints involved in accident investigation can also affect how it is used. Several participants, for example, remarked that the depth of analysis they can achieve with their preferred technique is limited by the time available to them.

4.4.4.2 Model reliability

If a systemic analysis technique is adopted by a practitioner there are factors related to reliability which will affect its usage. A number of participants remarked on the influence that an individual's background and experience has on their analysis approach and how this can produce variation in investigation findings. Open discussions and analysis reviews which result in a consensus on the investigation findings can help minimise the biasing effects of individuals' backgrounds; a process which is common with full-time investigators:

"*The inspector will do a very structured presentation to a group of inspectors where we challenge what he's done, what he's said and what evidence he's got that's sufficient to make the conclusions that he's drawing together.*" (Accident investigator)

However, several participants commented on how the qualitative nature of the systemic analysis tools could increase the difficulty of reaching such an agreement:

"*If you turned up with an AcciMap and said 'the system is safe because I've analysed it in an AcciMap' you'd just get laughed out of the room. They'd pick it to pieces because it's far more subjective.*" (Human factors expert)

4.4.4.3 Data requirements of SAA

Several factors relating to the data requirements of SAA were considered by participants to impact on their ability to use the systemic analysis methods. For example, the system-wide data needed to perform SAA is not always available:

"*If I were to go and work in industry now I think I would have to revert back to more simple accident analysis methods just because the data wouldn't be there to support them [the SAA methods].*" (Researcher)

Some practitioners mentioned that the accident information databases they are required to use employ coding taxonomies which reflect the theoretical (cause-effect) underpinnings of sequential techniques. This may influence the type of data that is collected and one individual observed that, even if they gather data relevant to SAA, they must transpose their findings into a non-systemic format. These issues appear to stem, in part, from the fact that researchers and practitioners have fundamentally different approaches to analysis and therefore different data requirements:

"*Sometimes I do feel there is an important division between how practitioners and some academics treat accident investigation. We're always looking at specifics and therefore evidence will sometimes take us down a very specific path and we don't need to consider the wider aspects and vulnerabilities of the system.*" (Accident investigator)

4.4.5 Organisational influences on the research–practice gap

4.4.5.1 Organisational policy

Some individuals have the freedom to choose which analysis technique they adopt and use. However, in many cases, organisational policy dictates which methods are used:

"*We tend to find that when people come here [for investigation training] they want to know all about the models and how to use all of them but often they go back to an organisation that says 'this is what we use' so they don't really get the opportunity.*" (Researcher)

Practitioners who provide investigation services on a consultancy basis also commented that requests from some clients to use in-house analysis techniques can produce similar barriers to analysis tool usage. Organisational policy can also impact on the resources available for practitioners to learn and use new analysis methods and therefore create the issues described in Sections 4.4.2.3 and 4.4.4.1.

A link between safety culture and organisational policy was referred to by several individuals who observed that their analysis approaches were, in part, dictated by the senior management and the safety culture they instilled. A number of participants also commented that safety-related changes they recommended to senior management teams, such as introducing new accident investigation policies, sometimes needed to be presented in cost-benefit, rather than safety improvement, terms:

"*When I turned up at [company name] there was no health and safety. They didn't care about which safety regulation said they had to do risk assessments. What I had to do was sell them the cost-effectiveness [of safety]. When I put it into a dollar sign they understood it and then their attitude became 'this is good for the company and it prevents reputational damage as well.'*" (Health and safety professional)

4.4.6 Industry influences on the research–practice gap

4.4.6.1 Regulatory requirements

The degree of regulation within a given industry can have a large influence on what type of analysis techniques are used in accident investigation and risk assessments:

"*Regulators [in the nuclear industry] dictate exactly what methods need to be used and they're very slow to update their opinions on these things.*" (Human factors expert)

"*There is a degree of flexibility. No one is telling me that I have to use the SCM and that is it. This is an International Maritime Organisation resolution, don't forget, and is not mandatory.*" (Accident investigator)

The comments of many practitioners indicated that SAA-based regulation is not in place across industry in general. This may be due to a lack of SAA awareness at the regulatory level, rather than a decision to reject it:

"*The regulation probably doesn't recognise [the systems approach] or encourage it at the minute. I don't know about the military or anyone like that but certainly in the railway industry it doesn't seem to.*" (Health and safety professional)

4.4.6.2 Industry characteristics

In addition to the regulatory environment of an industry, the suitability of performing SAA within a given industry may depend on a range of domain characteristics, e.g. the degree of operational complexity:

"*If you look at highly dynamic, very complex systems then the systems approach is more appropriate. If you're looking at things like the manufacturing industry, it's probably less appropriate and things like the Bowtie method or something a bit more linear are probably more suitable.*" (Human factors expert)

"*If you are in a highly defined, highly automated environment requiring software reliability, for instance in medical systems, then it makes absolute sense to use the STAMP technique. It's an issue of 'horses for courses.'*" (Health and safety professional)

4.4.6.3 Resistance to change

The effort and cost of implementing an innovation, such as SAA, within an organisation or throughout an industry by means of new regulations can create resistance to change. This inertia can increase with the level of regulation:

"*Once you get a nuclear power plant licensed you don't ever want to change it because you've spent so much money. So, by its very nature, a very heavily regulated industry cannot be innovative.*" (Health and safety professional)

"*I would say changing anything in healthcare at a national level is really, really difficult. It takes a long time and there's a lot of consultation involved. If* *we were going to change the way we work, there's huge numbers of people who have a stake in what we do.*" (Human factors expert)

4.5 Discussion

The topics presented in Section 4.4 describe a wide range of issues that can affect if, and how, research is applied by practitioners. All of the issues discussed in Chapter 3 (see Section 3.5), e.g. method resource requirements and analyst bias, were also highlighted by participants in this study, thereby providing a degree of validity to the findings of Study 1. The additional factors raised by the participants provide justification for looking beyond the results of Study 1 and, therefore, conducting this study.

Whilst any of the factors presented in Section 4.4 may be sufficient to prevent a practitioner from conducting SAA, it is more likely that they all, to a greater or lesser extent, combine to inhibit the application of the systems approach. When considering all of these factors together they can be viewed as providing a wider context in which the research practice-gap is played out. Whilst not an exhaustive list, it is believed that the range of themes included in Section 4.4 is comprehensive enough to provide an adequate representation of the gap. The findings are graphically summarised in Figure 20, which is based on the evaluation framework derived from the work of Rohrbach et al. (1993) (see Section 4.3.6). A discussion of the issues contributing to the SAA RPG and the implications for SAA is provided in the remainder of Section 4.5.

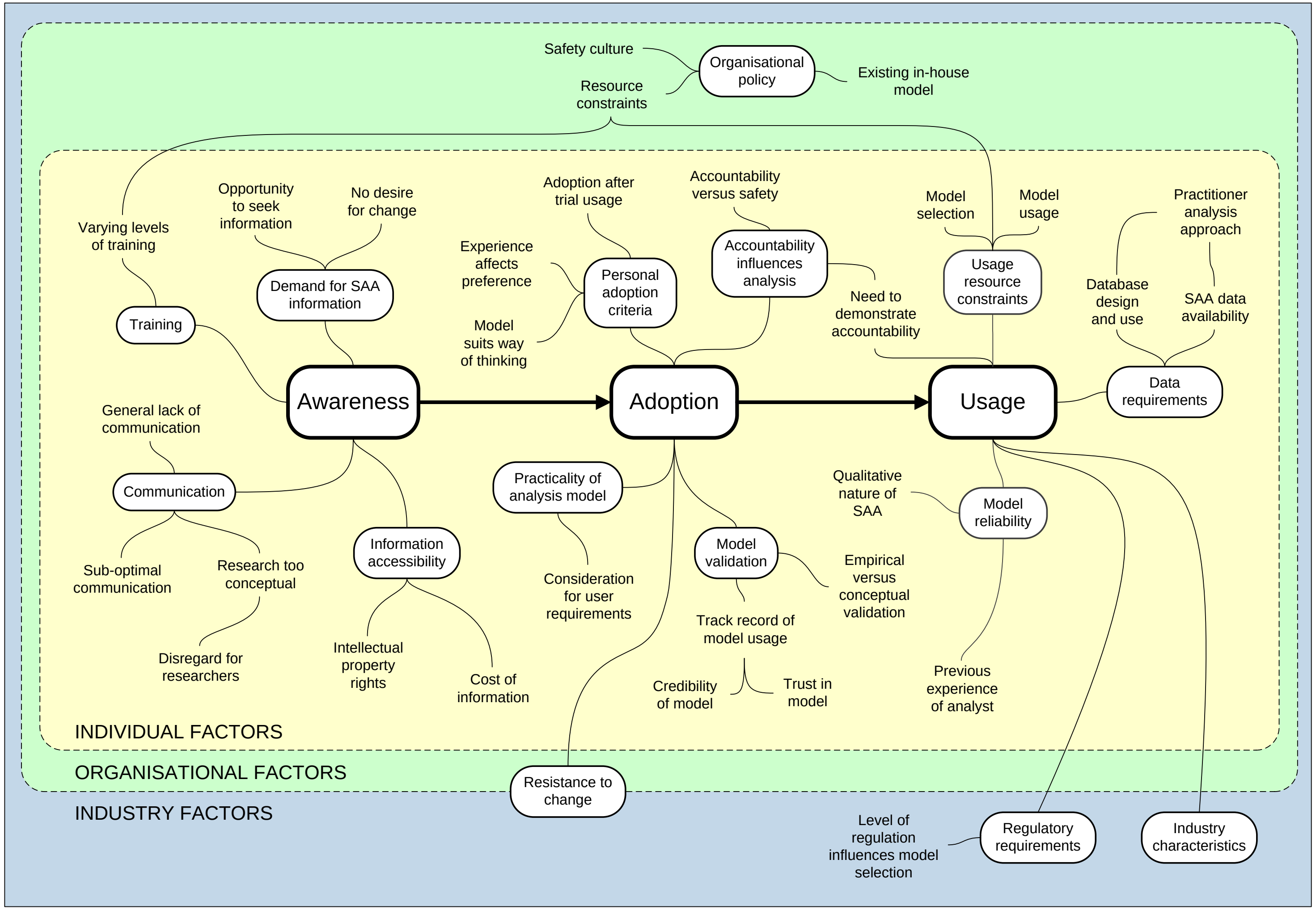

Figure 20 - The SAA RPG

4.5.1 Issues associated with the research–practice gap

The majority of the issues raised by participants may contribute, at least in part, to a general gap between accident analysis research and practice. Therefore, these factors could hinder the success of any new analysis method, regardless of its theoretical underpinning. What then are the characteristic features of the SAA RPG? This question is explored further within the context of SAA awareness, adoption and usage in the rest of Section 4.5.1.

4.5.1.1 SAA awareness

The opportunity to learn about new analysis techniques, e.g. via training (see Section 4.4.2.3), access to and the communication of the relevant information (see Sections 4.4.2.4 and 4.4.2.5) will affect a practitioner's awareness of any technique. However, it is worth commenting on how these issues relate to SAA.

It is acknowledged within the literature that SAA requires extensive theoretical and domain knowledge, training and formal education (e.g. Hollnagel and Speziali, 2008; Johansson and Lindgren, 2008; Salmon et al., 2012a; Sklet, 2004) (see Section 3.4.2). It is therefore conceivable that practitioners will only be made aware of systemic analysis tools in the more in-depth training courses. In addition, it seems that the majority of SAA information is presented via the research literature and at conferences (e.g. Kazaras and Kirytopoulos, 2011; Salmon et al., 2010b). However, as these sources of information appear to be the third and fifth most popular resources for practitioners (see Table 10), it is arguable that SAA is not being promoted in the most effective way.

The cost of training, research literature and conference proceedings can limit SAA awareness. However, information regarding SAA is freely available on the internet from sources such as Google Scholar, Nancy Leveson's MIT website (http://sunnyday.mit.edu/) and Erik Hollnagel's FRAM related website (http://www.functionalresonance.com/). This suggests that it is the issues surrounding SAA communication (see Section 4.4.2.5) that may be a more significant influence on awareness. Given that practitioners can lose interest in research that is too conceptual it is possible that the considerable amount of accident causation theory present in the systems approach literature (see Section 3.5.1) may dissuade them from learning more about SAA.

4.5.1.2 SAA adoption

As with the awareness of SAA, there are several factors related to the adoption of an analysis technique which are influenced by features of the systems approach.

The importance of an analysis method's usability was reflected in the comments of practitioners (see Section 4.4.3.1). Whilst there is varying opinion within the literature with regard to the usability of the systemic analysis techniques, their use has been viewed in some cases as time-consuming (e.g. Ferjencik, 2011; Johansson and Lindgren, 2008; Salmon et al., 2011) (see Section 3.4.2). This issue can become increasingly problematic for individuals whose main responsibilities do not include the investigation of accidents, as they may have less time to conduct analyses. SAA may not be suited to and, therefore, adopted by them.

The notion that more effective safety recommendations can be devised by the avoidance of blaming a suitable culprit is well established in the SAA literature (e.g. Leveson, 2004) and was echoed in the comments of several participants (see Section 4.4.3.3). However, searching for human error makes it easier to find out who is responsible for an accident and various practitioners emphasised that demonstrating accountability, particularly from a legal or commercial perspective, is still an objective of accident investigation (Reiman and Rollenhagen, 2011). Therefore, practitioners may be incentivised to use non-systemic analysis techniques to ease the identification of culpable personnel.

Johansson and Lindgren (2008) state that most practitioners in safety-oriented businesses tend to prefer well established methods; a point which was also raised by the participants. Although STAMP, FRAM and AcciMap have been applied across a variety of safety-critical domains this has mainly taken place within an academic context, e.g. accident analysis case studies such as Salmon et al. (2012a). The comments of participants, therefore, suggest that SAA methods will require considerable empirical validation within an industrial setting if they are to gain acceptance from practitioners (see Section 4.4.3.4).

4.5.1.3 SAA usage

If a practitioner takes the decision to adopt a systemic analysis method they are faced with several issues which can hinder the application of SAA. SAA is not a simple endeavour and requires significant analyst effort and access to various subject matter experts (Salmon et al., 2012b). SAA may, therefore, only be suited to major accident investigations where funding, time and personnel are sufficient to obtain the amount of information required for SAA. Indeed, both Leveson (2004) and Salmon et al. (2012b) suggest that the data requirements of STAMP and AcciMap are only typically met via the comprehensive reports produced after a large scale accident. Furthermore, individuals may not be able to gain access to the data required for SAA. For example, such information may exist outside of the organisation 'affected' by the accident (e.g. commercially sensitive documentation from an equipment supplier) or an individual may be in the 'wrong' position within an organisation to address the whole scope of an accident (e.g. unable to interview senior managers) (Dien et al., 2012). In addition to the varying levels of information access, the type of data that is collected can also influence the application of SAA. Accident data is reported, collected and compiled in databases over time in line with national regulations and established codification systems (Mullai, 2004; Mullai and Paulsson, 2011). However, in some cases these databases and coding schemes are not based around the systems approach (e.g. they just focus on local events at the 'sharp end' of a system) and the information required to populate them is, therefore, unlikely to enable thorough SAA (Roelen et al., 2011; Salmon et al., 2012b).

4.5.1.4 Organisational and industry issues

A significant influence on a practitioner's selection of a model is the safety culture of their organisation. The comments of a number of participants (see Section 4.4.5.1) reflect the findings of Lundberg et al. (2012), who suggest that four aspects of safety culture can influence the decision to implement safety-related changes: (1) institutionalised low safety standards; (2)

prioritisation of safety; (3) the decision making criteria to adopt changes; (4) the level of resources allocated to implement them. These factors clearly apply to the implementation of any new analysis method. However it is arguable that, in some cases, obtaining organisational (or regulatory) commitment to making a fundamental shift to employ SAA may be harder than implementing a modification of an existing sequential technique.

The comments from practitioners (see Section 4.4.6.2) indicate that, depending on the industry in question, the use of SAA may not always be appropriate. This notion is supported by Hollnagel (2008), who suggests that systemic models are best suited to accidents within highly complex, intractable systems, e.g. nuclear power plants. Therefore, whilst the generic nature of the systemic models means that they can be applied in any domain, the idea that ‘one size does not fit all’ means that the resulting ‘competition’ from other analysis techniques represents a further barrier to SAA adoption (Mullai and Paulsson, 2011; Salmon et al., 2012a). This subject is discussed further in Chapter 7 (see Section 7.4).

4.6 Study limitations

Given that this study utilised a non-representative convenience sample, as described in Section 4.3.2, a number of limitations were placed on the findings. For example, statistically testing the relative importance of themes identified by the participants or the differences observed across roles, industries and countries would not produce results that could be generalised. This means that the representation of the RPG in Figure 20 can only present the contributing factors, rather than their relative influence. However, the use of a convenience sample resulted from the resource constraints of the study rather than a lack of consideration of sample design. Given the number of people who are involved in accident analysis, achieving a representative sample from which results could be generalised would be a significant challenge. Despite the limitations imposed by the nature of the sample, it is considered that the findings of this study offer some useful insights into the SAA RPG.

4.7 Conclusion

This study examined various issues stemming from both the research and practice communities which may hinder the application of SAA. When considered together, these factors provide a description of the SAA RPG. Some of these factors are indicative of a general RPG in accident analysis, e.g. usage resource constraints. However, others are more pertinent to SAA, such as its lack of track record within industry and the possible incentive to use non-systemic techniques to facilitate the attribution of blame. Although a single factor may be sufficient to prevent a practitioner from conducting SAA, it is more likely that they all, to a greater or lesser extent, combine to inhibit the application of the systems approach.

4.7.1 Future work

So far, this thesis has described and discussed a number of features that contribute to the formation of an SAA RPG. A number of important questions naturally follow this discourse. Firstly, is the presence of the SAA RPG problematic, i.e. does the gap need to be bridged? This question is addressed in Chapter 5, which considers the extent of the gap, and is discussed further in Chapter 7 (see Section 7.4). Secondly, if the SAA RPG is to be bridged, which of the issues presented in Section 4.4 should be tackled? An initial step in answering this question can be made by considering the key themes contained in Table 8. As stated in Section 4.4.1, the majority of these themes focus on two aspects: (1) ensuring that the SAA methods meet the needs of the practitioners; (2) communicating SAA research in a more effective manner. The first of these solutions is examined in Chapter 6. Clearly it is important to understand the adaptations required of the SAA methods before any modifications are performed. Therefore, user evaluations should be conducted to ascertain the strengths and weakness of the analysis techniques: this is the focus of Chapter 6.

Chapter 5 – Study 3: Systemic accident analysis vs. the Swiss Cheese Model

5.1 Chapter overview

The research presented in Chapters 3 and 4 provide a description of the SAA RPG and the factors which contribute to it. This chapter takes a step further by examining the extent of the gap to understand whether it needs to be bridged. The analysis model most widely used throughout industry is the SCM and this chapter begins by describing the academic debate that exists regarding its suitability for SAA. A major accident case study is then analysed using an SCM-based model, developed and used by practitioners (the ATSB investigation analysis model), and two SAA methods (AcciMap and STAMP). The analysis outputs and usage of the techniques are compared and the issue of whether the SCM can offer a systems approach to accident analysis is discussed. Finally, an assessment of the extent of the SAA RPG is presented.

5.2 Introduction

So far, this thesis has described and discussed a number of features that may prevent the awareness, adoption and usage of SAA techniques by practitioners. As suggested in Section 4.7.1, an important question that naturally follows this discourse is: does the SAA RPG need to be bridged? The proposed benefits of SAA presented in Section 2.3, i.e. gaining an improved understanding of accidents which may lead to more effective recommendations, suggest that it should be. Research that has compared SAA methods with non-systemic analysis techniques (e.g. Belmonte et al., 2011; Herrera and Woltjer, 2010) indicates that these benefits can be achieved and, therefore, that SAA should be promoted throughout safety-critical domains (see Section 2.4.3).

However, emerging fields of research often define themselves in terms of existing traditional fields against which they are reacting and can describe these traditional fields in a simplified or even misleading way, neglecting the fact that different perspectives often have more commonalities than disagreements (Hoffman and Militello, 2009; Saurin and Carim Júnior, 2011). This is evidenced by the lengthy academic debate on accident models and by new techniques often criticising or even disqualifying older ones (Ghirxi, 2010; Jacobsson et al., 2009). A notable case in point can be found when considering the SCM.

5.2.1 SAA vs. the SCM

Undoubtedly the most popular accident causation model, the SCM has been widely adopted in various industries (e.g. aviation and healthcare) (Salmon et al., 2012a). Classified by some (e.g. Hollnagel, 2004) as an 'epidemiological' model, the SCM suggests that longstanding organisational deficiencies can create the necessary conditions for a frontline 'active failure' to trigger an accident. The presence of these conditions and events in the system represents the inadequacy/absence of defensive barriers (e.g. physical protection, training and procedures) designed to prevent accidents. The defences within a system and their associated inadequacies are graphically represented by layers of and holes in Swiss cheese (see Figure 21). When the 'holes' in a system's defences align, an accident trajectory can pass through the defensive layers and result in a hazard causing harm to people, assets and/or the environment, as depicted in Figure 21 (Reason, 2008 p.101).

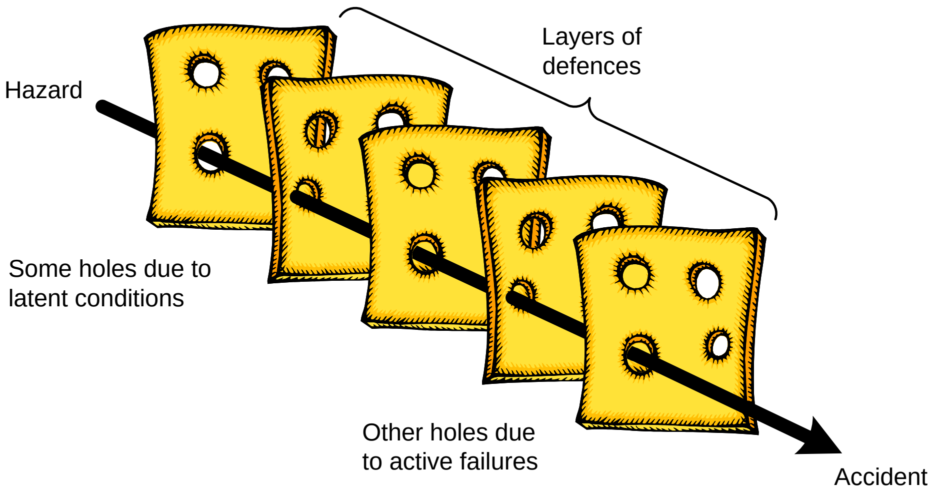

Figure 21 - Swiss Cheese Model. Adapted from Reason (2008).

The SCM has drawn criticism from a number of researchers (e.g. Dekker, 2006 p.89; Hollnagel, 2012 p.14; Leveson, 2012 p.19) who describe it as a sequential technique which oversimplifies accident causation by not considering the complex interaction of system components. In addition, some authors (e.g. Dekker, 2006 p.89; Hickey, 2012 p.19) suggest that the sequential nature of accident causation is portrayed in the signature image of the SCM (see Figure 21). The implication is that the SCM no longer provides an appropriate description of accident causation.

Other criticisms of the SCM focus on its application. For example, some researchers comment on the model’s lack of specificity about a number of its features, e.g. how the holes in the layers of cheese line up and how this affects its ease of use (Le Coze, 2013b; Wiegmann and Shappell, 2003). Furthermore, Shorrock et al. (2004) suggest that an overly prescriptive application of the SCM can lead to accidents being entirely (and incorrectly) attributed to senior management, i.e. overlooking the contribution of individuals at the frontline.

5.2.2 Performing SAA with the SCM?

The perceived drawbacks of the SCM described in Section 5.2.1 only represent one side of the academic debate, however. In contrast to the idea that the SCM is a sequential model, Reason et al. (2006 p.9) state that it describes accident causation as the ‘unlikely and often unforeseeable conjunction of several contributing factors arising from different levels of the system’. In other words, events and/or conditions happen together to produce an accident. As per SAA, the SCM provides a holistic multi-level analysis approach and later versions of the model also take account of the fact that ‘active failures’ are not required for an accident to occur (see Reason, 1997 p.17). Furthermore, the connection made by the SCM between normative serialisation (i.e. cause-effect) and the temporal orderliness of events that occurred is entirely unintended (Reason et al., 2006 p.16).

The SCM is underspecified but Reason et al. (2006 p.21) state that it was never intended to be a used as a detailed accident analysis model and that criticising it for a lack of specificity seems unjustified. Regardless, this issue has been resolved by the various methods which have been developed to operationalise its concepts, such as HFACS and Tripod Delta. Additionally, a number of organisations (e.g. the Australian Transport Safety Bureau (ATSB) and EUROCONTROL) have purposely neutralised the language used in their SCM-based models to avoid attributing blame, an important aspect of SAA.

Whist the development of accident models has been required to explain the increasing complexity of STS, the introduction of a new model does not necessarily mean that existing ones become obsolete (Hollnagel and Speziali, 2008 p.37; Reason et al., 2006 p.21). Indeed, the SCM (and methods based on it) is still used by researchers to perform accident analysis (e.g. Szeremeta et al., 2013; Xue et al., 2013) with some suggesting that it offers a systemic view of accidents (e.g. Salmon et al., 2012a; Stanton et al., 2012). However, if the critiques of the SCM are justified then the continued use of this (arguably outdated) model means accident investigations may not achieve the necessary understanding of major accidents to prevent recurrence. Given that the SCM is in widespread use throughout various industries and SAA methods are yet to be widely adopted by practitioners, the outcome of this debate has clear ramifications with regards to improving safety. Therefore, it is important to understand whether or not the SCM can provide a systems approach and remain a viable option for accident analysis. Gaining this understanding will help define the extent of the SAA RPG and whether or not it needs to be bridged.

5.2.3 Study aim and objectives

The aim of this study is to consider whether the SCM can provide a systems approach to accident analysis and, in order to achieve this, has three main objectives:

- Analyse a major accident (the train derailment at Grayrigg) using three techniques: an SCM-based model developed and used by practitioners (the ATSB investigation analysis model) and two SAA methods predominantly used by the research community (AcciMap and STAMP)

- Compare the outputs and application processes of the models, via an evaluation framework, in order to examine their theoretical and usage characteristics
- Reflect on the similarities and differences between the models and the implications for applying the systems approach in theory and practice

The intention is to examine this issue within an applied context, rather than a purely conceptual one. By giving a practical example of how the SCM compares to SAA techniques, it is hoped that the study will be able to demonstrate whether the SCM does apply the systems approach or not. Furthermore, a more detailed understanding of how AcciMap and STAMP apply the systems approach will be obtained, thereby addressing the second limitation of Study 1 (see Section 3.6). An overview of the ATSB model, AcciMap and STAMP, a description of the Grayrigg accident, details of the analysis processes used and the model evaluation criteria are provided in Sections 5.3, 5.4, 5.5.1, and 5.5.2 respectively.

5.3 The analysis methods

This section presents a description of the three analysis techniques selected for the study and the justification for their use. AcciMap and STAMP have already been described in Chapter 3. However, brief summaries of the methods are provided in Sections 5.3.2 and 5.3.3 in order to incorporate the relevant SAA literature that has been published since Study 1 was conducted and, therefore, present an updated description of the techniques.

5.3.1 ATSB investigation analysis model

The ATSB investigation analysis model (referred to hereafter as the ‘ATSB model’) is a modified version of the SCM. As per the SCM, the ATSB model provides a general framework that can be used to guide data collection and analysis activities during an investigation (ATSB, 2008 p.36). However, various alterations to the original SCM were made by the ATSB to improve its usability and the identification of potential safety issues. Such changes include an enhanced ability to combine technical issues into the overall analysis, the use of neutral language (which does not infer blame) and emphasising the impact of preventative, as well as reactive, risk controls. To highlight the changes made, the ATSB (2008) presented a latter version of the SCM (see Figure 22) and their adaptation of it (see Figure 23).

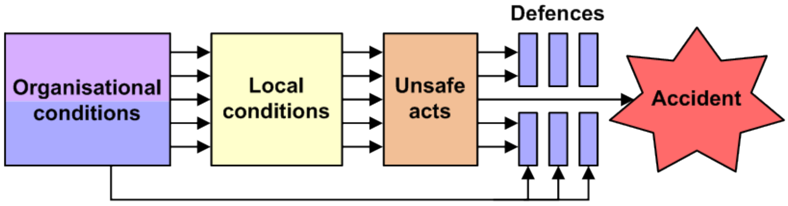

Figure 22 - Latter version of the SCM. Adapted from ATSB (2008).

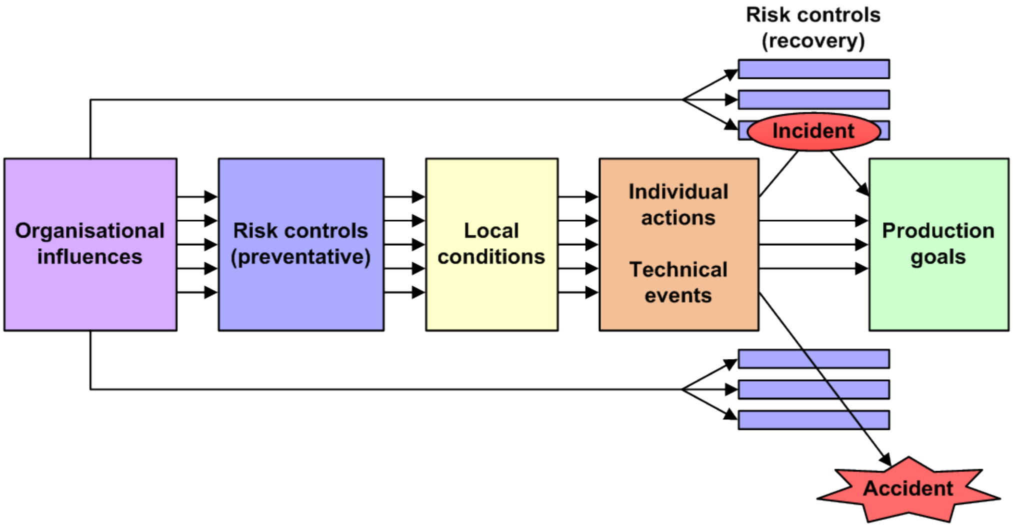

Figure 23 - ATSB adaptation of the SCM. Adapted from ATSB (2008).

As indicated by Figure 23, the ATSB model views organisations as goal seeking systems whose performance can become unsafe from the result of interacting events and conditions. In this situation, risk controls are required to prevent an accident from occurring or minimise the severity of its consequences (ATSB, 2008 p.36). These risk controls are akin to the layers of defences portrayed in Figure 21.

Whereas Figure 23 highlights some of the changes that the ATSB made to the SCM, the official representation of the ATSB model which is used during investigations is presented in Figure 24. The model represents the operation of a system via five levels of 'safety factors', where a safety factor is an event or condition that increases safety risk (ATSB, 2008). The first three levels correspond to 'safety indicators', i.e. safety factors dealing with the individual or local aspects of an accident. The upper two levels address 'safety issues', i.e. safety factors associated with organisational or systemic issues.

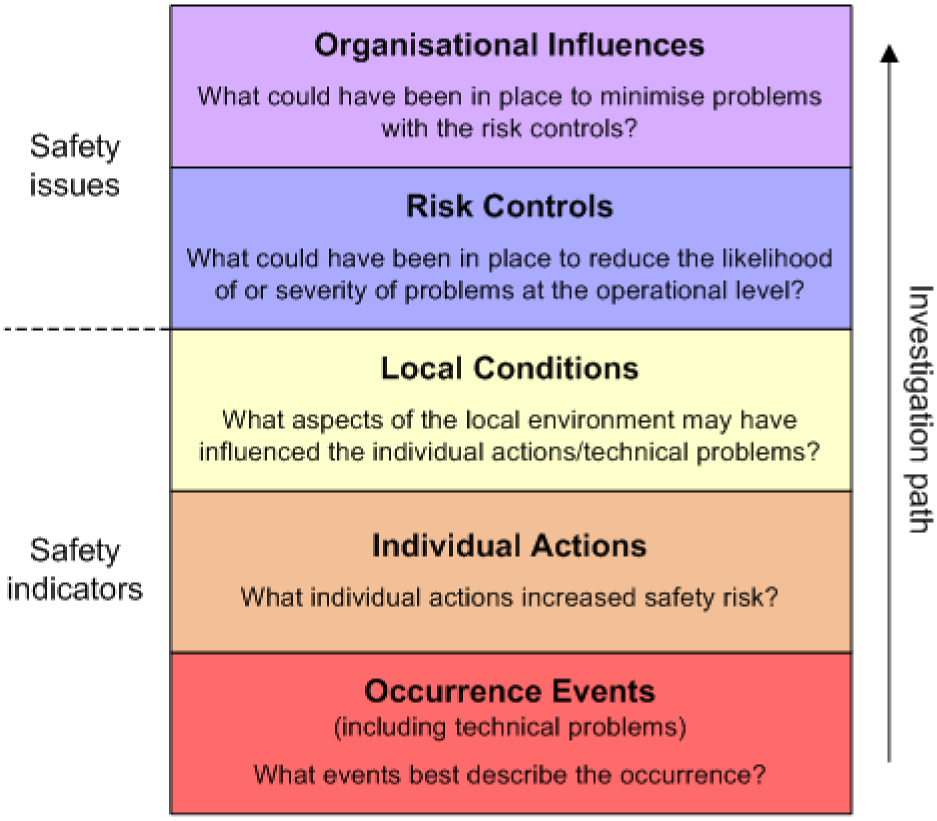

Figure 24 - The ATSB Investigation Analysis Model. Adapted from ATSB (2008).

The ATSB model was selected for use in this study for a number of reasons. Firstly, although modified, it is based on the SCM and therefore, according to various SAA researchers (see Section 5.2.1), can be classed as a sequential model. Secondly, the model has been used in transport accident investigations by the ATSB since 2002 (ATSB, 2008). As such, the model has been empirically validated by a governmental investigation agency, which is highly regarded within the accident investigation community (ATSB, 2008). Therefore, the ATSB model represents a 'tried and tested' analysis technique used by investigation experts. Furthermore, a publically available description of the model and its use is provided by the ATSB (2008), thereby enhancing its inter-rater reliability.

5.3.2 AcciMap

AcciMap, developed by Rasmussen (1997) and Svedung and Rasmussen (2002), was designed to take a control theory-based systems approach to accident analysis. Consequently, accidents are considered to result from the loss of control over potentially harmful physical processes. According to Rasmussen (1997), every organisational level in a system affects the control of these hazards and a vertically integrated view of system behaviour is required. The dynamic nature of STS means that an accident is likely to be prepared over time by the normal efforts of many individuals throughout a system and that a normal variation in somebody's behaviour can 'release' an accident (Rasmussen, 1997). AcciMap was developed as a means of analysing the series of interacting events and decision-making processes which occurred throughout a STS and resulted in a loss of control (Branford et al., 2009). To do so, it combines the classic cause-consequence chart and the RMF, which depicts the control of STS over six organisational levels (see Figure 17).

Although the AcciMap forms part of a broader risk management process, it has been used independently of this approach to analyse individual accidents (e.g. Salmon et al., 2012a; Stanton et al., 2012) (Branford et al., 2009). The method was selected for use in this study for this reason and also because: it is one of the most popular SAA methods (see Section 3.4.2), it has been used previously to analyse rail accidents (e.g. Branford et al., 2009; Salmon et al., 2013) and guidance material is available which would improve the inter-rater reliability of the analysis (see Svedung and Rasmussen, 2002).

5.3.3 STAMP

The STAMP model, based on systems and control theory, focuses on safety as a control problem (as per the AcciMap approach). Emergent system properties (e.g. safety) are controlled by imposing constraints on the behaviour and interaction of system components (Leveson, 2012). Three basic constructs are used by STAMP to determine why control was ineffective and resulted in an accident: (1) safety constraints; (2) hierarchical safety control structures; (3) process models.

Safety constraints can be passive, which maintain safety by their presence (e.g. a physical barrier), or active, which require some action to provide protection (i.e. detection, measurement, diagnosis or response to a hazard). Accidents occur only when system safety constraints are not enforced. Hierarchical safety control structures are used by STAMP to describe the composition of systems (see Figure 13). Each hierarchical level of a system imposes constraints on and controls the behaviour of the level beneath it. Control (two-way communication) processes operate between system levels to enforce the safety constraints. Process models are incorporated into STAMP as any human or automated controller requires a model of the process they are responsible for controlling, if they are to control it effectively (Leveson, 2012).

The STAMP model was selected for comparison with the ATSB model and AcciMap for several reasons. It is the most frequently cited SAA model (see Section 3.4.2) and has been used previously to analyse rail accidents and incidents (e.g. Ouyang et al., 2010; Song et al., 2012). In addition, detailed guidance on the application of STAMP is provided by Leveson (2012) and, therefore, would enhance the inter-rater reliability of the analysis.

5.4 The Grayrigg accident

5.4.1 Case study selection

The train derailment at Grayrigg was selected as the analysis case study for various reasons. Firstly, the event represented a major accident on the UK rail network; a complex system with many stakeholders, including infrastructure controllers, train and freight operating companies and maintenance contractor organisations. Therefore, it was appropriate to utilise systems thinking concepts to analyse the event. Furthermore, the rail industry in the UK is currently expanding and creating an increased usage demand on the network and continued pressure to reduce costs (Office of Rail Regulation, 2013). With these conditions, it is clear that safety research within this industry is an on-going requirement. This is evidenced by the current rail-based research within and outside of the UK (e.g. Dadashi et al., 2013; Read et al., 2013; Salmon et al., 2013; Wilson, 2013). The accident garnered significant media coverage and resulted in Network Rail (the organisation that manages the rail infrastructure in the UK) receiving the largest fine imposed since the Office of Rail Regulation was established. As such, the derailment represents one of the highest profile accidents in UK rail history. Finally, the event resulted in a full investigation by the Rail Accident Investigation Branch (RAIB), the independent railway accident investigation organisation for the UK. The RAIB investigated a wide range of factors across various parts of the rail network system, e.g. the activities of frontline staff, management teams and regulatory inspectors. Therefore, the scope of the investigation and the comprehensiveness of the final report (see RAIB, 2011) provided a suitable data source for a systemic analysis.

5.4.2 Description of the accident

On 23rd February 2007 an express passenger train derailed as it entered the points (known as Lambrigg 2B points) located near Grayrigg in Cumbria, UK (RAIB, 2011). Points are an assembly of two movable (switch) rails and two fixed (stock) rails which are used to divert vehicles from one track to another (see Figure 25). For a detailed description of points components and operation see RAIB (2011 p.210-214).

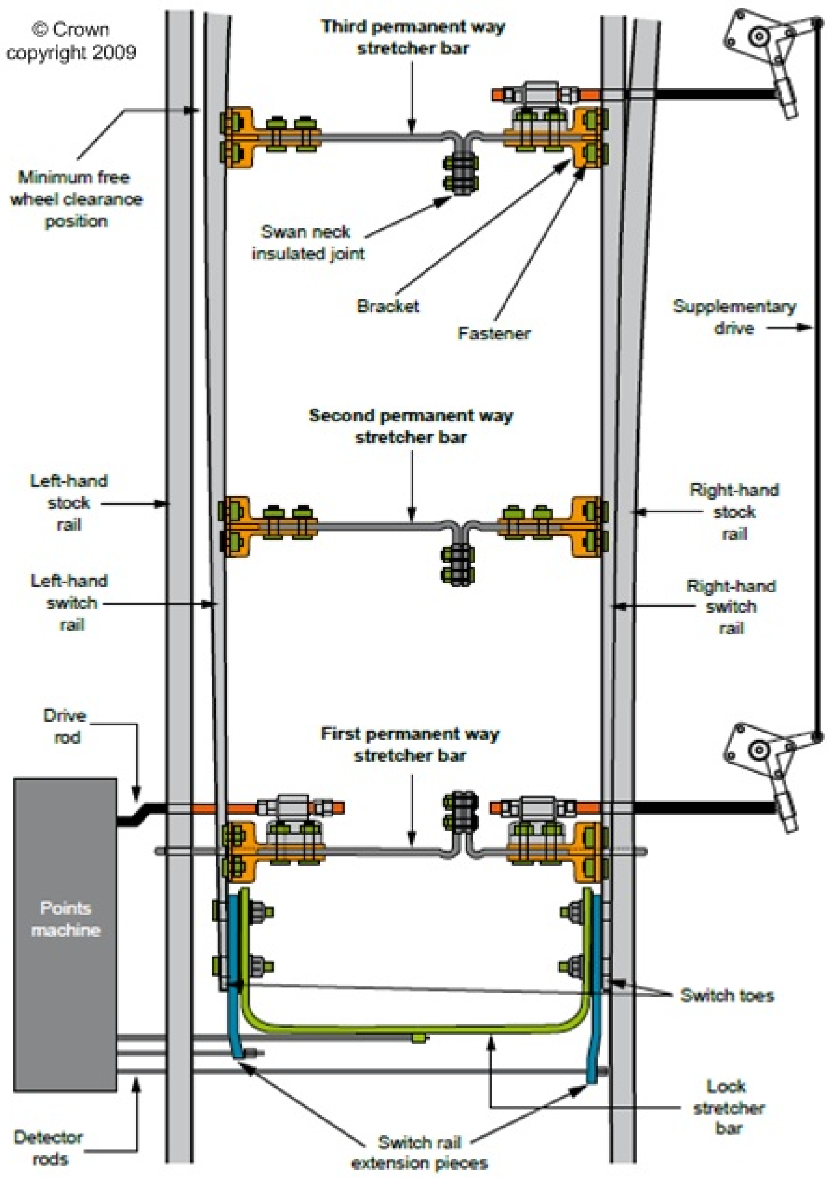

Figure 25 - Layout of points showing switch and stock rails and stretcher bars. From RAIB (2011).

All nine vehicles of the train derailed, eight of which subsequently fell down an embankment with five turning onto their sides (see Figure 26). The train was carrying four crew and at least 105 passengers at the time of the accident. One passenger was fatally injured; 28 passengers, the train driver and one other crew member received serious injuries and 58 passengers received minor injuries (RAIB, 2011).

Figure 26 - Aerial view of the derailed train (numbers represent train vehicle number). From RAIB (2011).

The subsequent investigation determined that the train derailed as it passed over 2B points, which were in an unsafe state that allowed the left-hand switch rail to move towards the left-hand stock rail. The left-hand wheels of the leading vehicle were subsequently forced into the reducing width between the switch rails and derailed by climbing over the rails. All the other vehicles derailed as a consequence. The RAIB concluded that various operational and environmental aspects (e.g. the actions of the driver, the condition of the train, the weather) had no bearing on the accident (RAIB, 2011 p.14). Therefore, the derailment was a maintenance related accident.

The unsafe state of the points was caused by successive failures of all three permanent way stretcher bar (PWSB) assemblies and the lock stretcher bar assembly. Three factors were deemed to have combined to create this situation: (1) the failure of the joint connecting the third PWSB to the right-hand switch rail which, together with (2) excessive residual switch opening (the gap between the rail heads of adjacent switch and stock rails on the closed side of points), caused the left-hand switch rail to be struck by passing train wheels (the resultant large cyclic forces caused rapid deterioration and the eventual failure of the remaining stretcher bars and their fasteners); (3) an inspection, scheduled for 18th February 2007, which should have detected the degradation, was not performed.

The omitted inspection was due to be undertaken by the local track section manager (TSM), who had volunteered to perform a routine visual check of the track. The RAIB concluded that restricted track access (resulting from a change in access policies in 2005 and the reduced daylight hours in winter) and limited staff availability contributed to the decision of the TSM to combine his own supervisory inspection with a basic visual inspection. The TSM, however, forgot to complete the points inspection. This omission was not identified in the maintenance review meeting on the following day and the maintenance records were incorrectly updated to show that the inspection had been completed. These events, which reduced the likelihood of any corrective action being taken, were also considered by the RAIB to have contributed to the accident.

A number of ‘underlying’ factors (which the RAIB associates with the overall management systems, organisational arrangements or the regulatory structure) were considered to have influenced the derailment. Examples include: (1) an incomplete understanding within Network Rail of points maintenance requirements, which resulted in an absence of clear, properly briefed standards for maintaining loose PWSB fasteners and residual switch opening; (2) the performance measurement of points was not based on a thorough understanding of risk and control measures; (3) underestimating the risks associated with the design of points with non-adjustable stretcher bars (as per the points involved in the derailment), which adversely affected inspection regimes, reporting of faults and maintenance activity. The official findings of the RAIB investigation are provided in Appendix 5.1 for reference.

5.5 Methods

5.5.1 Accident analysis process

The ATSB model and STAMP analyses of the Grayrigg derailment were performed by the first researcher (Underwood), as per the processes described in Sections 5.5.1.1 and 5.5.1.3[6]. The AcciMap analysis of the

[6] The analysis process described in Section 5.5.1 represents the approach taken by Underwood and Waterson (2013b). However, prior to the publication of the article the analysis of the Grayrigg accident had been performed with all three analysis techniques by the first researcher, the outputs of which were reviewed by the second researcher. The revised approach presented in Section 5.5.1 was employed in response to the comments from the article reviewers, who suggested that a more robust approach would involve both researchers independently conducting analyses with each method and the reviewing the differences between the findings. This was beyond the resource constraints of the study and

accident was performed by the second researcher (Waterson) in accordance with the process described in Section 5.5.1.2. Both individuals (human factors researchers) have experience of applying accident analysis methods in various domains (e.g. rail, aerospace, healthcare) and used the RAIB (2011) investigation report as the data source for the analysis activities. The report was imported into NVivo 9 and the text contained within the document, considered relevant to each analysis, was qualitatively coded (see Sections 5.5.1.1-5.5.1.3 for further details). This coded information was subsequently used to create the various analysis diagrams to ensure a direct link between the text in the report and the analysis outputs. Upon completion of the analyses, the researchers exchanged and reviewed the outputs and any discrepancies or disagreements were resolved through discussion until consensus was reached, as per the approach taken by Salmon et al. (2012a). As the researchers were familiar with all three methods and their application processes prior to commencing the study, it was judged that the cross-checking process was sufficiently robust. Only pre-derailment events were analysed due to study resource limitations.

5.5.1.1 ATSB model analysis process

The guidance provided by the ATSB (2008) on the use of the ATSB model refers to its application within live investigations. Therefore, no specific guidance was available with regards to its use for the analysis of completed investigations. The analysis process consisted of applying the ATSB safety factor definitions, as a coding framework, to the information in the RAIB (2011) report (see ATSB, 2008 p.38-42). When a given piece of information was identified as a safety factor the text was coded with and subsequently captioned, colour-coded and mapped on to the relevant section of an analysis chart, as per the format used by the ATSB (see ATSB, 2008 p.46).

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consequently the process described in Section 5.5.1 was adopted, i.e. the second researcher performing an AcciMap analysis of the accident which was reviewed by the first researcher. However, the data presented in this chapter, regarding the AcciMap analysis output and method evaluation, is primarily based on the original findings produced by the first researcher, which were very similar to those produced by the second researcher. This has been done to demonstrate that the first researcher has first-hand experience of using AcciMap and, therefore, can present the findings (e.g. the AcciMap analysis diagram, see Figure 29) in this chapter as original work.

Relationships between the safety factors were represented by arrows, to indicate the direction of influence, as per the ATSB (2008) approach.

5.5.1.2 AcciMap analysis process

AcciMap analyses have been conducted in various formats since the method's creation. This prompted Branford et al. (2009) to develop a standardised application process for the method, aimed at improving the consistency of its usage. However, it was judged that this process was too far removed from the original format introduced by Rasmussen (1997), which has been used in more contemporary research (e.g. Salmon et al., 2013; Stanton et al., 2012). Therefore the guidance offered by Svedung and Rasmussen (2002) was selected for use in this study. Information within the investigation report was coded if it described: (1) the topography of the accident scene; (2) a decision/action taken by an actor in the system; (3) a direct/indirect consequence; (4) a precondition requiring no further evaluation. This information was subsequently captioned, mapped on to the relevant sections of an AcciMap diagram and linked by arrows to represent the influence a given factor had on another, as per the format in Figure 17.

5.5.1.3 STAMP analysis process

The process of applying STAMP to analyse an accident consists of nine stages and is defined by Leveson (2012 p.349) as the CAST approach. The stages of CAST are summarised below:

1. Identify the system(s) and hazard(s) involved in the loss
2. Identify the system safety constraints and system requirements associated with the hazard
3. Document the control structure in place to control the hazard and enforce the safety constraints
4. Determine the proximal events leading to the loss
5. Analyse the loss at the physical system level
6. Analyse the higher levels of the control structure
7. Examine the overall coordination and communication contributors to the loss

8. Determine the dynamics and changes to the system and its control structure over time
9. Generate recommendations

The first eight steps of the CAST process were completed in order, although this was not a necessity, as noted by Leveson (2012 p.350). The final stage, i.e. generating recommendations, was not performed as this was outside the scope of the study. The information required for each stage of CAST was used as a coding framework to facilitate the identification of relevant data within the RAIB (2011) report. For example, once a higher-system level component had been identified, text was coded if it described the component's: safety-related responsibilities; unsafe decisions and control actions; the reasons for the unsafe decisions/actions; relevant contextual information (as per stage 6 of the CAST process).

5.5.2 Analysis model evaluation

The analysis techniques were evaluated using a modified version of the evaluation framework developed in Study 1 (see Figure 11) which focused on two topics of interest: (1) coverage of systems theory concepts and (2) model usage characteristics. As described in Section 3.3.4.2, the ability of an analysis model to employ the systems approach is governed by the number of the core systems theory concepts it incorporates; an issue of clear importance to this study. Furthermore, the usage characteristics of an analysis technique will affect whether an individual can effectively perform SAA or not (see Section 3.3.4.3), hence the inclusion of the second section of the framework. The following alterations to the Study 1 framework were made to ensure a greater relevance to this study: an examination of the model development process was not required and, therefore, the first part of the Study 1 framework was removed; the systems approach characteristics were revised to reflect the factors highlighted in the SAA literature, as identified in Study 1 (see Section 3.4.1) and described in the more recent literature (see Section 3.5.3); the usage characteristics included in the updated framework were, based on the findings of Studies 1 and 2, considered more appropriate to evaluate model usage. The evaluation framework is graphically depicted in Figure 27.

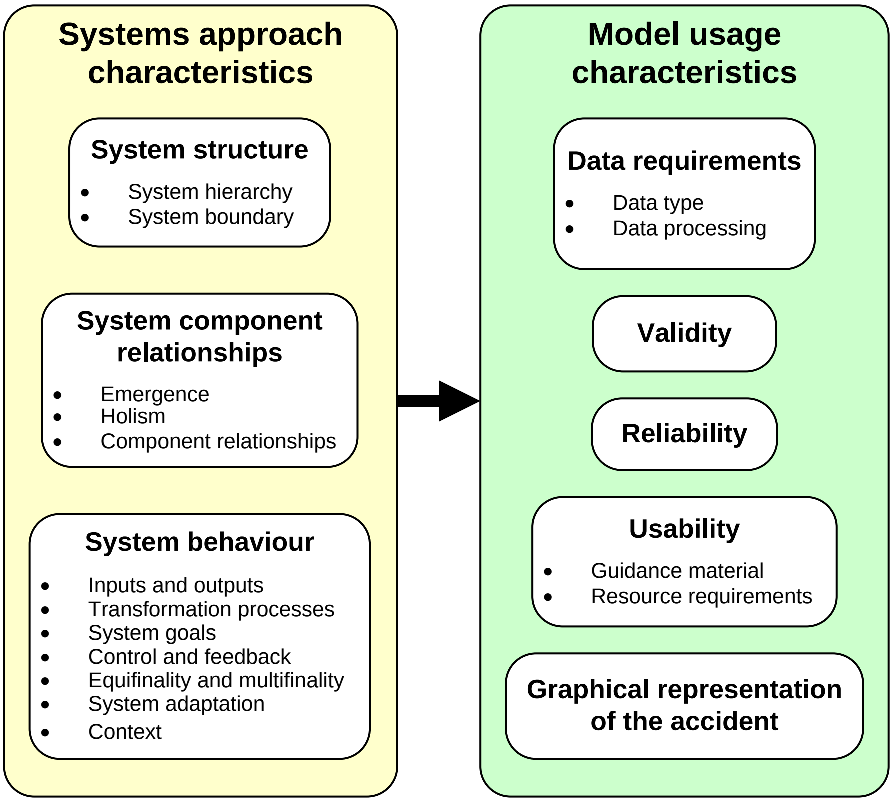

Figure 27 – Study 3 evaluation framework

For the sake of clarity, the different elements of the evaluation framework are described in Sections 5.5.2.1 and 5.5.2.2.

The outputs and usage of the models were assessed by both analysts in relation to the components of the evaluation framework, in order to facilitate a systematic comparison. As per the accident analysis process, any disagreements in the evaluations were resolved through discussion until consensus was reached[6].

5.5.2.1 System approach characteristics

System structure

Systems are generally based on a hierarchy of subsystems which are formed in order to perform specific functions (Skyttner, 2005). In order to understand a system, it is necessary to examine each relevant hierarchical level and its relationship with adjacent levels. Moving up the hierarchy provides a deeper understanding of a system's goals, whereas examining lower levels reveals how a system functions to meet those objectives (Vicente, 1999). Furthermore, determining the boundary of a system, i.e. distinguishing between what is part of the system and what is part of the environment, is an important aspect of specifying its hierarchy (Jönsson, 2007).

System component relationships

The interaction of system components results in emergent behaviour, e.g. safety (Leveson, 2012). Therefore, STS will display characteristics and operate in ways not expected or planned for by their designers (Wilson, 2013). Such behaviour cannot be explained by studying system components in isolation: the whole is greater than the sum of its parts. A system must be studied holistically, i.e. all components, human and technical, need to be considered as well as the relationships between them (Read et al., 2013).

System behaviour

Inputs are converted into outputs, via transformation processes, in order to achieve system goals, e.g. safe operations. If system goals are to be reached and safety maintained, a system's components must be controlled via feedback mechanisms when deviations in behaviour occur (Skyttner, 2005). Dynamic system behaviour means that a goal can be achieved from a variety of initial starting conditions (equifinality). Alternatively, systems can produce a range of outputs from an initial starting point (multifinality). This dynamic behaviour also means that systems can adapt over time to changing conditions and may migrate towards a state of increased risk and drift into failure (Dekker, 2011; Leveson, 2011). Furthermore, system components do not operate in a vacuum and their performance must be placed within context, i.e. how local goals, resources and environmental conditions influenced their behaviour.

5.5.2.2 Model usage characteristics

Data requirements

The output of any analysis is defined, in part, by the ability of a method to analyse and incorporate a given piece of evidence (e.g. photographic, documentary, witness testimony etc.). Furthermore, the information that a method requires to produce a thorough analysis (e.g. data related to technical failures, human factors, organisational practices etc.) can impact on the evidence collection process in an investigation. The importance of how a method processes information and its data requirements has been recognised in previous method evaluation studies (e.g. Herrera and Woltjer, 2010; Stanton et al., 2012; Waterson and Jenkins, 2010).

Validity and reliability

The closely related issues of validity and reliability are important factors in successfully applying any type of analysis method. Previous studies have acknowledged this significance by including validity and reliability (and topics related to them) as method evaluation criteria (e.g. Benner, 1985; Stanton et al., 2012; Wagenaar and van der Schrier, 1997). The need for valid and reliable methods was also identified as a requirement of practitioners who are engaged in accident analysis (see Section 4.4.3.1).

Usability

The usability of an SAA technique will clearly affect whether an analysis is performed effectively and efficiently and, therefore, it must be easy to understand and apply. The availability and clarity of guidance material as well as the training and resources required to use SAA methods have all been cited as factors which can influence their usability (e.g. Branford et al., 2009; Johansson and Lindgren, 2008; Stanton et al., 2012).

Graphical representation of the accident

The graphical output of a method also affects the ability of an individual (or team of investigators) to successfully perform an analysis. Graphically representing an accident has been considered to be useful by both researchers (e.g. Sklet, 2004; Svedung and Rasmussen, 2002) and practitioners (e.g. ATSB, 2008) for a number of reasons. For example, it can be easier to see the relationships between system components and identify gaps/weaknesses in the analysis. Also, charting an accident can be useful for communicating the findings of complex investigations (ATSB, 2008).

5.6 Findings

5.6.1 Applying the analysis models to the Grayrigg accident

5.6.1.1 ATSB model analysis output

The analysis chart produced by the ATSB model analysis is presented in Figure 28.

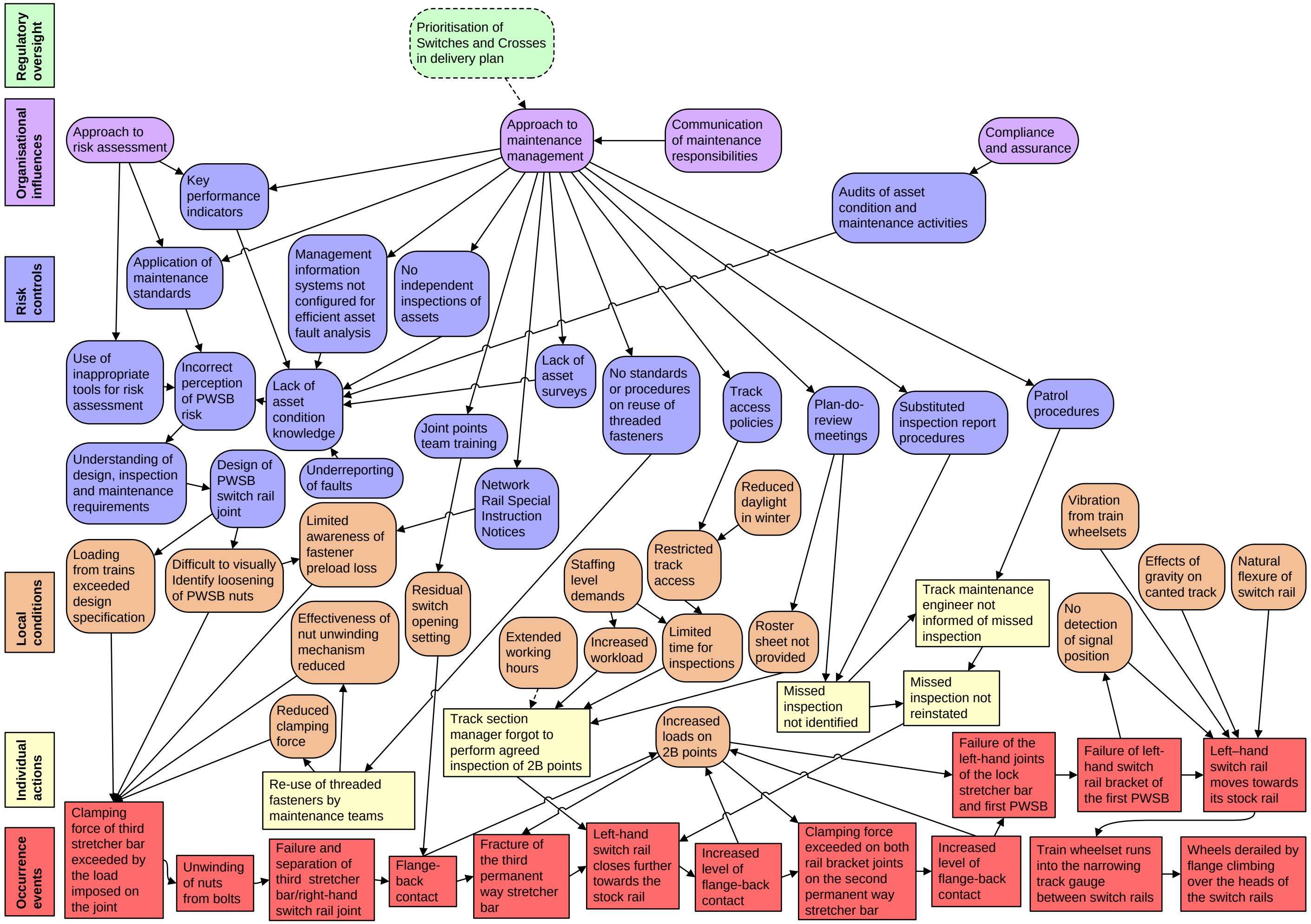

Figure 28 – ATSB model analysis of the Grayrigg accident (dashed lines indicate a possible but not probable factor/relationship)

The derailment of the wheels of the leading vehicle was the single occurrence event attributed to the accident. However, various technical issues were included in the analysis chart to represent the gradual deterioration and failure of the points which led to the derailment. These technical problems were also incorporated to more clearly describe the multiple interactions between them and the individual actions and local conditions associated with the accident. Figure 28 shows that there were few, albeit important, individual actions/inactions that contributed to the accident, such as the missed inspection of the points by the TSM. Conversely, a larger number of local conditions and inadequate risk controls were identified as factors which negatively affected the work of the maintenance staff and condition of the points. However, as shown in Figure 28, some of the local conditions resulted from technical problems and individual actions. Few organisational influences were classified during the analysis. However, these factors were shown to have a wide ranging adverse influence on numerous risk controls. In particular, Network Rail's approach to maintenance management was identified as a significant influence on the ineffectiveness of many risk controls. The analysis chart shows six levels of safety factors to account for the role that regulatory oversight played in the accident. Although this sixth 'regulatory' level goes beyond the official format of the ATSB model (see Figure 24), charting the influence of the regulators has occurred in previous ATSB investigations (ATSB, 2008 p.46). Therefore, given that the RAIB investigated the actions of the regulator, it was deemed acceptable to incorporate the additional safety factor level. However, as indicated on the analysis chart, the actions of the regulator were not considered to have a significant impact on Network Rail's maintenance management.

5.6.1.2 AcciMap analysis output

The AcciMap diagram resulting from the analysis is presented in Figure 29.

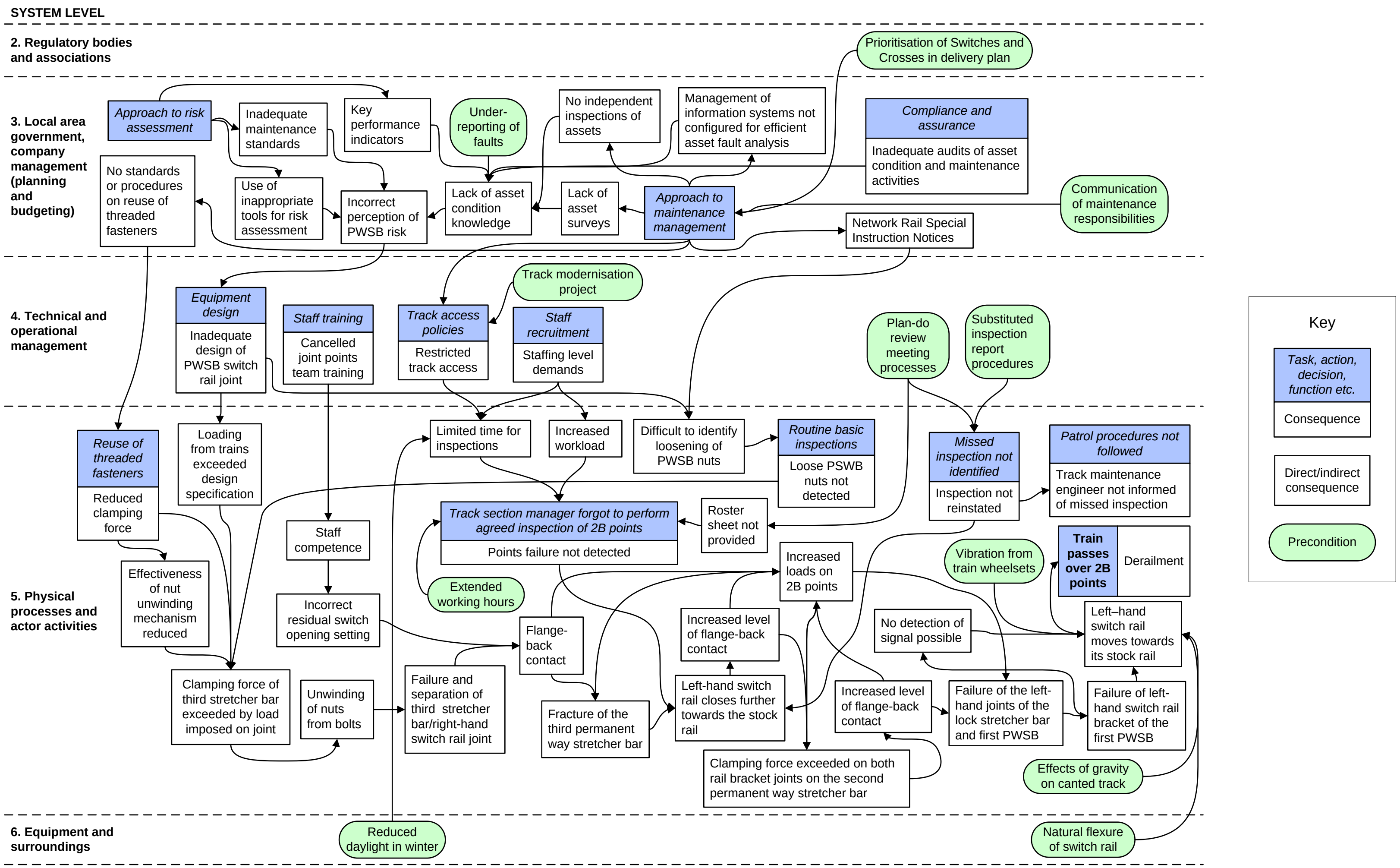

Figure 29 - AcciMap analysis of the Grayrigg accident

Similarly to the ATSB model analysis, the train passing over the failed 2B points and derailing were considered to be the critical event and its direct consequence respectively. Only two ‘equipment and surroundings’ related issues were identified during the analysis. However, they both influenced two key factors in the accident, i.e. the missed inspection by the TSM and the movement of the left-hand switch rail, which contributed to the points being impassable. Five human actor activities were included in Level 5 of the AcciMap diagram and focused on two important issues: (1) the reuse of threaded fasteners and (2) the undetected physical faults. These actor activities either directly or indirectly contributed to the physical processes associated with the points’ degradation. For example, the reuse of threaded fasteners directly contributed to the inability of the points to withstand the physical loads from rail traffic. Furthermore, the missed TSM inspection indirectly contributed to the failure of the points, as an opportunity to identify the required maintenance was missed. A relatively higher number of physical processes, in comparison with actor activities, were incorporated into the analysis diagram to describe the gradual deterioration and failure of the points. A number of influential decisions taken at Level 4 of the system, i.e. technical and operational management, were identified. These decisions had direct consequences which subsequently affected the physical processes and actor activities linked with the derailment, e.g. local track access policies restricted the time available to conduct inspections. Additionally, the relatively fewer risk assessment and maintenance management decisions attributed to the Level 3 company management influenced numerous direct and indirect consequences. These consequences, in turn, either directly or indirectly influenced activities at the lower system levels, as shown on the analysis chart. The AcciMap diagram did not include Level 1 of the system, i.e. national government, as no information was available in the report to populate this section of the chart.

5.6.1.3 STAMP analysis output

The first stage of the STAMP analysis, as described in Section 5.5.1.3, required the identification of the system and hazard involved in the accident. These were defined as the ‘UK railway’ and ‘train derailment due to failed points’ respectively. Two system safety constraints were subsequently associated with controlling the hazard: (1) the physical points components must operate within design limits; (2) maintenance and repair activities must correct any points defects. The hierarchical control structure, as it existed at the time of the accident, consisted of multiple organisational functions which had a responsibility for ensuring safety on the railway (see Figure 30).

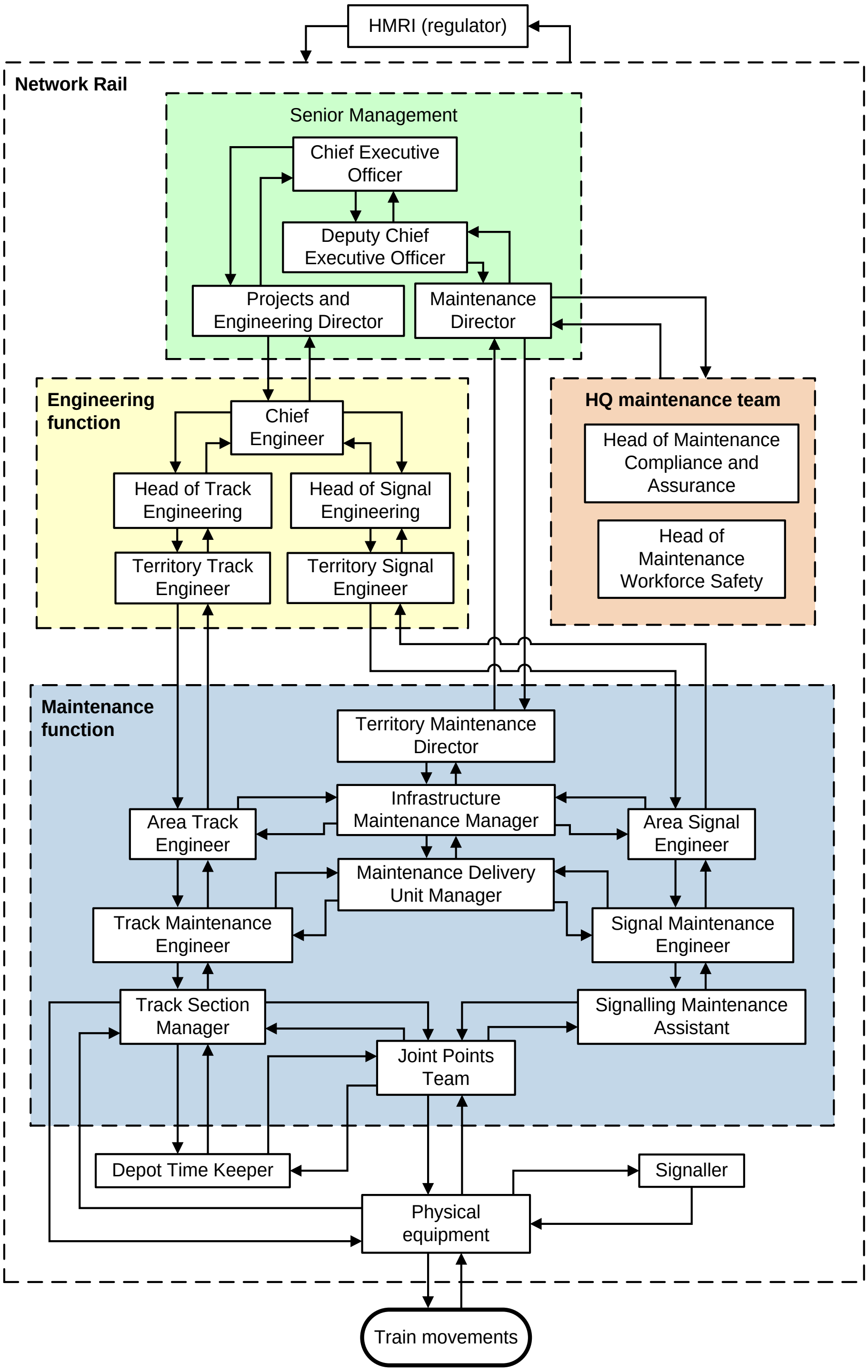

Figure 30 - The control structure in place at the time of the Grayrigg accident

Defining the control structure involves describing the roles and responsibilities of each component in the system, as well as the controls and feedback available to them. However, for the sake of clarity and because some of this information was not available in the RAIB (2011) report, this description has not been included in Figure 30. The proximate events leading up to the accident are described, in terms of the condition of the points and the maintenance activities, in Table 11. These events, e.g. the missed inspection on 18th February 2007, acted as reference points to begin the analysis of the derailment at the physical system level and the lower levels of the control structure.

Date	Event
1st December 2006	Supervisor's inspection identified loose check rail bolts on crossing of 2B points
6th-7th January 2007	Overnight repair of defects identified on 1st December 2006
7th January 2007	Basic visual inspection identifies third PWSB right-hand bracket joint fasteners had failed and were renewed
8th January - 12th February 2007	Third PWSB right-hand bracket failed again, third PWSB subsequently fractures
14th January 2007	Routine patrol reported no defects
21st January 2007	Routine patrol reported no defects
25th January 2007	Supervisor's inspection identified alignment defects with rectification required within six months
28th January 2007	Routine basic visual inspection reported no defects
4th February 2007	Routine basic visual inspection reported no defects
11th February 2007	Routine basic visual inspection reported no defects
11th-21st February 2007	Second PWSB joints failed and PWSB missing from points
18th February 2007	Missed basic visual inspection
21st-23rd February 2007	First PWSB and lock stretcher bar failed
23rd February 2007	Derailment

Table 11 - The proximal events leading to the Grayrigg accident. Adapted from RAIB (2011 p.123-24).

The subsequent analysis of the system components, considered to have had the most influence on the accident, is presented in Figure 31 and Figure 32.

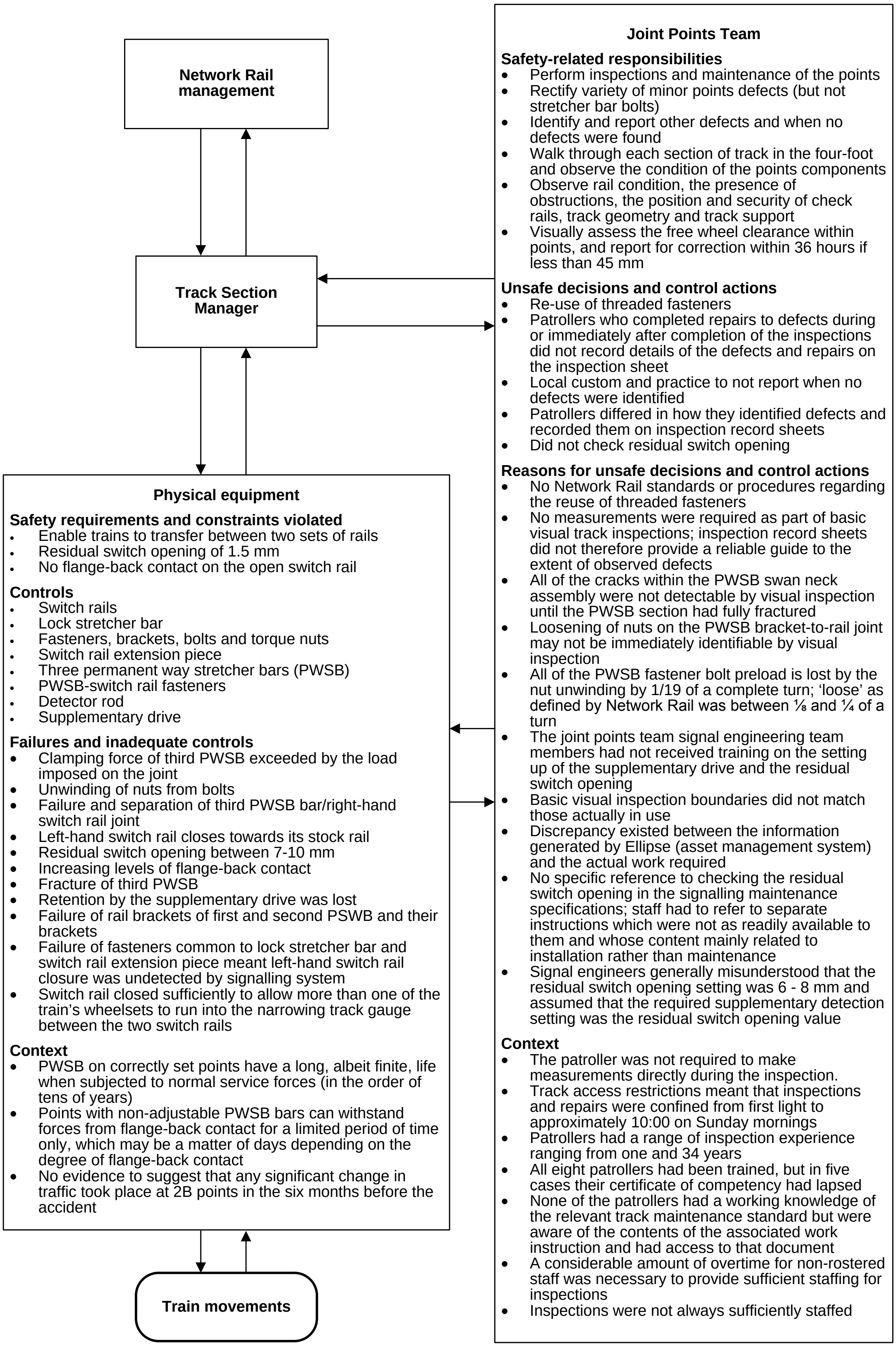

Figure 31 - STAMP analysis of lower-level system components

Network Rail management

Safety-related responsibilities
- Specify and manage maintenance policies, regimes, work instructions, technical specifications and engineering standards
- Provide leadership and technical guidance to engineering and maintenance technical specialists
- Accountable for the quality of technical advice and support provided to the business
- Ensure compliance of patrolling, inspections, examinations and maintenance to company standards and procedures
- Ensure infrastructure was compliant with company standards and available for operation
- Disseminate information regarding maintenance regimes throughout the organisation

Unsafe decisions and control actions
- No standards or procedures regarding the reuse of threaded fasteners were produced
- Evaluation of the effect of timetable changes did not consider or identify that any changes might lead to greater difficulty for maintenance and inspection staff in gaining access to the track
- Network Rail neither routinely nor regularly carried out surveys across a representative sample of point components to provide a reliable source of independent data on asset condition
- Management information systems (SINCS and Ellipse) were not configured to permit efficient analysis of types of failures and identification of trends across a large population of switches and crossings
- Management processes no longer required that independent inspections of asset condition were carried out, as had been the case when maintenance was carried out by contractors
- Key performance indicators did not include any specific reference to the condition of stretcher bars, brackets, fasteners or flangeway clearance
- Audit process did not include checks of asset condition or observation of inspection/maintenance activities
- Approach to the assessment of risk from points defects was based on the RSSB's safety risk model and the linked precursor indicator model which did not provide an appropriate level of resolution to enable the risk impact of individual components to be identified or the input of data derived from 'bottom-up' analytical techniques
- Monitoring of the reliability of non-adjustable stretcher bar components was incomplete and it did not carry out a detailed assessment of the adequacy of the design and inspection/maintenance arrangements

Reasons for unsafe decisions and control actions
- There was an absence of awareness throughout Network Rail of the importance of the residual switch opening and its relationship with flange-back contact, and of the need to check and rectify residual switch opening
- Network Rail did not have any comprehensive data about the condition of stretcher bars, brackets and fasteners across its network at the time of the accident which contributed to an incomplete understanding of the performance of its switches and crossings assets at component level
- The high reliance on historical data at the system level and the limited application of predictive tools reduced the likelihood that Network Rail would recognise the performance of non-adjustable stretcher bar components as an important risk management issue
- Network Rail did not see switches and crossings with non-adjustable stretcher bars to be a significant risk, providing they were properly set up, maintained and inspected
- At all levels of the organisation, managers considered the tightening of bolts on stretcher bars to be a routine, normal activity that had always been undertaken by maintenance staff
- Understanding of the performance of its existing points with non-adjustable stretcher bars was incomplete
- Senior managers had not recognised that at some locations the safe performance of existing S&C with non-adjustable stretcher bars had become over-reliant on routine inspection and maintenance activities

Context
- Inherited standards and working practices, e.g. joint points team working, from previous infrastructure owner, operator and maintenance organisation and sub-contractors
- Network Rail standards for the maintenance of signalling assets recognised the value of predicting the hazards associated with failures of both systems and components (and failures to inspect or maintain), by using techniques such as failure modes and effects analysis, Hazard and Operability Study and Task Analysis. However, application of the standards was only mandated for changes to maintenance regimes, or for new assets.
- Until April 2006 there had been no requirement to report loose or missing bolts on stretcher bars. Once this became a requirement there is evidence of significant underreporting

Track Section Manager

Safety-related responsibilities
- Perform supervisor's inspections
- Identifying work to be planned and carried out
- Review trends in condition
- Identifying items to be proposed for renewal
- Check that basic and special track inspections, maintenance and renewal work were effective
- Measurement free wheel clearance
- Determine and prioritise the actions needed to address defects identified
- Arrange entry of defects that required remedial work into Ellipse asset management system
- Manage track engineering staff in the joint points team
- Manage the competence of track engineering staff

Unsafe decisions and control actions
- Forgot that he had agreed to carry out basic visual inspection of track section, which included points, as well as his own supervisor's inspection on 18^{th} Feb 2007
- Produced a report for his inspection, using a template which referenced the supervisory inspection boundary at 23 miles 1320 yards as the northern limit of his inspection, even though he had stopped 640 yards south of this point

Reasons for unsafe decisions and control actions
- Did not receive a copy of the inspection roster sheet, as per normal, and was therefore not reminded that he had agreed to inspect the points on 18^{th} Feb 2007
- Began his inspection on 18^{th} Feb 2007 with two specific objectives in mind: re-check a site of remedial tamping and inspect a section of track where severe rail head wear was occurring, i.e. possibly distracted from inspecting the points

Context
- Usually worked 50 to 60 hours per five day working week, including Sundays when rostered, to meet workload demands
- Did not manage to achieve all the inspections that he was required to do personally, although they were being carried out by his assistants.
- Volunteered to cover basic visual inspection the same time as undertaking a supervisor's inspection in order to release two members of staff to undertake outstanding maintenance work
- Inspection and maintenance activity was undertaken at the specified frequency but was of varying quality, which affected the reliability of the outcome

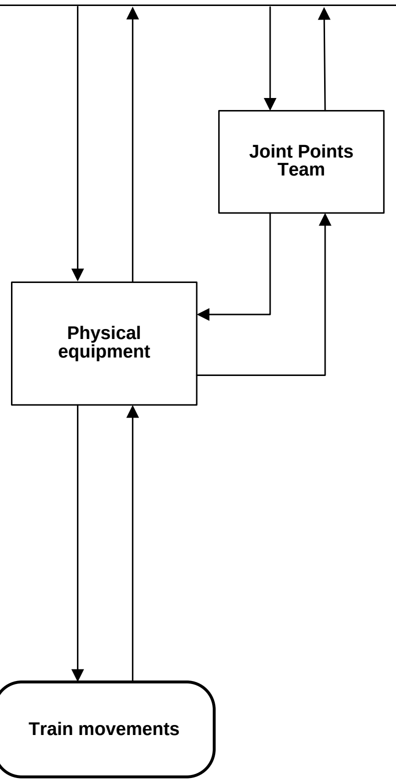

Figure 32 - STAMP analysis of higher-level system components

Many of the actions and decisions taken by the higher levels of the control structure were summarised by the RAIB (2011) as Network Rail's management arrangements. Therefore, these higher level components were amalgamated into a 'Network Rail management' component in order to facilitate the analysis.

A number of long-standing and proximal issues were identified whilst assessing the overall coordination and communication throughout the system. Respective examples include: no training was provided to the maintenance teams concerning the required setting for residual switch opening; the points failure was undetectable by the signalling system. Network Rail experienced large changes to its control structure since it took over the running of the rail infrastructure in 2002. However, it was not possible to identify whether these changes resulted in the system migrating to a higher state of risk and increasing the chance of an accident.

5.6.2 Comparing the analysis models

5.6.2.1 Systems approach characteristics

System structure

All three techniques require the analysis of the whole system hierarchy which was responsible for preventing the accident, up to and including the regulatory level. However, the ATSB model and AcciMap require the description of events, actions and conditions, rather than system components. Therefore, their analysis charts provide little information about the structure of the system in question, or its boundary. Conversely, the STAMP analysis requires the documentation of the system control structure and provides a clear visual description of the system hierarchy. The boundary of the system (and those of its sub-systems) is defined by the boundary of responsibility for a given hazard and safety constraint (Leveson, 2012). For example, the condition of the points was the responsibility of Network Rail, whereas the condition of the train involved in the accident was the responsibility of a different maintenance organisation (Alstom Transport West Coast Traincare Ltd).

System component relationships

Each model requires the analyst to take a holistic view of the system, i.e. examining the interaction between the various elements of the system, albeit in different ways. The ATSB model and AcciMap analysis charts, rather than describing the system components and their relationships, show the outputs of these relationships and how they reduced system safety. By documenting the control structure, the CAST process shows the relationships between the various system components. The subsequent stages of the analysis then examine how the dysfunctional interactions between a given component and the rest of the system contributed to its unsafe actions and/or decisions (see Figure 31 and Figure 32).

System behaviour

The ATSB model and AcciMap analysis charts describe (via the caption boxes) key input and output conditions of system components. The transformation processes, which convert the inputs to outputs, are indicated by arrows, although details of the processes are not provided. In keeping with its control theoretic underpinnings, STAMP describes system inputs as the information available to a given component and the control instructions it receives. Component outputs, e.g. unsafe control actions, are described as well as the reasons why they happened, i.e. why the associated transformation processes failed.

Neither the ATSB model nor AcciMap require the analyst to state the safety-related goals of the system. However, they are implicitly addressed, as the principal goal of the system is clearly the avoidance of the main occurrence/critical event. STAMP, however, explicitly defines the system- and component-level safety-related goals during the various stages of the analysis.

The adequacy and impact of the controls and feedback within the system is addressed by the ATSB model via the analysis of the risk controls created by the organisation. The same is true of the AcciMap method, although this information is presented in the decisions and/or consequences caption boxes across the diagram. However, the influence of missing/inadequate feedback on management activities and decisions is not included in either analysis chart. Examining the control and feedback in a system is a core requirement of the STAMP analysis process. As such, this is clearly documented in the system control structure and the detailed analysis of each component.

The ATSB model prompts the investigation of how the system's behaviour changed over time. This is achieved by examining and charting the proximal events and conditions that occurred locally to the accident site, as well as the organisational and regulatory factors that were created further back in the system's history. This approach is also taken by the AcciMap method. The requirement of CAST to determine the proximal and historic events leading to an accident ensures that the changes in system behaviour are analysed.

The context in which actions and decisions were taken by the various frontline system components are explicitly incorporated into the ATSB model via the description of the local conditions. Although the context in which organisational and regulatory issues were created is not present in the analysis chart, the ATSB suggests that this contextual information can be a useful addition to an analysis (ATSB, 2008 p.44). By describing preconditions and the direct/indirect consequences created throughout the system, AcciMap depicts the context in which decisions and activities took place at the various system levels. The local context in which system component behaviour took place is explicitly addressed by CAST via the detailed analysis of the control structure (see Figure 31 and Figure 32).

Given that accident investigation involves determining why a particular set of events and conditions contributed to an accident, the ability of the models to represent equifinality and multifinality is a moot point. A summary of the systems approach characteristics comparison is provided in Table 12.

Systems approach characteristic	ATSB model	AcciMap	STAMP
System structure	Requires analysis of the whole system. Describes system as combination of events, actions and conditions. Little information about system structure or boundary provided.		Requires analysis of the whole system. System structure and boundary defined by hierarchy of components responsible for controlling safety constraints. System structure graphically described.
System component relationships	Takes a holistic view of the system. Describes the safety-related outputs of relationships throughout the system and their affect on other relationships.		Takes a holistic view of the system. Describes component relationships throughout the system and their impact on safety.
System behaviour	Incorporates all aspects of system behaviour, although some are only partially described (e.g. feedback availability and context of behaviour at the organisational level). Short- and long-term system history is examined.	Incorporates all aspects of system behaviour, although some are only partially described (e.g. systems goals and feedback availability at the organisational level). Short- and long-term system history is examined.	Incorporates all aspects of system behaviour, which are described in the analysis output. Short- and long-term system history is examined.

Table 12 - Systems characteristics approach comparison

5.6.2.2 Model usage characteristics

Data requirements

Due to their holistic approach, all of the models require various types of data to be collected from all of the relevant parts of the STS and its environment. In practice, accident investigators will obtain this evidence in a variety of formats, such as photographic, documentary and witness testimony. A range of preliminary analysis activities is required to convert this data into a format suitable for the subsequent analyses (ATSB, 2008 p 49). This involves the use of techniques to interpret and organise data, e.g. employing photogrammetry to measure the distribution of a wreckage trail from an accident site photograph. The ATSB model, AcciMap and STAMP analyses are, therefore, summaries of the findings produced by these more specific analytical processes. Consequently, the type of information that the models can analyse is not restricted by the original format of the data. More data is, however, explicitly required by STAMP, e.g. details on the system structure and components.

Validity

Capturing all of the complexity in a large STS is seemingly beyond the capability of an individual analysis model and the resource constraints of accident investigation. Therefore, proving the internal validity of the three analysis techniques is not possible. In fact, the ATSB model does not attempt to describe all of the complexities involved in accident causation. Rather it favours providing a general framework that helps guide data collection and analysis during an investigation (ATSB, 2008 p.36). Conversely, AcciMap purposefully sets out to analyse the dynamic behaviour that exists within a system and how it contributes to accidents. Likewise, STAMP deliberately addresses how complexity within a system influences accident events. Regardless of these different approaches, each model was devised specifically for the purposes of accident analysis, is based on a recognised theory of accident causation and has been used across multiple domains, which suggests an acceptable degree of face and external validity exists.

Reliability

The qualitative nature of the models negatively impacts on their reliability. None of the techniques provide a detailed taxonomy of contributory factors, which further reduces their reliability and the chance to perform accident trend analysis. However, this also means the analyst has more freedom in how they classify such factors. It is understood that the ATSB use a taxonomy in their accident database, however, details about its content are not publically available (see ATSB, 2008 p.9). The reliability of the ATSB model and STAMP is, however, improved by the detailed descriptions of safety factors and accident causes and the model usage guidance provided by the ATSB (2008) and Leveson (2012). Therefore, both models are considered to have moderate inter-rater reliability. The AcciMap guidance material (e.g. Svedung and Rasmussen, 2002) provides little support in comparison and, therefore, was considered to have low inter-rater reliability.

Usability

Assessing how easy the analysis tools are to understand and apply clearly involves the subjective opinion of the user, an issue which is discussed in Section 5.7. However, a number of observations regarding the availability and clarity of the guidance material which supports the techniques can be made.

The ATSB (2008) provide a substantial amount of information regarding the theoretical aspects of their model and how it can guide the collection and analysis of data in an investigation. Structured approaches for identifying potential safety factors and testing their validity are also given. The usage guidance provided for STAMP (Leveson, 2012) is also considerable and describes systems theory, how it is applied by STAMP and how to use STAMP to analyse accidents. Therefore, the analyst is provided with a body of information that can facilitate a more effective and efficient analysis. However, the ATSB model and STAMP guidance contains a substantial amount of jargon, such as ‘safety factor’ and ‘safety constraint’, and the analyst is required to read a considerable amount of information to gain a full understanding of how to apply the models. The guidance available for AcciMap also provides a detailed description about the conceptual aspects and purpose of the method, i.e. the analysis of a system's dynamic behaviour and the variable performance of its components. However, little guidance is provided about how to apply the method and, although there is arguably less jargon associated with the technique, it seems likely that the analyst would have to carefully study the available information to fully understand how to apply AcciMap. Whether the analyst is taught how to use any of these models via self-learning or a training course, conveying such a large amount of information will clearly require more time and funding compared with simpler analysis techniques. The holistic approach taken by the models also means significant resources will be required for data collection.

Graphical representation of the accident

The graphical output of the ATSB model, based on the AcciMap format, provides a description of the accident scenario on a single diagram (see Figure 28). The use of colour coding helps to distinguish between the various different types of safety factors presented on the chart. The influence that a given safety factor has had on others is clearly indicated by arrows linking the caption boxes. Furthermore, by including the sequence of occurrence events leading up to the accident, the reader is provided with a sense of how the accident developed over time. In combination, these features provide a relatively simple means of understanding and communicating the findings of an analysis, albeit that knowledge of the ATSB model and its terminology is required to interpret the diagram. Similarly, AcciMap describes the accident scenario on one diagram (see Figure 29), provides information about the proximal sequence of events (via information contained in Level 5 of the analysis chart) and the relative influence of the identified actions, decisions and consequences etc. Given that there is comparatively little jargon associated with the method, the AcciMap chart is also relatively simple to understand. However, the lack of colour-coding utilised by Rasmussen (1997) and Svedung and Rasmussen (2002) (see Figure 17) arguably increases the difficulty in reading an AcciMap analysis chart (additional colour-coding was implemented by the researchers to ease the visual communication of the AcciMap findings). STAMP presents the findings of an analysis over several documents, some of which are mainly text based (e.g. Figure 31), and does not lend itself to a simple graphical representation of an accident (Leveson, 2012 p.91). Therefore, graphical communication of the accident analysis findings is not performed as efficiently as the ATSB model or AcciMap. A summary of the model usage characteristics comparison is provided in Table 13.

Model usage characteristic	ATSB model	AcciMap	STAMP
Data requirements	Data required from all system levels. Compatible with all forms of data.		
Validity	Provides a general framework devised for accident analysis. Underpinned by a recognised accident causation theory. Used in multiple domains. Face and external validity provided.	Specifically designed to analyse the dynamic behaviour of a system. Underpinned by a recognised accident causation theory. Used in multiple domains. Face and external validity provided.	Specifically designed to analyse the complexity in a system. Underpinned by a recognised accident causation theory. Used in multiple domains. Face and external validity provided.
Reliability	Qualitative technique with no detailed (publically available) taxonomy of contributory factors. Safety factor definitions and analysis process guidance provided. Moderate reliability achieved.	Qualitative technique with no detailed taxonomy of contributory factors. Little analysis process guidance provided. Low reliability achieved.	Qualitative technique with no detailed taxonomy of contributory factors. Structured analysis process guidance and classification of accident causes provided. Moderate reliability achieved.
Usability	Substantial guidance provided about the model, its application and safety factor identification and testing. Resource intensive to learn and use.	Substantial guidance provided about system behaviour and the purpose of Accimap. Little application guidance provided. Resource intensive to learn and use.	Substantial guidance provided about systems theory, its use in STAMP and the application of the model. Resource intensive to learn and use.
Graphical representation of the accident	All (colour coded) safety factors, their relationships and proximal timeline included in one diagram. Effective visual communication of accident.	All actions, decisions and consequences etc., their relationships and proximal timeline included in one diagram. Effective visual communication albeit lack of colour-coding reduces effectiveness.	Findings presented over several documents. Model does not lend itself to simple graphical representation. Ineffective visual communication of accident.

Table 13- Model usage characteristic comparison

5.7 Discussion

5.7.1 Comparing the analysis models

5.7.1.1 Systems approach characteristics

The ATSB model, AcciMap and STAMP all employ the systems approach, i.e. they require the analysis of a system's structure, the relationship of its components and its behaviour. However, there is a considerable difference between how the models achieve this.

A number of the systems theory concepts are only implicitly and/or partially contained within the ATSB model. This is particularly true with respect to the description of the system structure and its boundary, the impact of missing/inadequate feedback and contextual factors on the actions and decisions made at the organisational level (see Section 5.6.2.1). Indeed, the ATSB (2008 p. 47) suggest that the model does not fully explain the complex, dynamic nature of accident development. Therefore, strict adherence to the format of the ATSB model may result in an incomplete application of the systems approach. However, although such usage may prevent investigators from exploring all of a system's complexity, the model does not preclude this in anyway either (Ghirxi, 2010). If investigators understand and apply the systems theory concepts during an investigation then the ATSB model can fulfil its intended role as a framework for analysis activities and act as a gateway to SAA (see Section 5.3.1).

Similarly to the ATSB model, AcciMap implicitly or partially describes the system structure, its boundary and the impact of missing/inadequate feedback. It does, however, provide a clearer representation of the context in which managerial decisions and activities took place. Nevertheless, a prescriptive application of the method may also result in an incomplete systemic accident analysis. Some of the system theory concepts implicitly covered by the ATSB model and AcciMap would naturally be addressed by investigators, such as identifying the components involved in an accident. For example, an 'individual action' cannot be examined until the person who performed that action is known. However, without explicit instructions to do so, some information may remain uncollected and/or undocumented, e.g.

missing/inadequate feedback. In the case of AcciMap, this problem can be overcome by using the ActorMap and InfoFlowMap techniques that also form part of the risk management process suggested by Svedung and Rasmussen (2002 p.403). The ActorMap identifies the organisational bodies and individual actors involved in risk management whereas the InfoFlowMap graphically represents the communication between these decision makers. Whilst originally intended for use in risk management, these techniques could easily be utilised to provide information about the system components involved in an accident and any missing/inadequate communication. However, the use of additional techniques has usage implications, which are discussed in Section 5.7.1.2.

STAMP more clearly embodies the core components of systems theory (see Table 12). This is unsurprising, given that it was specifically designed to employ a systems approach to accident analysis. Furthermore, the structured process for applying STAMP deliberately guides the analyst to consider these core components. By doing so, STAMP arguably provides a more effective means of applying the systems approach. Therefore, when considering how much of the systems approach *could* be applied during a live investigation, the difference between the models seems to be a small one. Instead, the more noticeable difference between the ATSB model, AcciMap and STAMP comes from how they guide investigators to apply the components of systems theory. The systems approach characteristic comparison of the models is visually represented in Figure 33.

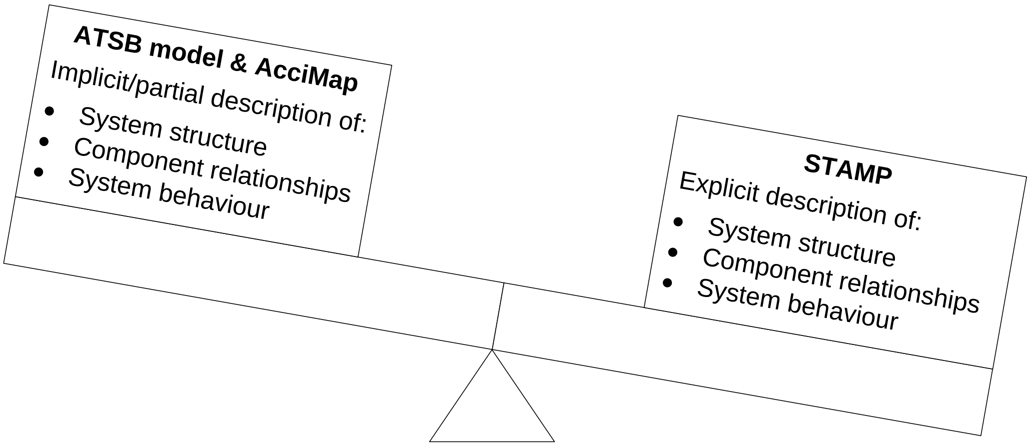

Figure 33 - Systems approach characteristic comparison of the ATSB model, AcciMap and STAMP

5.7.1.2 Model usage characteristics

As mentioned in Section 5.6.2.2, the ability of an individual to employ the systems approach depends on the usage characteristics of their chosen method. When comparing the models in relation to these characteristics, it appears that the data requirements, validity and reliability of the ATSB model and STAMP are not significantly different (see Table 13). Therefore, it is arguable that these aspects of the techniques will not necessarily hinder the application of systems thinking relative to one another. Whilst similar in its data requirements and validity, the arguably lower reliability of AcciMap suggests that its application of the systems approach may be more problematic. However, without formally testing the models (e.g. utilising the approach of Branford (2007) (see Section 3.4.2.7)), this evaluation is a subjective one.

The usability of an analysis tool is affected not only by its features but also by the characteristics of its users (Thomas and Bevan, 1996). Therefore, although aspects relating to the usability of the models seem to be similar, as mentioned in Section 5.6.2.2, any judgement about a technique's usability involves a degree of subjectivity. This is evidenced by the conflicting opinions regarding the usability of AcciMap and STAMP contained within the research literature (see Section 3.4.2). The most significant usability issue encountered by the first and second researcher of this study related to the classification of evidence. In the case of the ATSB model analysis, some of the safety factors did not neatly fit into one of the levels of the model. Similarly with the STAMP analysis, it was sometimes hard to distinguish between the reasons why unsafe decisions and control actions were made and the context they were made in. Furthermore, the lack of specificity in the investigation report, regarding which elements of the Network Rail management contributed to the accident, made it hard to determine which AcciMap system level to attribute various decision/actions and consequences to. The application time of STAMP in this study was approximately double that of the ATSB model and AcciMap. This was attributed to the greater number of steps required to complete the CAST process and the associated need for more information about the system structure and its components. It is considered by the researchers that, had the ActorMap and InfoFlowMap methods been employed to complement the AcciMap and produce a more thorough analysis, the application time would have been similar to that of STAMP.

The clearest difference between the models, in terms of their usage characteristics, lies in their graphical outputs. The ATSB model and AcciMap analysis charts provide a relatively succinct summary of all of the safety factors which contributed to an accident. This similarity is not surprising, given that the ATSB model charting format is based on the AcciMap. However, the different features of the underlying models do produce notable variations in the graphical outputs of the techniques. For example, the researchers believe that the ATSB model chart more clearly delineates the various events, activities and conditions that occurred at a local level. Conversely, incorporation of the RMF format enables AcciMap to provide a more detailed description of the accident across the different organisational levels of the system. In the ATSB's experience, the use of their charting format has helped investigators maintain awareness of their progress during an investigation and assists the explanation of complex occurrences to industry personnel (ATSB, 2008 p.45). It seems likely that AcciMap would provide the same benefits, particularly if colour-coding was used to improve the effectiveness of its visual communication (as per Figure 29). In the researchers' opinion, STAMP would also enable an awareness of an investigation's progress to be maintained. However, given that STAMP does not lend itself to a simple graphical representation of an accident, its usefulness in communicating an investigation's findings to a non-expert audience may be limited (Leveson, 2012 p.91). This problem may also exist if AcciMap were to be complemented by the ActorMap and InfoFlowMap techniques. The differing usage characteristics of the models are described in Figure 34.

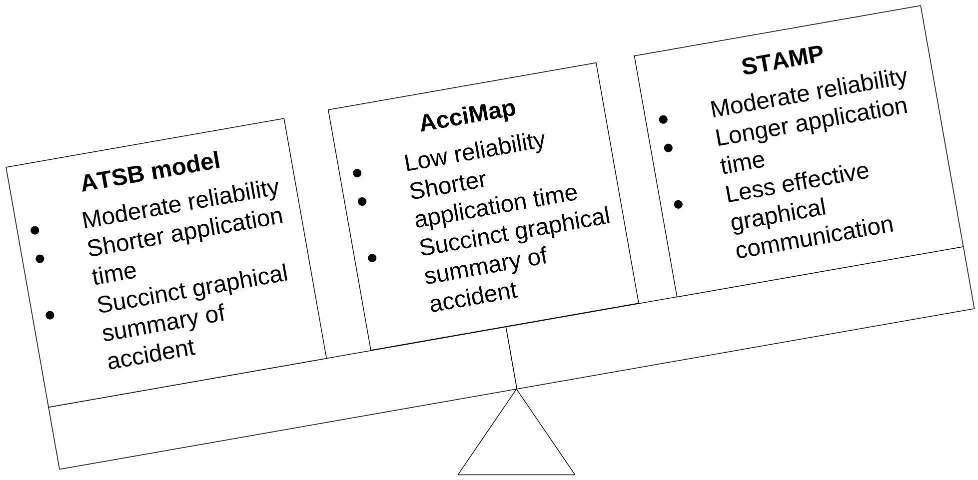

Figure 34 - Usage characteristic comparison of the ATSB model, AcciMap and STAMP

5.7.2 The extent of the research-practice gap

The discussion, so far, has focused on the similarities and differences between the ATSB model, AcciMap and STAMP. What implications do these factors have on the application of the SCM and the systems approach? The modifications made to the SCM by the ATSB when developing their model (see Section 5.3.1) supplemented the concepts embodied by the SCM, rather than eliminate them. Therefore, as the various components of systems theory can be applied with the ATSB model, this suggests that the underlying SCM can also achieve this and act as a gateway to SAA. Consequently, it seems that the SCM does provide a viable means of applying the systems approach.

This statement, however, comes with an important caveat. As described in Section 5.2.2, the SCM is not a detailed accident analysis model, nor was it intended to be (Reason et al., 2006 p.21). Therefore, it should be applied via a method to ensure that the systems approach is correctly utilised. However, this places an onus on the developers of SCM-based analysis methods to ensure that their techniques promote, rather than restrict, this application. This requirement is obviously true of any systemic analysis method. However, methods which explicitly incorporate the key concepts of systems theory, such as STAMP, go some way to resolving this problem. Therefore, it could be argued that such SAA techniques represent an evolution, rather than a revolution, in the application of the systems approach. In other words, the extent of the SAA RPG may not be significant for practitioners using SCM-based methods, assuming, of course, that they correctly apply the method. Consequently, the need to bridge the RPG may not be as great as some proponents of SAA suggest (e.g. Dekker, 2006; Hollnagel, 2012; Leveson, 2012). However, the SCM is not used exclusively throughout industry and other sequential methods remain popular (e.g. FTA), as indicated by Figure 18. Therefore, the SAA RPG could still be extensive in some instances. This issue is discussed further in Chapter 7.

5.8 Analysis and study limitations

An important question in this type of study is whether any of the analysis techniques highlighted systemic issues that were not addressed in the investigation report. The findings presented in Section 5.6.1 indicate that insufficient information was provided in the report to complete the AcciMap and STAMP analyses. In the case of AcciMap this manifested as an inability to analyse the influence of the governmental level of the system, whereas it was not possible to examine the long-term changes to the system over time with STAMP. In contrast, the ATSB model analysis was relatively complete. However, the next stage of analysis would naturally be to examine why the organisational and regulatory issues existed.

These limitations raise the important issue of when to stop evidence collection in an investigation. To fulfil the data requirements of AcciMap, STAMP and (to a lesser degree) the ATSB model, the RAIB would have needed to expand the boundary of the system they were investigating and look further back into the system’s history. The collection of this extra information may not have occurred for a number of reasons, e.g.: the resource constraints of the investigation; the analysis processes used by the

RAIB did not need the information; the required evidence was not available. Even if one of the three models used in the study had been adopted by the RAIB, it is possible that resource constraints and/or evidence availability would have prevented a complete analysis. Therefore, suggesting that a more extensive SAA would have yielded more in-depth results, whilst true, does not necessarily account for the practicalities of accident investigation. Furthermore, the RAIB (2011) report was written for a general audience and therefore, it is unclear what information was left out of the report for the sake of readability, personal or commercial sensitivity etc.

Due to the resource constraints of this study, only three analysis models were utilised. Therefore, comments about how the SCM and its related methods compare in general to the SAA techniques are not necessarily representative of all of the available methods. However, it is felt that the comparison of the methods is indicative of the current state of accident analysis in research and practice. The resource limitations of the study also prevented the researchers from independently performing an analysis of the derailment with each model. This would have been the ideal approach to take as it would have removed any influence that one researcher's findings would have had on the other researcher's understanding of the accident, prior to discussing the analyses. Furthermore, it would also have provided a deeper insight into the inter-rater reliability of the techniques. However, the researchers consider that the analysis process employed in the study (see Section 5.5.1) was sufficiently robust and provides accurate findings.

5.9 Conclusion

Debate exists within the research literature over whether the popular and widely adopted SCM provides an outdated view of accident causation or remains a viable means of applying the systems approach to accident analysis. This issue was examined by applying an SCM-based analysis model (the ATSB model) and two SAA methods (AcciMap and STAMP) to the Grayrigg train derailment. A comparison of the analysis outputs and usage of the techniques showed that each model did apply the systems approach, albeit in different ways. The ATSB model and AcciMap did not explicitly address all of the key systems theory concepts but graphically presented their findings in a more succinct manner. Conversely, STAMP more clearly embodied the concepts of systems theory but did not provide a simple graphical representation of the accident. The findings of this study suggest that the SCM remains a viable model for understanding accidents and that SAA methods offer an evolutionary progression, rather than complete transformation, in accident analysis. Furthermore, the SAA RPG gap and the need to close it may not be as significant as some SAA proponents claim.

Chapter 6 – Study 4: Evaluating a systemic accident analysis method

6.1 Chapter overview

This chapter follows on from the findings of Study 2, which indicate that SAA methods must meet the needs of practitioners if they are to be adopted and used. A practitioner evaluation of the STAMP method is presented in this chapter. Six trainee accident investigators were recruited to perform a STAMP analysis on data they collected during an accident investigation simulation and assess the effectiveness and usability of the method. The findings of the study are presented and subsequently discussed with regards to how the usage characteristics of STAMP may affects its use by practitioners.

6.2 Introduction

The findings of Study 2 indicate that SAA methods must meet the needs of practitioners if the SAA RPG is to be bridged (see Section 4.4). Such requirements include: the usability of an analysis method, its validity and the usefulness of its output format (see Section 4.4.3.1). However, the use of SAA methods to analyse accidents has predominantly existed within research and very little is known about their application by practitioners. Therefore, in order to understand if the systemic techniques meet the needs of practitioners, it must be established how these methods cope with the demands of live investigations. Recruiting practitioners to apply and evaluate the SAA methods would be a useful start towards achieving this goal. Indeed, involving users in the development of a method/product/system can play an important part in gaining user acceptance (Damodaran, 1996; Olson and Ives, 1981). This is evidenced by a number of analysis methods which, when developed by researchers in collaboration with practitioners, have become successful in (and beyond) their intended industries.

Two well-known examples of where such collaboration has proved effective are HFACS and Tripod Delta. There are a number of notable features about the development process of these techniques: they were purposefully developed for use within a certain industry (military aviation and oil and gas in the case of HFACS and Tripod Delta respectively), researchers based the methods on contemporary accident causation theory whilst practitioners supplied guidance on end-user requirements, the methods employed a taxonomic approach to standardise error classification and facilitate the examination of aggregated accident data and each technique was extensively validated in field-tests conducted with the sponsor organisations prior to their adoption. This high level of practitioner involvement combined with the theoretical input of researchers appears to have been a key factor in the success of implementing the methods. If a similar development process was adopted for the SAA techniques it is arguable that some of the existing issues hindering their usage may be overcome (see Section 4.4). For example, field-testing the methods could help establish the industry track record which is currently lacking and generate end-user feedback that may help to improve the tools' functionality, usage guidance and training material. Developing industry-specific taxonomies for classifying contributing systemic factors may also help to improve the reliability of the SAA methods and their suitability for multiple accident case analysis (Salmon et al., 2012a).

6.2.1 The use of scenario-based training

From a research perspective, it would be favourable to collect data on practitioner usage of the SAA methods within a live investigation. However, there may be reluctance to trial new analysis techniques in an investigation. Furthermore, this goal may be practicably difficult to achieve for a number of reasons, such as: the unpredictable schedule of accident investigations; the expense of extended field-based research; gaining access to sensitive information.

The use of scenario-based training (SBT), in the form of high fidelity simulations, can offer a solution to these problems. The use of simulations offers a degree of control over various aspects of accident investigation, e.g.: a predictable schedule can be achieved; the severity of the accident can be matched to the training resources; accident site boundaries can be easily established. It also offers practitioners an environment in which they can trial new methods without any negative consequences on safety within their industry. Therefore, the use of high fidelity simulations can provide a suitable environment for data collection which balances the realism of an investigation with the theoretical and practical needs of researchers. SBT is well established as a technique to improve the performance of individuals/teams in safety-critical industries, such as healthcare (Crawford et al., 2010), energy (Saurin and Carim Júnior, 2011) and defence (Kropewnicki et al., 2010). However, relatively little information regarding the use of SBT for accident analysis exists within the research literature. One notable example is the research conducted by Woodcock et al. (2005).

Accident stories, based on actual events, were created by Woodcock et al. (2005) to, amongst other issues, compare the effect of using two different analysis techniques versus a freestyle investigation approach. Participants (accident investigators) were initially provided with a brief synopsis of the accident and then proceeded to ask questions. Data was provided verbally by the experimenter until the participants were satisfied with their understanding of the accident, who then reported their conclusions. This laboratory-based simulation method allowed the participants to generate and test hypotheses in a flexible format and was considered by them to closely resemble the processes used during real investigations. Therefore, the use of simulated accidents seems to provide an appropriate means in which to perform research studies, such as method evaluations. However, some participants (experienced investigators) highlighted that a lack of site visits limited the realism of the exercise. Therefore, the preferred format for an accident simulation should involve field-based elements.

6.2.2 Study aim and objectives

The aim of this study is to provide an insight into the application of an SAA method by practitioners. In order to achieve this aim, the study has two main objectives:

- Obtain a practitioner evaluation of an SAA method, based on their experience of using it in a (high-fidelity, partly field-based) simulated investigation

- Understand how the usage characteristics of the method affect its use in a live investigation scenario

By conducting this study, it is hoped that a greater understanding of the extent of the SAA RPG can be achieved.

6.3 Methods

6.3.1 Mixed methods approach

Whilst the research undertaken for this thesis adopted a mixed-methods approach overall (see Section 1.3.2), the use of multiple methods was a key feature of this study. The objectives of the study could have been achieved with a single method, e.g. a method evaluation questionnaire. However, a concurrent mixed methods approach was taken for a number of reasons. Firstly, it was judged that the different objectives could be achieved by more than one method and using them in combination would compensate for their relative weaknesses and improve the validity of the overall findings. Secondly, the nature of the study was, to a degree, exploratory in nature (an evaluation of an SAA method within a simulated accident investigation has yet to be published). Therefore, it was believed that the breadth and depth of data that could be collected via a mixed methods approach would facilitate a comprehensive evaluation. Finally, the time available to conduct the study was limited to two days in the week following the investigation exercise. Therefore, it was necessary to use the methods concurrently (as long as multiple methods are administered in the same time frame and conceptualised as part of the same study they are considered concurrent) (Bronstein and Kovacs, 2013 p.358).

Furthermore, previous studies involving accident investigation simulations have used a mixed methods approach (e.g. Gordon et al., 2005; Woodcock et al., 2005). In particular, Gordon et al. (2005), in an evaluation of their Human Factors Investigation Tool (HFIT), measured the inter-rater reliability of the HFIT users and gathered their feedback on the method's ease of use and validity via user evaluation forms, written feedback and informal discussions. This approach revealed both strengths and weaknesses of HFIT and the need for further development of the method. Therefore, given the similarities between the objectives of this study and that of Gordon et al. (2005), the use of mixed methods was deemed to be suitable.

6.3.2 SAA method selection

The STAMP method was chosen for evaluation for a number of reasons. As described in Section 3.4.2 it is the most frequently cited SAA technique. It was previously used in Study 3 and would, therefore, allow a comparison between its use in the research and practice contexts. Finally, detailed guidance about the application of the technique is available (see Leveson, 2012), thereby facilitating the training of participants in the use of STAMP.

6.3.3 Sampling strategy

A combination of the stratified purposive and convenience sampling strategies, as defined by Miles and Huberman (1994), was employed in this study. The objectives of the study necessitated the recruitment of a particular group of individuals, i.e. practitioners employed (on a full- or part-time basis) as accident/incident investigators. However, due to their unpredictable working patterns, the recruitment of experienced investigators was considered unfeasible. Therefore, participants were recruited from a group of individuals that were training to be full-time aviation accident investigators or aviation safety professionals (e.g. safety managers) with a part-time responsibility for accident investigation.

The participants were enrolled on a six week training course run by the Cranfield Safety and Accident Investigation Centre at Cranfield University, which consisted of an initial three week module entitled ‘Fundamentals of Accident Investigation’ and a supplementary three week ‘Applied Aircraft Accident Investigation’ module. Individuals from various modes of transport were present during the first module, whereas only aviation practitioners were present during the second module. The investigation simulation exercise used within the study occurred over the second and third weeks of the ‘Fundamentals of Accident Investigation’ module. However, the study was conducted in the first week of the ‘Applied Aircraft Accident Investigation’ module, as the workload of the course delegates in the final week of the first module restricted their availability. Therefore, only aviation practitioners were available for recruitment and hence why a degree of convenience sampling was utilised.

6.3.4 Participants

Six participants (mean age: 43.8 years) were recruited for the study and were either employed as (and receiving additional training), or training to be, aircraft accident investigators. A summary of the participants' backgrounds and analysis experience is provided in Table 14.

During the first course module the delegates received training in a variety of sequential, epidemiological and systemic accident analysis methods from the researcher (Underwood). This information included the conceptual background of STAMP, its use via the CAST process (see Leveson, 2012 p.349) and an example of its application via a rail accident case study analysis. Therefore, although none of the participants were aware of STAMP before attending the training course, they had a basic knowledge of the method and its application process. This offered a degree of control over the experimental bias associated with the previous experiences of the participants.

Participant	Age	Country	Industry	Role	% of time spent analysing accidents/ incidents	Experience in analysing accidents/ incidents (years)	Number of accidents (incidents) analysed	Type of accidents and/or incidents analysed
1	35	Canada	Military aviation	Accident investigator	25	1	2 (0)	Aircraft fell off jack, nose wheel failure on landing
2	45	Australia	Military aviation	Accident investigator	50	0 as investigator (spent 2 years as flight/voice data analyst)	1 (6)	Ejection from fixed-wing aircraft, smoke and fumes in a helicopter
3	46	Australia	Military aviation	Aviation maintenance support	Unknown	Unknown	Unknown	Various maintenance related issues
4	53	UK	Military aviation	Accident investigator	60	>20	>20 (>100)	Rotary wing aviation (military and commercial)
5	40	Nigeria	Military aviation	Wing commander	Unknown	3	3 (4)	Flight into terrain, airborne near misses, hard landing, hydraulics failure
6	44	Japan	Civil aviation	Accident investigator	60	2	2 (0)	Flight into terrain

Table 14 - Participant information

6.3.5 Investigation simulation

The investigation exercise centred on a rail-based accident scenario which involved a train colliding with two track maintenance engineers, fatally injuring one of them. The exercise took place over 2.5 days; the first day consisted of field-based evidence gathering, the second day was dedicated to the analysis phase of the investigation and the remaining time was allocated to the presentation of the teams' findings.

The 34 course delegates were divided into four teams with each team having a nominated Investigator In Charge (IIC), i.e. a team leader. Each group received a pre-exercise brief detailing the learning objectives and site-safety instructions. The delegates were also provided with contextual information to increase the realism of the exercise, i.e. each team was formed of newly qualified 'National Investigation Agency' (NIA) investigators who were at the top of the call-out duty roster. However, no details were provided as to the mode of transport, location or stakeholders involved in the accident. Again, this was to maximise the realism of the exercise.

During various stages of the first day, each IIC was telephoned by the NIA duty coordinator, provided with initial details of the collision and told to deploy their team to the accident site. The deployments were staggered to ensure that each team had sole access to the site for a given period of time. Each IIC was responsible for allocating roles to their team members and assigning tasks based on the needs of the investigation. Typical duties involved documenting evidence, mapping the accident site and interviewing witnesses. Each team was provided with a location to hold meetings/conduct interviews (a spare carriage on a train not involved in the accident) and a supply of evidence collection/documentation, personal protection and communications equipment.

The teams were given 1.75 hours for site examination and a further 1.75 hours to conduct several planned witness interviews, e.g. with the surviving maintenance engineer. Several unplanned witness interviews also took place during the site examination as various 'witnesses', e.g. a passing member of the public, were introduced into the scenario. During the subsequent analysis phase, the teams were able to request additional evidence as they discovered/explored lines of enquiry. If available, this extra information was provided verbally or in the form of documentation, e.g. maintenance manuals. Two teams opted to use the ATSB model to guide their analysis, whereas the other teams used STAMP.

The different investigation approaches taken by the teams resulted in each group possessing slightly different factual information about the accident. This, in turn, resulted in each team presenting different factual and analysis findings. Therefore, no complete description of the accident was available, however, a general synopsis is provided in Section 6.3.6.

6.3.6 Accident synopsis

The simulated accident ‘occurred’ on the 25th January 2013 on a bridge located south of the Pitsford and Brampton station in Northamptonshire (see Figure 35).

Figure 35 - Simulated accident site

The section of track on which the accident occurred had been subject to a temporary 50 miles per hour (mph) speed restriction. The restriction was in place due to reported 'rough running' over the bridge caused by uneven track geometry which, in turn, was caused by dislodged ballast. The restriction was established between the Boughton signal box to the south of the accident site and the Pitsford and Brampton station (see Figure 36).

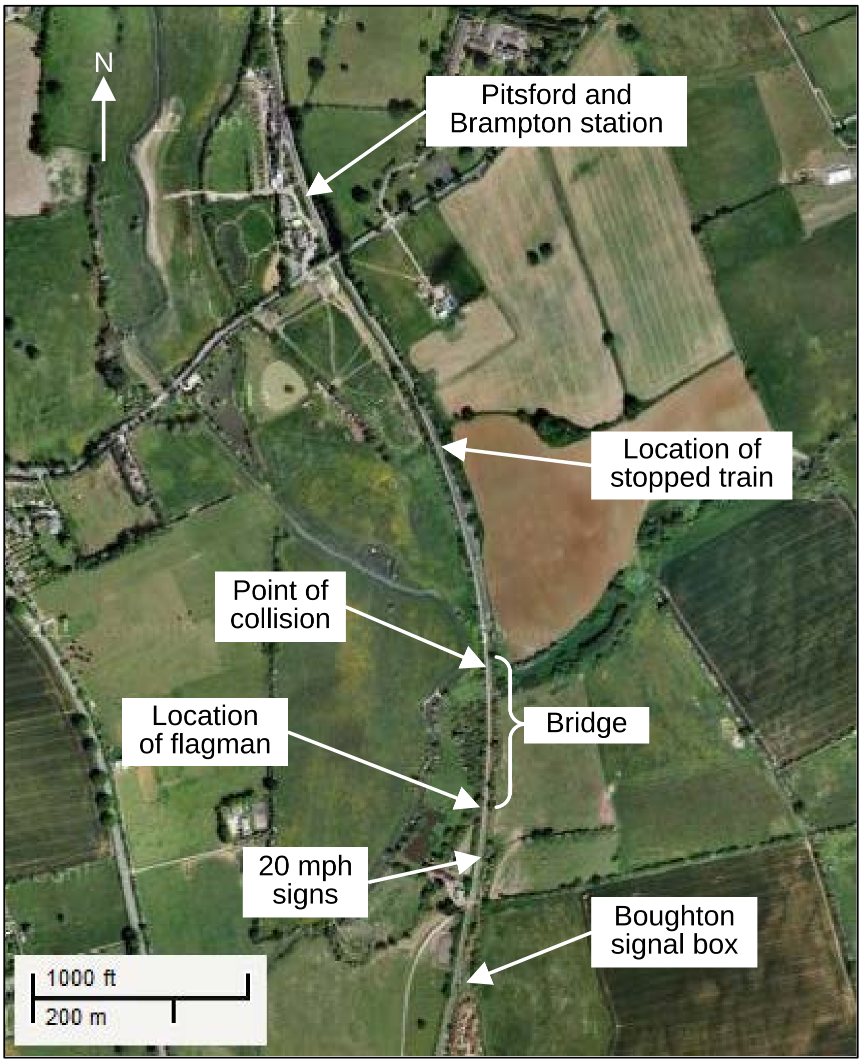

Figure 36 - Map of accident site

A track maintenance crew, consisting of two maintenance engineers and a lookout (flagman), were called to perform an inspection of the affected section of track at 00:30 on the 25th January 2013. The maintenance crew arrived at the site at approximately 06:00 and began their shift by walking to the Boughton signal box. The leader of the maintenance crew, the Controller of Site Safety (COSS), met with the Boughton signalman to complete the required documentation to authorise the track inspection. As per company policy, a 20 mph emergency speed restriction was to be established in the area where the track work was to be conducted. After leaving the Boughton signal box, the maintenance crew then installed the 20 mph signage and a warning light system 220 metres to the north (see Figure 36). However, this signage and light system was not adequately secured in place and ultimately toppled over before the train involved in the collision passed the Boughton signal box.

The maintenance crew took up their positions for the inspection and the COSS and his assistant engineer observed a scheduled train pass over the affected track at approximately 06:35. Subsequent to the inspection, the two engineers then agreed to carry out some unscheduled (and unauthorised) maintenance work to the track and replace the missing ballast. This decision was taken based on the understanding that the next train was not due to arrive until 07:40. Therefore, sufficient time was available to complete the necessary repairs and avoid the need for a second site visit. The two engineers then proceeded to a nearby engineering depot, returned to the bridge with the required equipment loaded on to a track-mounted trolley (see Figure 35) and began their maintenance tasks. Their journey from the depot was slowed due to a defect with the trolley, which restricted its movement. In addition, the trolley brakes were inoperable and the engineers resorted to chocking its wheels with ballast to secure it in place.

At approximately 06:50 an unscheduled train passed the Boughton signal box travelling northbound. The train slowed to 50 mph, as required, however, the train drivers were unaware of the 20 mph emergency restriction in place due to the fallen signage and warning lights. The flagman saw the approaching train but was unsuccessful in his attempts to warn the maintenance engineers. The train drivers observed the engineers on the bridge and applied the train's emergency brakes. The COSS and his assistant heard the train and, fearing that its collision with the trolley could result in a derailment, attempted to remove the trolley from the track. They were, however, unable to remove the trolley in time and were struck by the train. The COSS was fatally injured in the collision and his assistant sustained head and leg injuries. The assistant engineer was attended to initially by the second train driver before he was evacuated to hospital by the emergency services.

6.3.7 Data collection

6.3.7.1 Analysis workshop

The use of a workshop was judged to be the most appropriate environment for the participants to conduct a STAMP analysis. This decision was taken to maximise the level of control over the study conditions (e.g. each individual would be furnished with the same amount of time to complete the analysis and have access to support from the researcher) and minimise the required time for data collection.

The duration of the workshop was two hours and began with a 15 minute briefing, covering a number of topics. Firstly, the participants were informed of the format and the overarching aim of the workshop, i.e. performing a STAMP analysis of the data collected during the simulated investigation and providing feedback on their experiences of using the method. To minimise participant expectation bias, the group was not informed about how the study data was to be analysed. Secondly, the group was provided with rules that applied to their participation in the workshop: (1) discussions with other participants about evidence were permitted for individuals that had been team members during the investigation exercise. This rule was established to ensure that the participants did not introduce new evidence into their analyses, thereby possibly affecting their experience of using STAMP and increasing the workshop duration by creating debates about the nature of the evidence; (2) queries about the application of STAMP should be directed to the researcher, rather than the other group members. This instruction was given in order to reduce the influence that the participants would have on each other's analyses and to facilitate their own analysis, i.e. by gaining assistance from an experienced user of STAMP. Guidance on STAMP usage was provided by the researcher throughout the workshop. Although this influenced the participants' usage of the method it was deemed necessary to facilitate data generation. Finally, the participants were provided with a re-cap of STAMP and the CAST process, in order to prime them to conduct the analysis. Upon completion of the briefing, the remaining time was dedicated to the STAMP analysis. All but one of the participants were able to complete their analysis within the permitted time.

Each participant was provided with a range of material to help them complete their analysis, i.e. a summary of the CAST process and worksheets, based on the various stages of CAST, on which the participants could record their analysis (see Appendix 6.1). The terminology used in these documents was taken from Leveson (2012); the expectation being that issues regarding the ambiguity of the terms would be raised by participants and, therefore, highlight usability problems. The first step of the analysis process, i.e. identify the system(s) involved in the accident, was completed for the participants to facilitate the rest of the analysis. Each member of the group was also provided with an example of a STAMP control structure hierarchy based on the diagram presented by Leveson (2012 p.82). The participants were instructed to exclude the fourth step of the CAST process, i.e. defining the proximal event timeline. This instruction was given to facilitate the analysis, given that the four teams had all created detailed timelines during the investigation exercise.

An audio recording of the workshop was taken to identify any issues/questions raised by the participants and the support given by the researcher, in order to understand how these factors may have influenced the participants' analyses.

6.3.7.2 STAMP evaluation questionnaire

Upon the completion of the workshop, each participant completed an evaluation questionnaire (see Appendix 6.2). The questionnaire was designed to understand how the participants viewed different issues surrounding the validity and usability of STAMP by asking them to state their level of agreement with a number of statements. These statements were based on: the method evaluation topics used in the previous study (see Section 5.5.2), e.g. how effectively STAMP represents system component relationships; the questionnaire topics investigated by Gordon et al. (2005);

existing questionnaires employed in usability studies (e.g. Brinkman et al., 2009; Schnall et al., 2012; Viitanen et al., 2011).

Due to the number of evaluation topics, it was considered that a questionnaire would provide the most efficient means of collecting the resultant large quantity of data. In addition, it would generate quantitative data that could be used to make a statistical comparison of the participants' usage experience. With this comparison in mind, it was decided to utilise a seven-point simple rating scale format to ascertain the level of participants' agreement with the various statements. The scale values and their associated levels of agreement can be seen in Table 15 below:

Scale value	Level of agreement
0	Strongly disagree
1	Disagree
2	Slightly disagree
3	Neutral
4	Slightly agree
5	Agree
6	Strongly agree

Table 15 - STAMP evaluation questionnaire rating scale

Such a scale was chosen as it offered a neutral mid-point to the participants and provided an appropriate balance between data resolution and ease of questionnaire completion (DeVellis, 2012). The questionnaire was reviewed by a senior human factors researcher and minor amendments to the formatting were made before the start of the study.

6.3.7.3 Focus group

Subsequent to the completion of the evaluation questionnaire, four of the participants took part in a focus group. The objective of the session was to understand the participants' overall impression of STAMP. A number of questions were developed to gather this information:

- What are the benefits of using STAMP?

- What are the disadvantages of using STAMP?
- How would you improve STAMP?
- Would you use STAMP in future investigations?

Whilst these questions could have been incorporated into the STAMP evaluation questionnaire, it was deemed preferable to collect the participant responses via a focus group. This decision was made so that points of interest could be explored further, via the use of additional questions, and thus increase the breadth and depth of the data collected. The duration of the focus group was limited to 20 minutes due to the availability of the participants.

6.3.8 Data analysis

6.3.8.1 Initial analysis

The different data sources (see Section 6.3.7) were initially analysed separately. The analysis outputs created by the participants were converted into electronic documents and imported into NVivo 9. The documents were subsequently compared using an inductive analysis approach and any similarities/differences were coded in NVivo 9. This comparison was made to assess the different approaches of the participants, rather than make a judgement on the accuracy of the analyses or the reliability of STAMP (which was not possible given that the whole group was not using the same set of data). The study was not designed to formally test the validity and reliability of the method for a number of reasons: (1) the participants were first-time users of STAMP and, therefore, would not be expected to produce accurate analysis results; (2) the sample was formed of individuals from different investigation exercise teams whom had access to differing amounts of evidence; (3) a complete description of the accident was not available to compare the workshop analysis outputs against.

Data from the STAMP evaluation questionnaire was analysed with SPSS 20 in order to provide some descriptive statistics (mean, standard deviation, minimum and maximum values) regarding the participants' level of agreement with the various questions. The audio recordings of the analysis workshop and focus group were transcribed, imported into NVivo 9 and analysed inductively. All of the questions raised by the participants during the workshop and the answers provided by the researcher were coded, with similar questions/responses being grouped under parent-codes. Topics of interest related to the focus group questions were also coded and grouped as appropriate.

6.3.8.2 Data integration

The findings from the first stage of analysis were subsequently integrated for a second analysis phase in order to identify instances of data corroboration (the 'same results' are derived from both qualitative and quantitative methods), elaboration (the qualitative data analysis exemplifies how the quantitative findings apply in particular cases), complementarity (the qualitative and quantitative results differ but together they generate insights) and contradiction (where qualitative data and quantitative findings conflict), as defined by Brannen (2005 p.176). This analysis was performed deductively, using an evaluation framework as a coding template (see Section 6.3.8.3). An inductive approach was also taken to highlight any additional factors identified during the analysis.

6.3.8.3 Evaluation framework

The evaluation framework used in the integrative analysis phase (see Section 6.3.8.2) was based on the framework utilised in Study 3 (see Section 5.5.2). As the study was focused on understanding how the usage of STAMP by practitioners would impact on its suitability for use in live investigations, only the usage characteristics of the method were examined. Furthermore, the information presented in Figure 19 indicates that usability, validity and a useful output format are key practitioner requirements of a method, thereby justifying their inclusion in the evaluation framework. The evaluation framework is graphically represented in Figure 37.

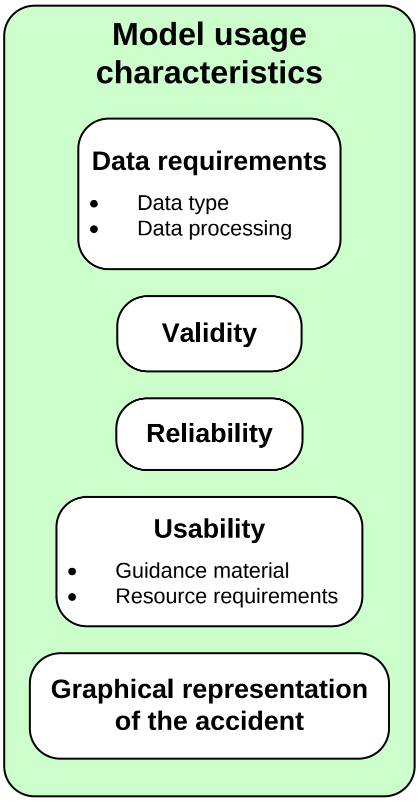

Figure 37 – Study 4 evaluation framework

6.4 Findings

A summary of the individual sets of data, collected via the methods described in Section 6.3.7, is provided in this section. The integration of the data is discussed under the various headings of the evaluation framework in Section 6.5.

6.4.1 STAMP analysis outputs

This section provides a summary of the analysis outputs produced by the participants during the workshop.

6.4.1.1 Identification of system hazards

All of the participants identified that at least one of the system hazards involved in the accident related to trains operating during periods of maintenance, which included people and/or equipment being present on the track (see Figure 38).

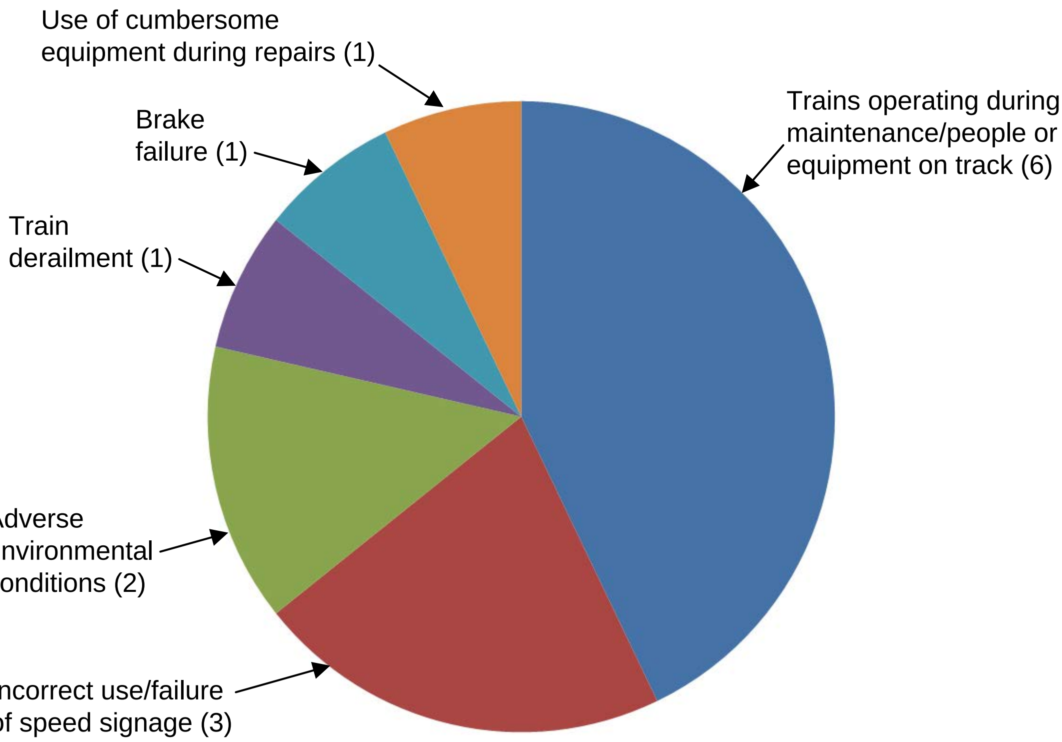

Figure 38 - System hazards identified during analysis (numbers in brackets = number of participants listing a given hazard)

Participants 1, 2 and 4 identified this as the only type of hazard, whereas Participant 6 listed a further two hazards and Participants 3 and 5 cited an additional three hazards. The hazards identified by each individual are detailed in Table 22 (see Appendix 6.3).

6.4.1.2 Identification of system safety constraints

The participants listed a total of 31 system safety constraints, which were related to three main topics: (1) speed restriction signage and warning systems; (2) personnel requirements, e.g. the use of a flagman and the need for the flagman to warn the maintenance engineers of an approaching train; (3) procedures, e.g. maintenance work permit forms (see Figure 39). A summary of system safety constraints identified by each participant is contained in Table 23 (see Appendix 6.3).

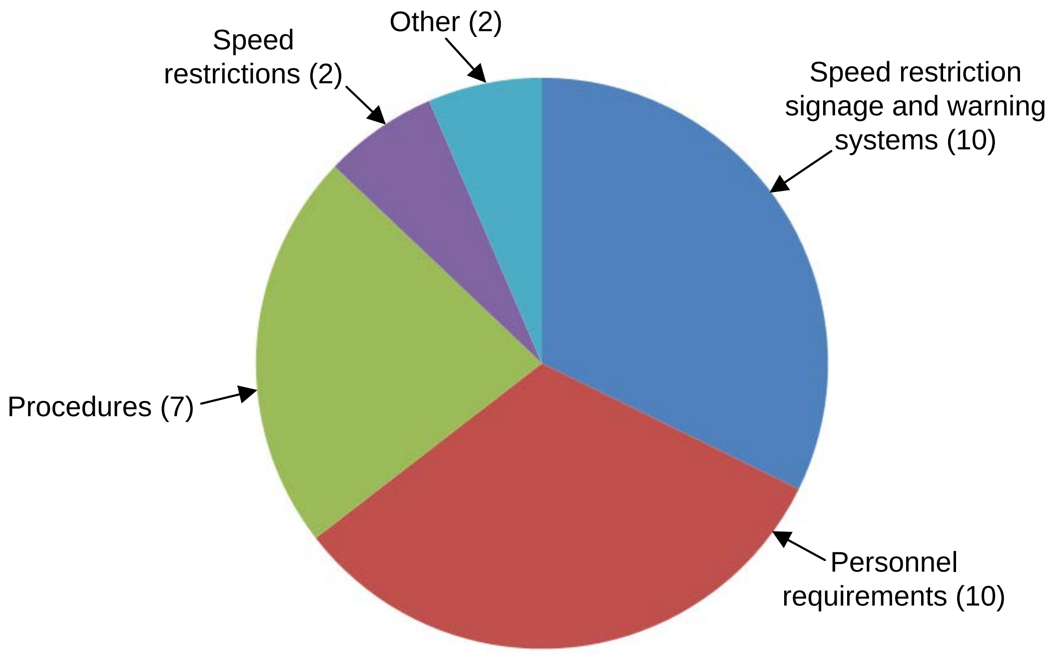

Figure 39 - System safety constraints identified during analysis (numbers in brackets = number of system safety constraints related to a given topic)

As per the identification of the system hazards, variation existed amongst participants with regards to the number of system safety constraints they identified. Participants 1 and 2 both listed the greatest number (seven constraints) and Participant 6 documented the least (one constraint). Of the total number of constraints identified, 86 % were recorded by Participants 1, 2, 3 and 4 (see Table 23 in Appendix 6.3).

6.4.1.3 Control structure hierarchy documentation

Only five of the participants documented the control structure hierarchy; Participant 6 did not attempt to define the control structure as they were struggling to complete the rest of the analysis. Examples of the control structure diagrams produced by the participants can be seen in Figure 40 and Figure 41.

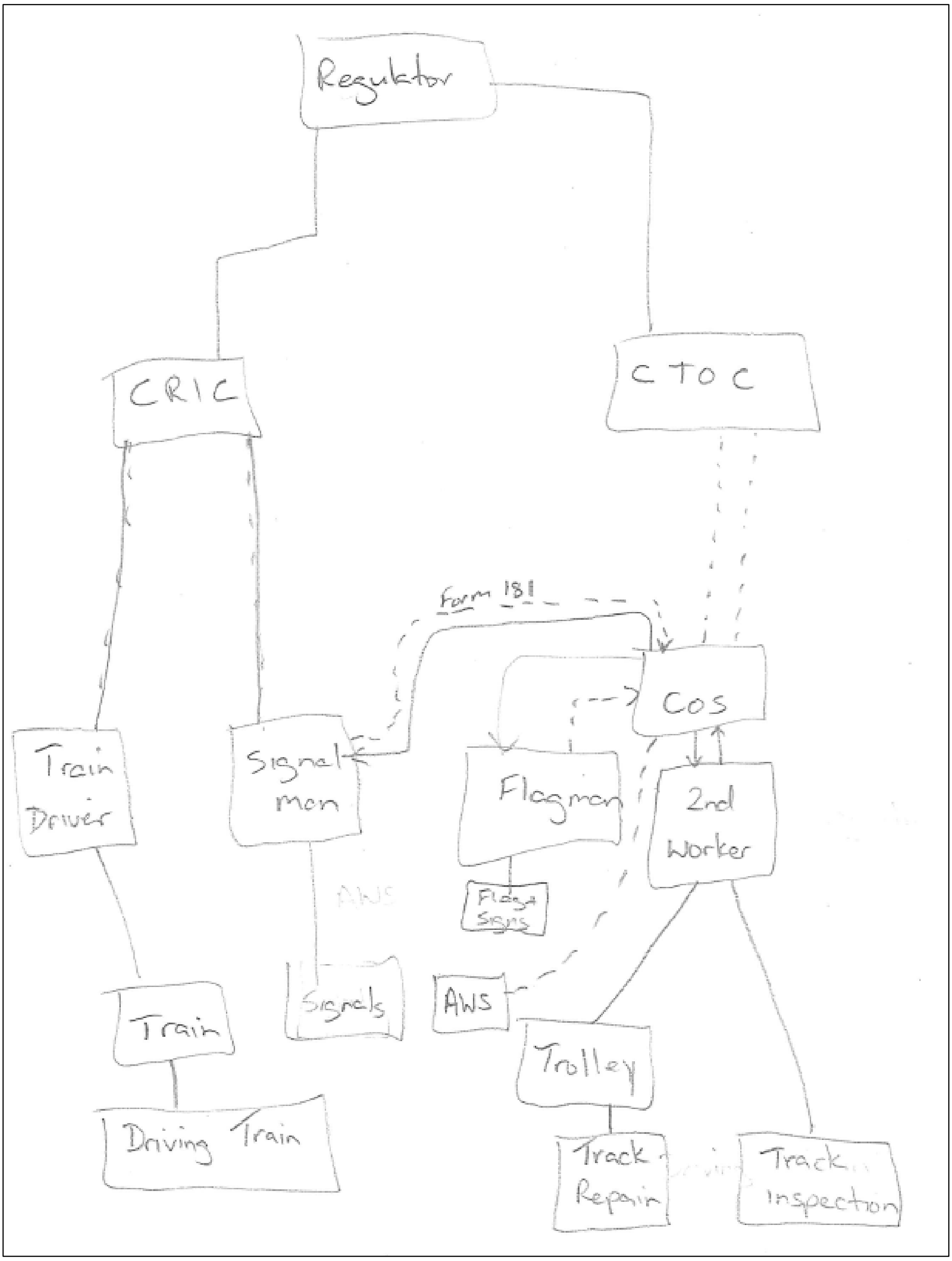

Figure 40 - Participant 2 control structure diagram (AWS = Automatic Warning System, CRIC = Cranfield Railway Infrastructure Company, CTOC = Cranfield Train Operating Company)

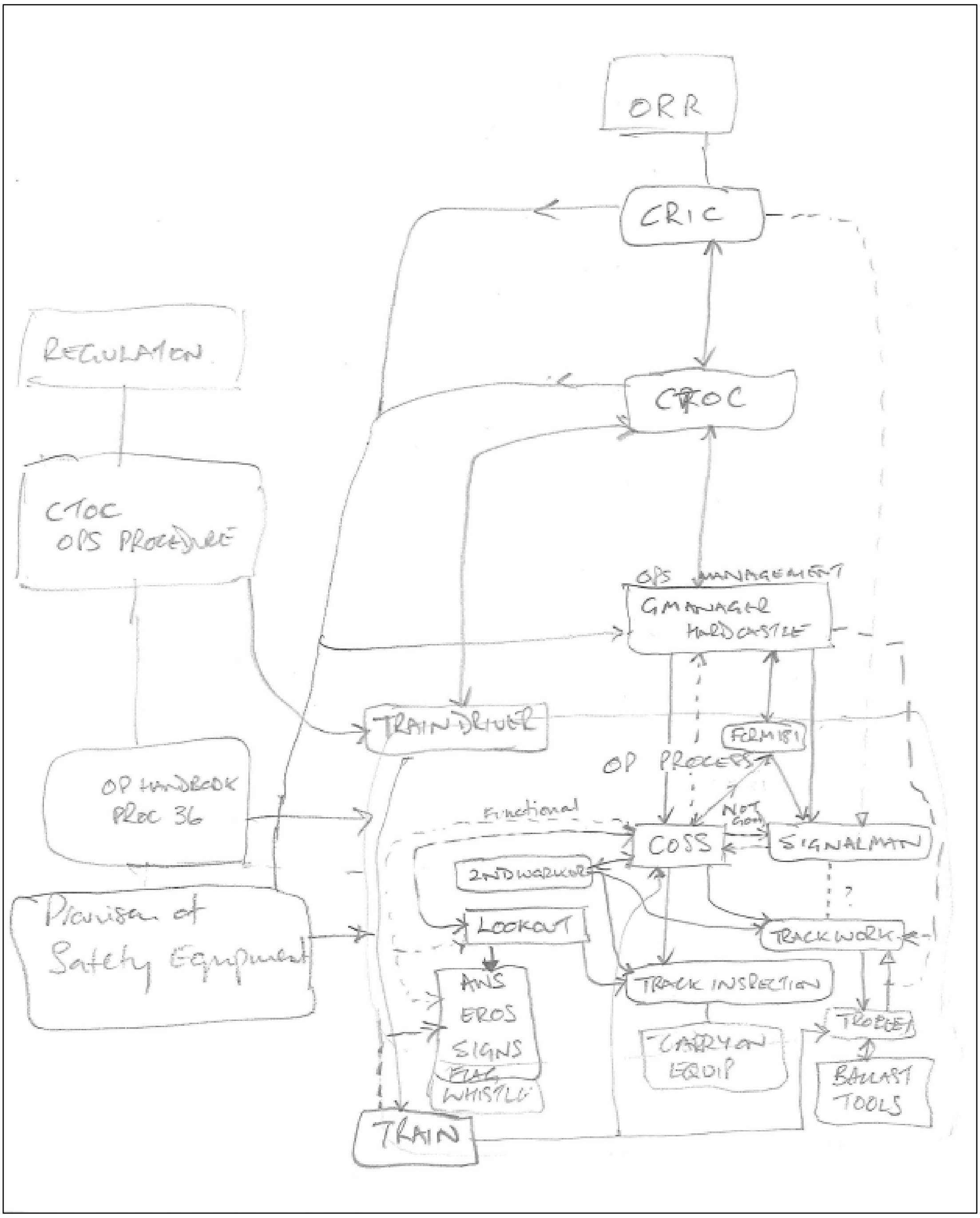

Figure 41 - Participant 4 control structure diagram (ORR = Office of Rail Regulation)

All of the participants who created diagrams of the system control structure utilised the format described by (Leveson, 2012 p.82), with four individuals describing control/feedback problems with dotted lines.

6.4.1.4 Physical system analysis

Four of the participants provided an explicit description of the physical system components they judged to be involved in the accident (see Table 16), with procedural documents and the signage and warning systems being the two most cited components.

Physical system component description		**Participant number**						**Total**
		1	**2**	**3**	**4**	**5**	**6**	
Explicit descriptions	Driver notification	1	0	0	0	0	0	1
	Procedural documents	1	1	0	1	0	0	3
	Signage and warning systems	1	2	0	1	0	1	5
	Train	0	1	0	0	0	0	1
Inferred descriptions	Personnel duties	0	0	1	0	1	0	2
	Procedural documents	0	0	1	0	1	0	2
	Signage and warning systems	0	0	1	0	2	0	3
Total		3	4	3	2	4	1	

Table 16 - Physical system component description[7]

Participants 3 and 5 did not provide any explicit descriptions of the physical system. However, three types of component could be inferred from the list of physical controls and violated safety constraints which they provided, albeit that one component (i.e. personnel duties) appeared to be more suitably defined as the safety-related responsibility of a higher-level system component.

When asked to provide a description of the controls available to the various physical system components, the majority of the controls listed referred to items of physical equipment (see Figure 42). Two participants also cited the flagman as a physical control, albeit that the flagman represents a higher-level system component (see Table 24 in Appendix 6.3). However, when describing how the physical system components failed or how the controls were inadequate, participants listed as many personnel-related issues as

[7] Yellow colour of cells used to highlight a non-zero value

physical equipment problems (see Figure 43). Again, these personnel-related issues seemed linked to the analysis of higher-level system components (see Table 25 in Appendix 6.3).

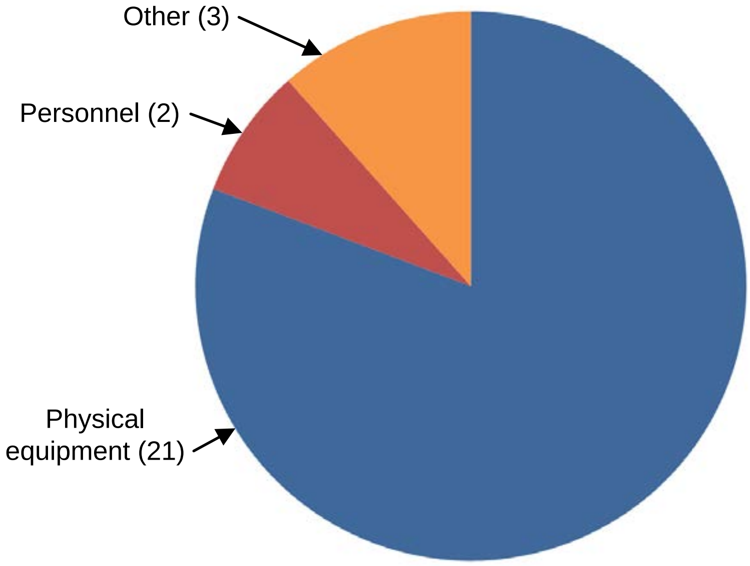

Figure 42 - Physical system controls (numbers in brackets = number of controls listed)

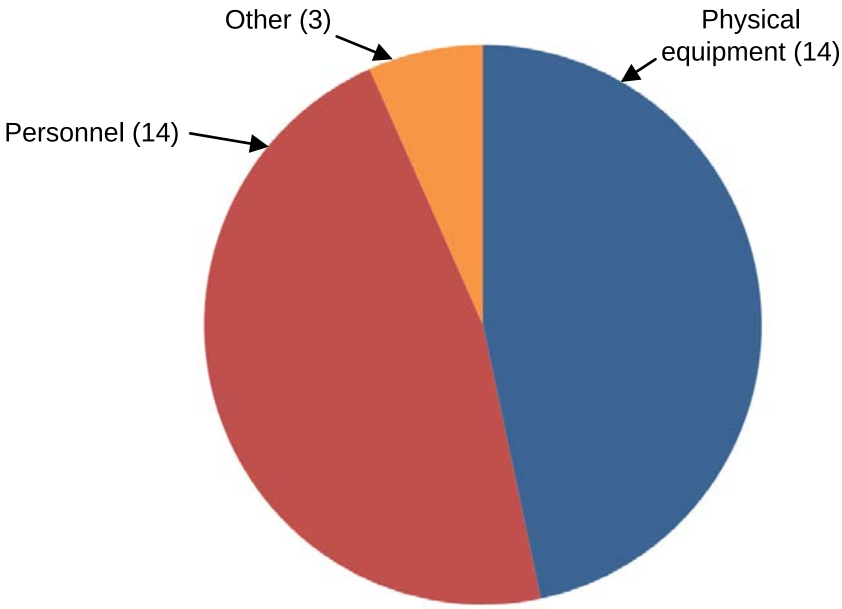

Figure 43 - Physical system failures and inadequate controls (numbers in brackets = number of failures/inadequate controls listed)

6.4.1.5 Higher system level analysis

Similarly to the physical system analysis, five participants provided explicit descriptions of higher system level components (see Table 17). Inferred system component descriptions were also identified from the safety-related responsibilities described by two participants. The majority (76 %) of the components documented by the group referred to frontline staff individuals and teams. Only Participant 5 listed system components from higher levels of the control structure, i.e. the company management. However, these components were not analysed by the participant.

Higher system level component description			**Participant number**						**Total**
			1	**2**	**3**	**4**	**5**	**6**	
Explicit component descriptions	Frontline staff	Assistant engineer	1	0	0	0	0	0	1
		COSS	1	1	0	0	0	0	2
		Engineers and technicians	0	0	0	0	1	0	1
		Flagman	0	1	0	0	0	0	1
		Maintenance team	0	0	0	0	1	0	1
		Signalman	0	1	0	0	0	0	1
		Train driver	0	1	0	0	1	0	2
	Company management	Supervisors	0	0	0	0	1	0	1
		Train company management	0	0	0	0	1	0	1
	Policies and procedures	Governmental policy	0	0	0	0	0	1	1
		Company regulation	0	0	0	0	0	1	1
		Procedure documentation	0	0	0	1	0	0	1
Inferred component descriptions	Frontline staff	COSS	0	0	1	1	0	0	2
		Flagman	0	0	0	1	0	0	1
		Maintenance team	0	0	1	0	0	0	1
		Signalman	0	0	1	1	0	0	2
		Train driver	0	0	0	1	0	0	1
Total			2	4	3	5	5	2	

Table 17 - Higher system level component description[7]

6.4.1.6 System coordination and communication

Due to the workshop time constraints, only four participants completed the analysis of coordination and communication issues within the system, albeit that one of these individuals (Participant 5) documented their findings in the ‘system changes over time’ analysis worksheet section (see Figure 58 in Appendix 6.1). Whilst the majority of issues that were identified centred on the themes of inadequate coordination and communication across various system levels, a number of additional issues were highlighted (see Table 18). These other factors appear to refer to unsafe actions, decisions and conditions, rather than coordination and communication issues.

Coordination and communication issues		Participant number			
		1	3	4	5
Inadequate coordination of work	Ambiguous instructions	0	0	1	0
	Authority gradient in maintenance team	0	1	0	0
	Inadequate coordination at organisational level	0	0	1	0
	Inadequate coordination at personal level	0	0	1	0
	Inadequate maintenance log and job-order procedures	0	0	0	1
	Ineffective issue and promulgation of work permit	0	1	0	0
	Lack of coordination between train operating and track maintenance companies	0	0	0	1
	Lack of procedures to inspect the track	0	0	0	1
	Unclear paperwork	0	0	1	0
	Unclear responsibilities	0	0	1	0
Inadequate communication	Inadequate communication at organisational level	0	0	1	0
	Inadequate communication at personal level	0	0	1	0
	Inadequate communication between train stations	0	0	0	1
	Inadequate maintenance team communication	1	0	0	0
	Inadequate overall communication	0	0	1	0
	Inadequate visual communication between driver and speed signage	1	0	0	0
Other	COSS changed maintenance plan	1	1	0	0
	COSS instructions to flagman were not carried out	1	0	0	0
	Decision to work in poor environmental conditions	0	1	0	0
	Maintenance assistant only expected an inspection	1	0	0	0
	Maintenance staff fatigue	0	1	0	0
	Signalman did not close track	0	1	0	0
Total		5	6	8	4

Table 18 - System coordination and communication issues[7]

6.4.1.7 System changes over time

As a result of the workshop time constraints, only three of the participants completed the final stage of the analysis. The majority of the identified issues reflect a normalisation of the risk associated with performing ad hoc maintenance work (see Table 19). However, Participant 3 also commented that no significant changes in the system over time were noted.

System changes over time	**Participant number**		
	1	**3**	**4**
Acceptance of ambiguous track blockage procedure	0	1	0
‘Can do’ attitude of workers	1	0	0
Inflexible system unable to cope with short-term changes in work plans	0	0	1
Long term friendships clouded professional judgement of individual responsibilities	0	0	1
Routine violations occurred	0	1	1
Total	1	2	3

Table 19 - System changes over time[7]

6.4.2 Workshop audio recording

The questions and comments raised by participants during the workshop related to three general issues. Firstly, some individuals had difficulty in understanding the concepts of STAMP. For example, two participants required clarification about the meaning of the control and feedback arrows used in the control structure diagram, whereas other individuals had difficulty understanding aspects of the STAMP terminology:

“*On this thing [control structure diagram] the lines are representing communication?*” (Participant 1)

“*What do you mean by dysfunctional interactions?*” (Participant 3)

“*System component description; is that a person?*” (Participant 2)

Secondly, the participants struggled to apply STAMP, e.g. every participant had trouble defining the system hazards. Other issues encountered by the group included: (1) difficulty in drawing the system control structure; (2) classifying the dysfunctional interactions of system components; (3)

analysing the physical equipment; (4) a general uncertainty of how to proceed with the analysis, e.g.:

"*I think that's what I have a lot of difficulty with, i.e. putting all of this in a picture. It took me three attempts to even draw it [the control structure].*" (Participant 1)

"*The ballast in the wheel of the trolley [used to chock the wheel]; that classes as a dysfunctional interaction?*" (Participant 3)

"*I'm not sure what I should be doing. What should I write?*" (Participant 6)

Finally, four of the individuals had difficulty recalling information they collected during the evidence gathering phase of the simulation and had to discuss the investigation with the other participants.

In addition, two participants commented on the effectiveness of STAMP in presenting the findings of the analysis and describing the analysis process itself:

"*…there's nowhere it specifically highlights what the analysis is, how you went about getting it and what you did with it.*" (Participant 3)

"*I tried to draw the control structure, as per the instructions, and then put dotted lines where it kind of falls down but then in the end what is this picture saying to somebody? You have to understand STAMP to understand this picture and what's going on.*" (Participant 2)

6.4.3 STAMP evaluation questionnaire

The first question of the evaluation questionnaire revealed that four of the participants had used the ATSB model to originally analyse their team's evidence during the simulation. The teams of the remaining two participants had used STAMP, however, these individuals had not been directly involved in the analysis and, as a result, had not used the method. Therefore, it was considered that their limited experience of STAMP would not prevent a fair comparison with the other participants' analyses and evaluations. All of the participants confirmed in the second and third questions that they neither knew of, nor had used, STAMP before attending the accident investigation training course. The answers to the remaining questions are presented in Table 20.

Question		Mean	SD	Min	Max
4	STAMP is a suitable method for analysing accidents	4.0	1.41	2	6
5	STAMP effectively describes the event timeline of an accident	2.5	1.76	1	6
6a	STAMP effectively analyses the contribution to an accident from technical components	4.2	1.17	3	6
6b	STAMP effectively analyses the contribution to an accident from human factors issues	5.0	0.63	4	6
6c	STAMP effectively analyses the contribution to an accident from organisational issues	5.0	1.10	3	6
6d	STAMP effectively analyses the contribution to an accident from environmental issues	3.3	1.03	2	5
7	STAMP provides a comprehensive description of an accident	3.5	1.05	2	5
8	STAMP effectively represents the relationships between systems components	5.0	1.26	3	6
9	STAMP correctly identifies the causes of an accident	3.7	1.37	2	5
10	STAMP could be applied to any type of accident in my industry	3.3	1.03	2	5
11	STAMP is an easy method to understand	2.3	1.51	1	5
12	The terms and concepts used in STAMP are clear and unambiguous	3.2	1.17	2	5
13	It is easy to identify the system safety requirements	3.7	1.37	2	6
14	It is easy to define the system control structure	3.7	1.03	2	5
15	It is easy to identify unsafe decisions and inadequate control actions	3.8	1.17	2	5
16a	It is easy to describe dysfunctional interactions	4.7	1.21	3	6
16b	It is easy to describe the context of decisions/actions taken by different system components	4.0	0.89	3	5
17	STAMP is an easy method to use	2.5	1.05	1	4
18	STAMP is easy to use in a team-based analysis	3.7	1.03	2	5
19	STAMP promotes team collaboration during analysis	4.3	1.03	3	6
20	A STAMP diagram is a useful communication tool	3.8	1.47	2	6
21	A STAMP analysis can be completed in an acceptable timescale	4.3	0.82	3	5
22	It would be easy for me to become skilled at using STAMP	3.5	1.38	1	5
23	I received sufficient training in the use of STAMP to effectively use the method	2.7	1.97	1	6

Table 20 - STAMP evaluation questionnaire results (SD, Min and Max columns present ±1 standard deviation, minimum and maximum values respectively)

Examining the participants' questionnaire responses in Table 20 (using the level of agreement values established in Table 15) reveals a number of noteworthy issues. As a group, the participants slightly agreed that STAMP is a suitable method for analysing accidents, albeit that there was a wide range of opinion, and that it correctly identifies the causes of an accident. Specifically, the participants agreed that STAMP effectively analyses the contribution to an accident from human factors and organisational issues and that it effectively represents system component relationships. Furthermore, they also agreed that it was easy to describe the dysfunctional interactions of system components. However, the group slightly disagreed that the accident event timeline was effectively described by the method (five of the participants either slightly disagreed or disagreed with the statement) (see Figure 59 in Appendix 6.4).

Collectively, the participants disagreed that STAMP was easy to understand and slightly disagreed that it was easy to use. In each case, only one participant agreed with the statement. However, four of the participants either slightly disagreed or disagreed that they had received enough training to effectively use the method. There was also a wide range of opinion amongst the group as to whether the participants could easily become skilled at using STAMP (see Figure 59 in Appendix 6.4).

6.4.4 Focus group

6.4.4.1 Benefits of STAMP

When asked, three participants provided examples of the benefits of using STAMP. These advantages related to the method's ability to provide insights into the contribution to an accident from the higher levels of a system, graphically describe a complex accident and visually communicate the findings of an analysis to senior management in an effective manner, e.g.:

"*I think the pros would be that, if you had a very complex accident, I think you would be able to represent it graphically with the STAMP method.*" (Participant 1)

"*It's great for looking at the overarching stuff [and] it was useful for [defining the] lines of responsibility trees and communication trees.*" (Participant 4)

6.4.4.2 Disadvantages of STAMP

Conversely, the group also mentioned disadvantages associated with the analytical and graphical representation capabilities of STAMP. Although Participants 1 and 4 felt that STAMP was suitable for higher system level analysis, they also stated that it did not provide an effective analysis of issues, e.g. human factors, at the lower system levels. Participant 4 also mentioned that the lack of an accident trending capability, due to the absence of a taxonomy, represented an analysis limitation. Furthermore, three of the participants remarked that the CAST process seemed too prescriptive, e.g.:

"*I felt as if the analysis was driving the evidence.*" (Participant 2)

"*You had the evidence and you had to slot into the analysis at the right levels, rather than you've got your timeline, you've got your evidence and say 'what happened here?'*" (Participant 4)

The issues raised by the group, in relation to STAMP's graphical representation of an accident, related to how effectively it communicates the findings of an analysis. In particular, all four members of the focus group commented that the inability of the method to chart the timeline of an accident posed an important limitation, e.g.:

"*That's the big issue with STAMP: it's not a logical representation. It's not time-lined.*" (Participant 1)

"*STAMP definitely needs a timeline somewhere in there to give you presentational stuff.*" (Participant 4)

The STAMP control structure diagram was also described as visually confusing by two participants. Participant 3 stated that it added no real value to an analysis and Participant 2 commented that the graphical output of the ATSB model was easier to understand. In addition, Participants 3 and 4 commented that drawing the system control structure was most difficult stage of the analysis process.

Other drawbacks of STAMP were associated with its usability. For example, Participant 1 stated that the method was not user friendly, whereas Participants 2 and 4 mentioned that it was hard to understand, due to the complicated analysis process. However, these participants also mentioned that their ease of using and understanding STAMP was influenced by the level of training that they had received, e.g.:

"*I'd have to do it three or four times, i.e. use it more and then go 'yeah, I've got the concept, it is good for this [type of accident/system]' but, having just done it once, I don't think I can really say it is good or it is easy to use.*" (Participant 2)

"*I did find it complicated at first and that's because it's brand new and we didn't understand it that well.*" (Participant 4)

6.4.4.3 Improvements to STAMP

The only improvement mentioned by the whole group referred to the inclusion of a timeline within the graphical output of the analysis, i.e. the system control structure diagram, despite being reminded that the creation of a timeline is a defined stage of the CAST process, e.g.:

"*An event-based timeline is the starting point [to improve the method].*" (Participant 3)

"*[I would] put a timeline at the start.*" (Participant 2)

The participants subsequently discussed possible alterations to the STAMP control structure format which would enable the integration of a timeline, such as drawing an event timeline and then use the standard control structure format to link relevant system components to the various events (i.e. have instantiations of the control structure arranged along a timeline).

6.4.4.4 Use of STAMP in future investigations

Participant 2 indicated that they may use the control structure diagram in future investigations, as a means of understanding the communication between system components. Conversely, Participants 3 and 4 explicitly stated that would not be inclined to use STAMP in the future. A number of reasons were cited for this decision: (1) a preference for using a multi-method hybrid approach; (2) being mandated to use a different method; (3) the resource requirements of STAMP are too high; (4) a reluctance to trial a new method in a live investigation; (5) reverting to methods used before.

Furthermore, the group commented on the need to select a method that meets the needs of the analysis, rather than dogmatically applying one technique:

"*I don't think there's any one key method that you can really lock down because it's the evidence that's driving the analysis.*" (Participant 3)

"*There's no one model that's perfect.*" (Participant 1)

6.4.5 Summary of findings

When considered separately, the different sources of data highlight a number of issues. The analysis outputs (see Section 6.4.1) showed that considerable variation existed between the participants in terms of the quantity and nature of the system components and factors that were identified as contributing to the accident. This is evidenced by, for example, the range of system safety constraints identified by the participants (see Section 6.4.1.2) and the fact that only four participants described any system coordination and communication issues (see Section 6.4.1.6). The workshop audio recording identified that the participants had difficulty in understanding and applying STAMP, as well as recalling information about the evidence they had collected. The STAMP evaluation questionnaire revealed that, as a group, the participants slightly agreed that the method is suitable for analysing accidents and that it correctly identifies the causes of an accident. However, the participants slightly disagreed that STAMP effectively describes the accident event timeline or that it was easy to use. Furthermore they disagreed that STAMP was easy to understand, albeit that four participants felt that they had not been sufficiently trained in the use of the method. Finally, the focus group discussion identified a mixture of opinions regarding the benefits and drawbacks of STAMP. Although it was commented that the method provides insights into the higher levels of a system, the participants also stated that it was not effective at analysing issues at the lower system levels, e.g. human factors problems. Furthermore, whilst three participants felt that the graphical output of STAMP aided the communication of analysis findings, the whole group noted that the method did not visually represent the event timeline effectively. Three participants also mentioned problems with the usability of STAMP, although they acknowledged that their opinion was influenced by the level of training that they had received.

When the findings are integrated, however, what can be said about the participants' experience of using STAMP and the subsequent implications for its adoption by practitioners? These issues are discussed in Section 6.5.

6.5 Discussion

6.5.1 Model usage characteristics

6.5.1.1 Data requirements

The evaluation of STAMP in Section 5.6.2.2 suggested that the type of information which can be analysed by the method is not restricted by the original format of the data. Some of the participants remarked, during the focus group, that STAMP was not effective at analysing information pertinent to lower system level components. Whilst this indicates variability in how STAMP analyses and incorporates data, the comments were contradicted by the evaluation questionnaire data, which showed that each participant at least slightly agreed that such information was effectively analysed. However, the participants did encounter some difficulties when trying to analyse and incorporate the evidence they had collected during the investigation exercise. For example, a degree of confusion existed over how some of the information should be processed. This was evidenced by the questions and comments raised during the workshop and the association of actions and decisions of personnel to the failures of the physical system components (see Section 6.4.2 and Figure 43). The difficulties of classifying data and incorporating it into the analysis were similar to those experienced when applying STAMP to the Grayrigg derailment in Study 3 (see Section 5.7.1.2) and those encountered by other researchers (Johnson and Holloway, 2003 p.8; Salmon et al., 2012a p.1168). This suggests that more detailed usage guidance regarding the treatment of evidence may be required to facilitate the analysis. However, these difficulties may also be indicative of the participants' lack of experience in using STAMP. Regardless, the problems encountered by the participants seem to result from usability issues associated with the method, rather than a fundamental restriction on the type of data it can analyse.

As described in Section 5.5.2.2, the information that a method requires to produce a thorough analysis can impact on the evidence collection process in an investigation. However, none of the teams based their evidence collection on the needs of any analysis model, i.e. the selection of analysis method was made after the evidence collection phase of the investigation exercise. Therefore it is not possible to evaluate whether STAMP aided the collection of data. However, it does offer a possible explanation as to why some of the participants felt that the CAST process was overly prescriptive (see Section 6.4.4.2). In other words, the perception that the participants were 'force fitting' some of the data into the STAMP analysis may have been lessened if the requirements of the method had guided their data collection.

The output of an analysis will always be limited by the amount and quality of the evidence gathered by investigators. The evidence collected by the teams did not relate to many organisational issues and, therefore, the participants were not able to perform a thorough analysis of the higher system levels. Therefore, the participant observations and questionnaire responses which suggest that STAMP is effective at analysing organisational issues seem to be based on the perceptions of the participants, rather than on their experience of using the method. Consequently, it is difficult to determine whether, in practice, STAMP facilitates the analysis of higher system level information collected during an investigation.

6.5.1.2 Validity

As explained in Section 6.3.8.1, the validity of STAMP was not formally tested. However, the questionnaire and focus group data suggest that the participants' consider the method to have a degree of face validity. For example, the questionnaire responses of the participants reveal that, as a group, they slightly agreed that STAMP is a suitable method for accident analysis and that it correctly identifies the causes of an accident. Furthermore, the participants' agreed that STAMP is effective at analysing organisational/higher system level issues. However, it is unclear whether the group agreed that STAMP could effectively analyse lower system level factors, as their questionnaire responses conflict with various comments made during the focus group. Also, five of the participants at least slightly disagreed that STAMP effectively describes the accident event timeline (see Table 20). This opinion was subsequently elaborated on by the members of the focus group, who suggested that the lack of a timeline within the control structure diagram was a drawback of the method (see Section 6.4.4.2).

Whilst STAMP appears to offer the practitioners a valid technique for analysis, this statement could be made with more confidence if: the participants gained more experience of using the method to thoroughly analyse each level of a system; improvements to the method were made, e.g. incorporating the event timeline into the control structure diagram. Therefore, although this apparent degree of face validity may start the process of building trust in the method, it seems that further work to develop and evaluate the method may be needed in order for it to gain acceptance by practitioners. This is supported by the findings of Study 2 (see Section 4.4.3.4) and the work of Johansson and Lindgren (2008), which suggest that practitioners require a method to have received empirical validation before they will adopt it.

6.5.1.3 Reliability

As per the validity of STAMP, the method's reliability was not formally tested for a number of reasons (see Section 6.3.8.1). Nonetheless, the analysis outputs show that there was considerable variation between the participants' analyses (see Section 6.4.1). Given that STAMP was considered to have moderate reliability during its application in Study 3 (see Section 5.6.2.2), would this level of variability be expected? As the participants were using their own sets of data, it is not possible to answer this question with a high degree of certainty. However, there was a considerable amount of similarity between the data used by each participant, and, therefore, it seems appropriate to discuss this variability.

As the participants were first-time users of STAMP, it is not surprising that this variation occurred. This variability existed despite the training the participants had been given prior to the workshop and the CAST process description they received before commencing their analyses. Therefore, this variation indicates that the training provided on STAMP and the CAST process was insufficient. Indeed, some of the participants highlighted that they had not received adequate training to effectively use the method in their questionnaire responses and focus group comments. The possibility of insufficient training was also evidenced by the difficulties the participants encountered during the analysis workshop (see Section 6.4.2). These findings are consistent with a method evaluation study performed by Baysari et al. (2011), who state that the inter-rater reliability problems they observed were, in part, due to a lack of participant training.

Analysis reliability can also be influenced by the backgrounds and previous experience of the participants, as described in Section 4.4.4.2 and by other researchers (e.g. Johnson, 2003). The data collected during the focus group suggests that at least two of the participants have an established analysis approach (see Section 6.4.4.4). Therefore, it is possible that this prior experience may have affected their use of STAMP and contributed to the variation across the analysis outputs.

The participants were not directly asked about their views on the reliability of STAMP and only one individual volunteered an opinion about the method's reliability. During the focus group, Participant 4 mentioned the accident trend analysis limitations imposed by STAMP's lack of a taxonomy; a feature of the method which also reduces its reliability (as described in Section 5.6.2.2). Whilst levels of experience and/or analyst bias seem to have affected the variability of the workshop analysis outputs, this connection was not made by them. This suggests that the reliability of a method was not a principal concern of the participants. This coincides with the views of the Study 2 participants, i.e. only 4% of the sample stated that reliability was a preferred feature of their ideal analysis method (see Figure 19). Alternatively, it suggests that the participants were not as aware of the variation as they might have been had they been working together as a team.

Regardless of the reason, maximising the reliability of an analysis is an important issue for investigators for a number of reasons: during an investigation it will facilitate the analysis process; it provides more consistent findings, thus easing accident trend analysis; it will ultimately improve the validity of safety recommendations and, therefore, the credibility of the investigation team. Given that detailed usage guidance material is available for the method, it is conceivable that the analysis variability may lessen if the participants became more experienced in using STAMP. Furthermore, the analysis review process that often takes place amongst the major accident investigation teams, as described in Section 4.4.4.2, would also improve the reliability of the analysis findings. However, as also indicated in Section 4.4.4.2, the qualitative nature of STAMP could increase the difficulty in reaching a consensus regarding the analysis. Furthermore, as some of the participants felt that CAST was overly prescriptive, there might be a tendency for some individuals to adapt, or even ignore, the application process and thereby lower the reliability of STAMP.

6.5.1.4 Usability

The various sources of data collected during the study clearly reveal that the participants found it hard to understand STAMP. Not only did some of the participants comment on the difficulties they experienced in understanding the method during the workshop but, as a group, their questionnaire responses show that they disagreed that the method was easy to understand. Furthermore, the comments raised by some of the participants during the focus group indicate that understanding the method was problematic (see Section 6.4.4.2). As described in Sections 6.4.4.2 and 6.5.1.3, such difficulties may be indicative of insufficient training and/or analyst bias. However, these findings do suggest that learning about STAMP and its application is not a quick process and that the participants would require multiple attempts at using the method before achieving a sufficient level of understanding. This highlights the resource implications of learning and using more complicated methods, such as the SAA techniques; a point which is raised by various authors, such as Johansson and Lindgren (2008) and Salmon et al. (2012a).

In addition to the difficulties the participants experienced in understanding STAMP, the questions and comments raised during the workshop revealed that the group found that the method was not easy to use (see Section 6.4.2).

Remarks made by the participants during the workshop and in the focus group suggest that these usage difficulties are, in part, related to an inadequate understanding of the method. The evaluation questionnaire also revealed that the participants slightly disagreed that STAMP was easy to use. However, other questionnaire responses did not reflect the usage problems encountered during the workshop. The responses for Q13-16b suggest that the group at least slightly agreed that it was easy to perform various aspects of the CAST process (see Table 20). This contradiction in the data cannot be explained by inter-participant variation in responses, i.e. individual participants contradicted themselves rather than consistently holding an opinion about the ease of using STAMP. Furthermore, no other reason for this conflict could be deduced from the data. Therefore, it is not certain from the findings of this study how the usability of STAMP would affect its use during an investigation.

Despite this issue, the majority of the data gathered during this study does indicate that improvements to STAMP's usability are required, if the method is to be learnt more easily and with fewer resources.

6.5.1.5 Graphical representation of the accident

As with aspects of STAMP's usability, contradictions were found across the sources of data with regards to the creation and usefulness of the graphical output of the method. Comments made during the focus group suggested that the control structure diagram effectively represents the complexity of an accident and that it would successfully communicate analysis findings to senior management individuals. The effectiveness of STAMP as a communication device was also reflected in the group's questionnaire responses, i.e. their slight agreement that the STAMP diagram is a useful communications tool. However, remarks made by some of the participants, during the workshop and focus group, suggest that the control structure did not facilitate the analysis process, e.g. identify gaps in the analysis, nor was it easy to understand. Furthermore, there was a clear need identified, during the focus group, for STAMP to graphically incorporate an event timeline. Again, it was not possible to explain this contradiction with the available data.

Interestingly, the majority of the participant responses concerning the graphical representation of the accident referred to the control structure diagram. This suggests that the participants considered this diagram as the focal point of the analysis documentation. This is arguably unsurprising, as many accident analysis methods utilise a diagram to summarise the findings of an investigation. However, STAMP does not lend itself to a simple graphical representation of an accident, as its outputs are spread over several documents, some of which are mainly text-based (Leveson, 2012 p.91) (see Section 5.6.2.2). Therefore, it does seem that there could be a mismatch between STAMP's outputs and the graphical needs that practitioners have of their analysis methods.

6.5.2 Implications for the adoption of STAMP

When examining the integrated study data, it appears that the usability of STAMP and its graphical output were the key concerns of the participants. In particular, the ease of understanding and usage of the method (and the subsequent need for extra training) and the lack of an event timeline in the control structure diagram were highlighted as problems. Based on the findings of Study 2 (see Figure 19), these issues highlight that two of the main requirements of an analysis model are not being met, i.e. acceptable usability and the usefulness of the method's output format. Therefore, unless these issues are addressed it is possible that STAMP will struggle to gain widespread acceptance within the practitioner community.

6.6 Study limitations

A number limitations were placed on this study which relate to the use of a simulated investigation scenario and the selection of participants. The use of a simulated accident cannot exactly recreate the experience of conducting a live investigation. Therefore, the participants' experience of using STAMP may have been affected by using it within this simulated context. However, the fidelity of the simulation was considered to be sufficiently high as to provide the participants with a representative experience of accident investigation. The small sample size limits the generalisation of the findings. However, only 10 individuals were eligible to participate in the study and would still have formed a small sample even if 100% recruitment had been achieved. The participants, all of whom were aviation professionals, had a limited knowledge of the rail industry. At the time of the study, Cranfield University only conducted aviation-specialist courses in the weeks subsequent to the ‘Fundamentals of Accident Investigation’ module, i.e. when data collection was feasible. Therefore, it was not possible to recruit trainee rail accident investigators. Consequently, the ability of the participants to effectively analyse the accident may have been compromised, thus impacting on their experience of using STAMP. However, previous experience of accident investigator training at Cranfield University suggests that this is not the case. Braithwaite (2004) comments that a trainee investigation team comprised of aviation and marine specialists performed comparably to other teams, which included rail experts, during a rail accident investigation exercise. This highlights that the key principles of investigation remain the same and that a lack of subject matter expertise (at least during training) is not necessarily problematic. Furthermore, the lack of industry knowledge amongst the participants provided a degree of control over the reliability of their analysis outputs and their experiences of using STAMP.

When considering the level of accident analysis experience of each participant, it is possible that Participant 4 could be considered an ‘outlier’ (see Table 14). In other words, their level of analysis experience may have significantly differentiated their usage of STAMP from the other participants. However, as show in the findings of this study (and their unreported comments captured during the analysis phase of the study) their STAMP analysis outputs and usage evaluation are comparable to that of the other participants (see Section 6.4 and Appendices 6.3 and 6.4). This is arguably a result of their similarly limited experience of using STAMP and justifies their inclusion in the study.

Due to the resource limitations of the study, it was only possible to conduct the evaluation of one of the SAA methods, i.e. STAMP. Whilst it would have been preferable for the participants to also conduct analyses with FRAM and AcciMap, this limitation represents an opportunity for future research.

Finally, the participants were given freedom to select their own analysis method during the simulated investigation. No team pre-selected a method and used it to guide their evidence collection. Therefore, the participants experience of using STAMP may well have been different, had they used it to inform their data gathering. However, given that the participants were analysing primary data during the workshop, the findings of the study are considered to provide a useful insight into the use of STAMP within an investigation.

6.7 Conclusion

Little is currently known about the use of SAA methods by practitioners and ensuring that their needs are met is an important factor in whether an analysis method will be adopted or not, as indicated in Chapter 4 (see Section 4.7.1). This study aimed to provide an insight into the usage of STAMP, by obtaining a practitioner evaluation of the method based on their experience of using it in a simulated investigation, and an understanding of how the usage characteristics of the method may affect its application in a live investigation scenario. The findings of the study suggest that STAMP does not currently meet the usability or analysis output requirements of practitioners and, therefore, that the method may struggle to gain acceptance within industry.

Chapter 7 – Discussion

7.1 Chapter overview

This chapter starts with a brief summary of the research findings presented in the thesis. The overarching topics of whether the SAA RPG needs to be bridged, how this can be achieved and, if indeed, it is possible to bridge it are then discussed. Finally the strengths and weaknesses of the research, as a whole, are presented.

7.2 Introduction

This thesis has presented the findings of four studies which have examined various facets of the SAA RPG using a mixed-methods approach. The aims of this research were to identify factors which contribute to the SAA RPG and gain a better understanding of the extent of the RPG. A summary of the findings from each of the studies presented in the thesis is provided in Section 7.3.

Based on these findings, what can be said about the SAA RPG? As referred to in Chapters 4-6, further examination of some important topics is required. Firstly, given that there seems to be a similarity between the SCM-based techniques utilised by practitioners and the SAA methods, does the RPG need to be bridged? If the gap should be bridged, which contributory factors should be addressed and how? Furthermore, can the gap be bridged? These questions are considered in Sections 7.4-7.6.

7.3 Summary of research findings

7.3.1 Study 1: Evaluating the systemic accident analysis models, methods and literature

The starting point for the thesis involved evaluating the ‘innovation’ of SAA to better understand what factors could affect its diffusion into practice. Consequently, the first study was designed to examine how the systems approach is presented within the SAA literature and identify the features of the systemic techniques which potentially hinder their adoption and usage by practitioners. To achieve this, the SAA literature was analysed to determine how key systems theory concepts had been interpreted by SAA researchers.

Examples of SAA methods were identified within the literature and the development processes, systemic and usage characteristics of the three most popular techniques (STAMP, FRAM and AcciMap) were evaluated.

It was discovered that the research literature has not presented a consistent or clear approach to applying systems theory within accident analysis; the implication being that this arguably ineffective communication of SAA may hinder its acceptance by practitioners. Model validation, analyst bias, limited usage guidance, resource constraints and the implications of not assigning blame for an accident were identified as issues which may influence the use of SAA methods within industry.

7.3.2 Study 2: Factors contributing to the SAA research-practice gap

Following on from the findings of Study 1, the need was established to further examine the factors which could contribute to the SAA RPG. In particular, the intention was to better understand the practitioner-related influences which may affect the gap. Therefore, to supplement and expand upon the information gathered from the document analysis of Study 1, an interview study was performed. The three aims of the study involved: (1) understanding how the awareness of, and need for, SAA within the practitioner community could inhibit its adoption and usage; (2) understanding how the factors influencing current analysis approaches may hinder the adoption and usage of SAA; (3) probing deeper into the issues stemming from research which may contribute to the SAA RPG. Semi-structured interviews were conducted with 42 safety experts, who were also asked to complete an analysis model awareness table.

Various factors, including those found in Study 1, were identified which can affect the awareness, adoption and usage of SAA methods. As such, it was considered that an adequate representation of the SAA RPG has been provided. The key issues seemed to relate mainly to the communication of SAA and the requirement for analysis methods to meet needs of practitioners. Whilst one factor may be sufficient to prevent a practitioner from conducting SAA, it seems more likely that they all, to a greater or lesser extent, combine to inhibit the application of the systems approach.

7.3.3 Study 3: Systemic accident analysis vs. the Swiss Cheese Model

The focus of the research then moved towards examining the extent of the SAA RPG. The SCM is the most popular accident causation model and is widely used throughout various industries. However, a debate exists in the research literature over whether the SCM remains a viable tool for accident analysis. Critics of the model suggest that it provides a sequential, oversimplified view of accidents (e.g. Hollnagel, 2012; Leveson, 2012). Conversely, proponents suggest that it embodies the concepts of systems theory, as per the contemporary systemic analysis techniques (e.g. Reason et al., 2006; Salmon et al., 2012a). The aim of this study was to consider whether the SCM can provide a systems thinking approach and remain a viable option for accident analysis. To achieve this, the Grayrigg train derailment was analysed with an SCM-based model (the ATSB model) and two SAA methods (AcciMap and STAMP). The analysis outputs and usage of the techniques were compared.

The findings of the study showed that each model applied the systems thinking approach. However, the ATSB model and AcciMap graphically presented their findings in a more succinct manner, whereas STAMP more clearly embodied the concepts of systems theory. The study suggests that the SCM remains a viable model for accident analysis and that SAA techniques represent an evolution, rather than a revolution, in the application of the systems thinking approach. Therefore, in the cases where practitioners correctly apply the SCM, the extent of the SAA RPG may not be that significant.

7.3.4 Study 4: Evaluating a systemic accident analysis method

The findings of Study 2 indicated that SAA methods must meet the needs of practitioners, if the SAA RPG is to be bridged. This was one of the two main issues observed in the key themes of the study (the other being communication of SAA, see Section 4.4.1). Little information is currently available about the application of SAA methods by practitioners and whether their needs are met. This final study was devised to provide an insight into this issue and consisted of two objectives: (1) obtain a practitioner evaluation of an SAA method; (2) understand how the usage characteristics of the method affect its use in a live investigation scenario. Six participants took part in a workshop to analyse data collected during a (high-fidelity, partly field-based) simulated investigation exercise using STAMP. The analysis outputs were assessed, along with the issues raised by the participants during the workshop and their questionnaire and focus group responses pertaining to their experiences of using the method.

When combining the mixed methods data generated during the study, a number of observations regarding the participants' experiences of using STAMP could be made. The difficulties in analysing accident data experienced by the participants seemed to result from usability issues, rather than a fundamental restriction on the type of data that STAMP can analyse. Some participants felt that the method was too prescriptive, although this may have resulted from not using STAMP to guide their data collection. Regardless, the participants seemed to consider that STAMP has face validity. Although not formally tested, low inter-rater reliability was observed. This was likely due to the lack of training provided to the participants and the biases they introduced, e.g. the effects of their previous analysis experience. Overall, the participants reported that STAMP was hard to understand, although mixed views were provided regarding its ease of use. Variation in the participants' opinions was also noted regarding the usefulness of STAMP's graphical output. However, there was a clear demand to incorporate a timeline into the method's graphical representation of an accident. Improving the usability and graphical output of STAMP were highlighted as key developments that may improve the method's acceptance by practitioners.

7.4 Does the SAA research-practice gap need to be bridged?

Following on from the discussion presented in Chapter 5 (see Section 5.7.2), this section examines whether the SAA RPG needs to be closed or not.

To recap, the proposed benefits of SAA presented in Sections 2.3 and 2.4.3, i.e. gaining an improved understanding of accidents which may lead to more effective recommendations, suggest that it should be. Indeed, research that has compared SAA methods with non-systemic analysis techniques indicates that such benefits are attainable and, therefore, that SAA should be promoted throughout safety-critical industries (see Section 2.4.3). The findings of Study 3 suggest that the SAA RPG may, in certain circumstances (i.e. for people utilising SCM-based methods), not be as extensive as some researchers suggest (e.g. Hollnagel, 2012; Leveson, 2012). Furthermore, due to the on-going academic debate as to whether or not the SCM provides a means of conducting SAA, the existence of an SAA RPG seems to depend on which view of accident causation is taken by an individual. Therefore, the need to bridge the gap could be questioned. However, whilst the SCM is undoubtedly the most popular accident analysis technique, there are many other non-SAA methods in use throughout industry. Does use of these methods increase the extent of the SAA RPG to the point where its existence becomes problematic, i.e. will the understanding of accidents be compromised? Due to resource constraints, evaluating every non-SAA technique is beyond the scope of this research and, therefore, it is not possible to give a definitive answer to this question. However, the work of (Hollnagel, 2008) provides some useful insights.

Expanding upon the NAT work of Perrow (1984), Hollnagel (2008) provides a means of characterising systems which considers their coupling and tractability (manageability). The coupling of a system can vary between being loose and tight and refers to how subsystems and/or components are functionally connected or dependent upon each other. As described in Section 2.2.3, various issues contribute to a tightly coupled system, such as: processes which occur rapidly and cannot be stopped, failed components that cannot be isolated or there being only one way to maintain safe operations (Perrow, 1984 p.5). A system's manageability can vary from high (tractable) to low (intractable). A system can be defined as tractable when: the principles of the system's functioning are known; descriptions of the system are simple and with few details; the system does not change while it is being described, i.e. changes in system activities are slow enough that the whole system can be described completely and in detail (Hollnagel, 2008).

Hollnagel (2008) characterised a number of systems by using the dimensions of coupling and manageability and adapting the system characteristics matrix created by Perrow (1984) (see Figure 44). A number of analysis tools were subsequently evaluated and mapped on to the coupling-tractability matrix (see Figure 45); the suggestion being that different generations of analysis technique are best suited to certain types of system.

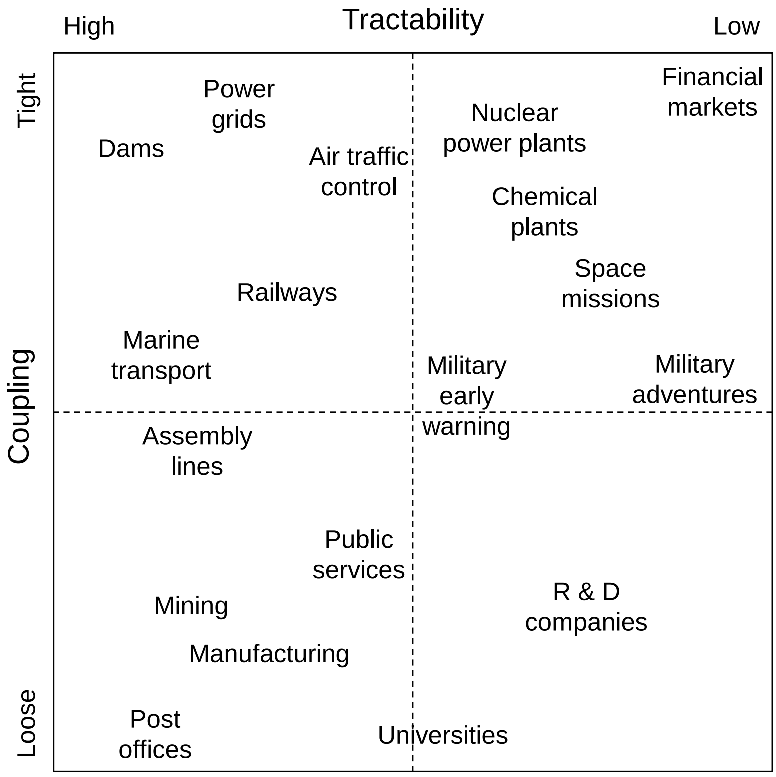

Figure 44 - System characteristics. Adapted from Hollnagel (2008).

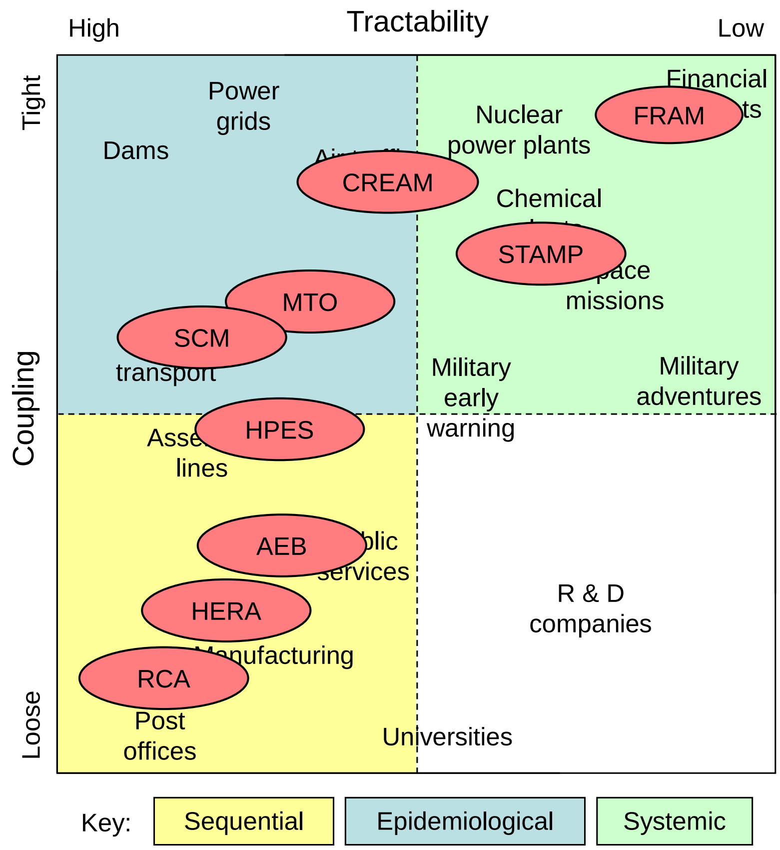

Figure 45 - Analysis technique suitability. Adapted from Hollnagel (2008).

As indicated by Figure 45, Hollnagel (2008) suggests that the STAMP and FRAM systemic methods are best suited for analysing accidents in tightly coupled systems with low tractability[8]. Although not addressed by Hollnagel (2008), it is considered that other SAA methods, such as AcciMap, would also be located in the upper-right quadrant of Figure 45. Given the ever-rising complexity of STS, it seems that the use of SAA methods will become increasingly important in the future. The implication is, therefore, that the traditional sequential techniques, e.g. FTA and Five Whys, will become increasingly inadequate at describing the nature of complex accidents and the size of the SAA RPG will increase. Furthermore, despite the ambiguity

[8] No class of analysis technique has been assigned to the lower right-hand quadrant of Figure 45 as, according to Hollnagel (2008), no models or methods are applicable for loosely coupled systems with low tractability. Hollnagel (2008) suggests that this is because no major accidents have occurred in systems of this nature and, therefore, there was no drive to develop any relevant analysis tools. It is also important to note that the locations of the boundaries between the model generation categories in Figure 45 are notional and will not be this distinct in reality.

surrounding the definition of a systemic method (see Section 5.2), it seems that SAA tools are theoretically capable of providing useful insights into complex STS accidents which are not generated by many traditional analysis methods. Therefore, efforts to bridge the SAA RPG should be made.

However, sequential techniques may remain effective in certain circumstances, e.g. the analysis of less complex systems or of sub-systems/components (Hollnagel and Speziali, 2008; Salmon et al., 2011). As described in Section 4.5.1.4, this notion is supported by the views of some safety experts, who commented on the importance of matching the analysis method with the characteristics of the system. Furthermore, emerging fields of research can neglect the commonalities they have with more traditional fields and developers of new models often criticise or even disqualify older ones, as noted in Section 5.2. However, in reality, different techniques can actually complement each other, due to their own strengths and weaknesses (Jacobsson et al., 2009; Katsakiori et al., 2009; Sklet, 2004). This issue has been examined in studies which combined systemic and non-systemic techniques (e.g. Ferjencik, 2011; Kontogiannis and Malakis, 2012; Salmon et al., 2013) and suggest that a more insightful analysis is achieved compared to that when using a single model.

Therefore, SAA methods may only represent one option in an investigator’s ‘analysis toolkit’ and bridging the SAA RPG does not necessitate the abandonment of every non-systemic technique. Rather, SAA methods could be integrated with the current analysis practices of accident investigators in order to provide them with a means of understanding the more complex major accidents. In this respect, it seems that the SAA RPG should be bridged to maximise the effectiveness of accident investigators.

7.5 Bridging the SAA research-practice gap

Given that bridging the SAA RPG seems justified, what should be done to achieve this? As indicated by the findings of Study 2, two key solutions focus on meeting the analysis method needs of practitioners and the effective communication of SAA.

7.5.1 Adapting SAA methods

An initial step towards implementing the first solution was made in Study 4, i.e. performing an evaluation of STAMP and ascertaining that the method's usability and graphical output were highlighted as insufficient. However, further effort is required if it is to be determined if, and how, the systemic methods need to be adapted to meet the demands of live investigations and accident trend analysis. This work has begun and discussions between the two communities are taking place, e.g. the annual STAMP and FRAM workshops organised respectively by Nancy Leveson and Erik Hollnagel. However, practitioner feedback has yet to be widely publicised. Therefore, further efforts should be made to establish whether the SAA methods can be effectively applied in industry. As suggested in Section 6.2, this work would ideally involve recruiting accident investigators to use, evaluate and help refine the systemic techniques; a process that was also involved in successfully establishing other analysis methods, such as HFACS and Tripod Delta. This would create researcher-practitioner engagement, make research more practitioner-focused and, ultimately, increase the amount of research applied by practitioners; three main strategies for bridging RPGs referred to in other domains, such as healthcare (e.g. Dobson and Beshai, 2013; Hofmann, 2013), manufacturing (e.g. Bacchetti and Saccani, 2012) and human factors (e.g. Chung and Shorrock, 2011) (see Table 3).

7.5.2 Communication of SAA

Achieving more effective communication of SAA research to practitioners can be accomplished via a number of routes. Table 10 suggests that, along with continued presentation of research at conferences, promoting SAA within the practitioner literature and professional institutes would increase the awareness of many practitioners. Steele and Pariès (2006) comment that successful communication of 'less traditional' perspectives on accident causality to practitioners target the layperson, convincingly summarise such ideas and make them seem like common sense. Information created for the practitioner-focused literature should, therefore, be produced to meet these criteria. This may be particularly relevant for practitioners who only have a part-time involvement in accident investigation.

Increasing the access to SAA research may also help to bridge the gap, as indicated by the findings of Study 2 (see Section 4.4.2.4) and Table 3. It seems that the majority of SAA information is presented via the scientific literature and at conferences, which can incur access costs. Publishing in open-access journals would remove the potentially unaffordable expense associated with journal subscriptions/purchasing articles whilst still providing peer-reviewed research. However, although the number of open-access journals is increasing, they still account for a relatively small amount (~12%) of the available journals (Solomon et al., 2013). Therefore, this solution is likely to be a long-term one.

Increasing the amount of SAA information provided in accident analysis training offers another important option for raising the awareness and adoption of systemic methods. Indeed, improving the amount/quality of training provided to practitioners is the most frequently cited solution in the recent RPG literature (see Table 3). Preferably this training would be conducted strategically to maximise its impact. As a starting point, the training should be provided to accident investigation trainers. This would utilise an existing network of professional trainers that can act as an effective and efficient interface between the researcher and practitioner communities. Ideally, industry regulators and senior safety managers should also be trained in SAA. If regulators and organisations formally adopt SAA then the need/requirement for individuals to employ systemic techniques in accident analysis will increase. However, until an SAA track record can be established in industry, it is unlikely that regulators and organisations will commit to formally adopt and use the systemic analysis techniques. Therefore, achieving this commitment is likely to be a long-term aim of bridging the RPG.

Communication is not a one-way process and, in addition to providing practitioners with more information about SAA, the information needs of researchers should also be considered. As indicated by Table 3, ensuring that research is focused on the needs of practitioners is an important means of bridging an RPG. If researchers are to accomplish this, there is a need to engage with practitioners in order to understand their analysis needs and the issues they encounter when investigating. As suggested by the recent RPG literature (see Table 3), possible options for creating this engagement include collaborative research projects, providing researchers with opportunities to observe live investigations and recruiting practitioners into the academic environment. Other options could include performing more participatory-based research, e.g. action research or design science (see Holmström et al., 2009; Kenny et al., 2012; Moore et al., 2012; van Aken, 2005), and the formation of safety-related knowledge transfer workshops, seminars and conferences akin to those established in domains such as healthcare, human factors and rail (see Appendix 7.1 for examples).

A considerable amount of research concerning the practices of accident investigators (and the challenges they face) has already taken place (e.g. Braithwaite, 2008; Lundberg et al., 2010; Okstad et al., 2012; Roed-Larsen and Stoop, 2012; Rollenhagen et al., 2010; Svenson et al., 1999). However, as SAA methods are yet to be widely adopted throughout industry, it seems there is a need for further research which specifically addresses the use of SAA in practice. Examples of successful research-practice collaborations, which have enabled the application of research within practice, exist within the domain of accident analysis (e.g. the development of the HFACS and Tripod Delta methods) and in other areas, such as human resource management (e.g. Hamlin et al., 1998), social work (e.g. Herie and Martin, 2002), management science (e.g. Hodgkinson and Rousseau, 2009) and healthcare (e.g. Tai et al., 2010). This suggests that increasing the collaboration and, therefore, communication between SAA researchers and practitioners can offer a credible solution for bridging the gap. If collaboration is not a viable option, practitioners could still provide useful feedback to researchers by publishing articles about how they have applied research and the successes/challenges they encountered (Chung and Shorrock, 2011).

Given that there are so many factors which can contribute to the SAA RPG, there may well be the need for a multifaceted solution, i.e. a combination of methods to bridge the gap. Indeed, as some contributory factors are likely to have varying impacts on individuals/organisations (e.g. training resource constraints), tailored solutions may be required. For example, organisations which allocate a larger percentage of their budget towards safety may be more willing to engage in collaborative research. However, regardless of how the gap is to be bridged, practitioners must see the value and applicability of SAA if they are to adopt it (Herie and Martin, 2002).

7.6 Can the SAA research-practice gap be bridged?

7.6.1 The differing needs of practitioners and researchers

Despite efforts in various fields of research over multiple decades, the bridging of RPGs can remain elusive (Holmström et al., 2009). The on-going struggle is exemplified by the considerable amount of research currently being produced (see Section 2.5.3). Holmström et al. (2009) suggest that theoretical and academic research interests do not seem to coincide with the needs of managerial practice and that the challenge of bridging an RPG is more fundamental than knowledge transfer, i.e. it is one of diverging interests. The proposed solutions described in Section 7.5 offer a means of bridging the SAA RPG. However, are the needs of accident analysis researchers and practitioners too different to completely close it? The differences between the needs of the two communities and their impact on SAA method adoption and usage are considered in the rest of Section 7.6.1.

7.6.1.1 Efficiency-thoroughness trade-off

In any form of analysis, a compromise must be made between the thoroughness of the analysis and the resources available to complete it. Practitioners can be placed under intense amounts of pressure (e.g. commercial and legal) to provide an explanation for an accident (Hayward and Lowe, 2004 p.378). There is also a need to conclude an analysis quickly so that feedback does not come too late to be of any use and resource expenditure, which can be significant, can be optimised (Hollnagel, 2009 p.70). Therefore, practitioners are likely to require a method which provides a thorough enough analysis to generate useful safety lessons whilst also ensuring efficient resource usage. Given that practitioner feedback on SAA methods has not been widely publicised, it is not possible to determine whether they can satisfy this efficiency-thoroughness trade-off. As mentioned in Chapter 5, the ATSB (2008 p. 47) claims that their model provides such a balance and, given the similarity to the ATSB model (see Section 5.6.2), it is arguable that AcciMap may also meet this requirement. However, as mentioned in Section 4.5.1.3, the SAA methods may only be suited to major accident investigations where funding, time and personnel are sufficient to match the large resource demands of the techniques.

Whilst researchers are also required to make an efficiency-thoroughness trade-off, the objective of their accident analysis is generally quite different. For example, accident case study analyses tend to focus on whether a given method can provide additional safety insights (e.g. Hickey, 2012; Stanton et al., 2012) or if it is suitable for use in a given domain (e.g. Kazaras et al., 2012). Furthermore, there is significantly less external pressure on researchers to deliver a timely analysis. Therefore, there is a justifiable tendency to perform as thorough an analysis as possible. In addition, the cost of performing such research is small in comparison to an accident investigation so the need for efficiency is arguably less. Based on the findings of Studies 1 and 3 (see Sections 3.5.2.4 and 5.6.2.2), it is possible that, due to the procedural requirement for an extensive analysis which incorporates all of the systems thinking concepts, STAMP, FRAM and the AcciMap-ActorMap-InfoFlowMap combination may be more attractive options for researchers conducting SAA. This is not to say that practitioners would find that these techniques do not provide an appropriate balance of thoroughness and resource demands. However, in everyday practice the efficiency of a method often outweighs the drawback of reduced thoroughness (Hollnagel, 2009 p.132).

Furthermore, simplifying these SAA methods so that it is easier to understand and apply them, may be problematic. Sacrificing thoroughness for efficiency may be worthwhile, if the aim is to increase the usage of systemic methods by practitioners. However, there is a counter argument for maintaining the depth of analysis that the methods require, i.e. reduced thoroughness may lead to an inadequate understanding about the causes of an accident. As Leveson (2013a) suggests, it may be worth the extra time to do a more thorough analysis if, in the future, fewer investigations are necessary and thus less time overall is spent in investigating accidents, even if time is the most important factor.

7.6.1.2 Analysis output requirements

Practitioners and researchers arguably have some dissimilar requirements of their analysis method outputs also. For example, practitioners will often need to classify the various findings of their analyses via a taxonomy, in order to conduct trend analysis. Although accident trend analysis is a well-established part of safety research (e.g. Lenné et al., 2012; Rashid et al., 2013; Schröder-Hinrichs et al., 2011), there is not such a pressing need for researchers to conduct accident case study analyses with a taxonomic method. Therefore, it is possible that researchers are afforded a wider choice of methods, including the SAA tools, which are yet to have industry-specific taxonomies developed for them.

It is widely acknowledged within the scientific literature that blaming individuals for causing accidents results in insufficient learning about the nature of the events (e.g. Dekker et al., 2011; Junior et al., 2012; Leveson, 2012), hence the popularity of SAA within the research community. Not all accident investigators are required to assign blame for an accident, however, it remains one of the key reasons for conducting accident analysis (Leveson, 2004). It seems unlikely that, due to the potentially vast commercial and legal implications of major accidents, this situation will change in the foreseeable future. Therefore, as described in Sections 3.5.2.5 and 4.4.3.3, some practitioners may favour the use of non-systemic methods in order to facilitate the apportioning of blame.

7.6.1.3 Analysis method validation

The track record of a method can also influence an individual's choice of technique (see Sections 3.5.2.1 and 4.4.3.4). Most practitioners in safety-oriented businesses tend to prefer well established methods and concepts and, therefore, may be reluctant to try new methods in a live investigation (Johansson and Lindgren, 2008). This is particularly relevant when investigators are conducting accident investigation on a consultancy basis and need to establish credibility with their client (see Section 4.4.3.4). Conversely, the research community, when conducting academic studies, may be incentivised to use relatively untested and/or developmental techniques (such as the SAA methods) in order to advance the understanding of accidents.

7.6.1.4 Scope of analysis

Within the domain of accident analysis, a number of SAA researchers (e.g. Dekker, 2011; Stanton et al., 2012; Zio and Ferrario, 2013) are continuing to explore the nature of systemic accidents by considering the behaviour of ever-larger 'systems of systems'[9]. For example, the drift into failure concept promoted by Dekker (2011) (see Section 2.2.5) encourages individuals to look 'up and out' at various factors which operate at a global level, such as sociological and political conditions, and how they affect system safety. The investigation of major accidents in various industries (e.g. aviation and marine transport) often involves the analysis of 'systems of systems', as the event can affect multiple stakeholders, some of whom may be large STS. In the case of aviation these stakeholders include aircraft manufacturers and operators, engine manufacturers, maintenance organisations, airport operating companies, national and international regulators etc. So, in the case of analysis scope, are the interests of researchers actually diverging from those of practitioners?

It seems, to a certain extent, that the answer to this question is 'no'. However, whilst some practitioners already perform 'systems of systems' analysis, investigating and rectifying issues which stem from sociological and political conditions is likely to remain beyond the scope of accident investigation, at least in the short term. This is due to a variety of issues, such as resource constraints and the difficulty of implementing safety interventions at the political and societal levels. Therefore, if researchers continue to examine issues which are currently outside the scope of accident investigation, practice will continue to lag behind research and the SAA RPG will not be closed.

Given that theory building and explanation remain an indispensable aspect of research, the development of accident causation theory will undoubtedly

[9] The boundary of a system is an abstract concept defined by the viewer of the system and Leveson (2013b) argues that a 'system of systems' is simply a larger 'system'. This is visually described in Figure 60 (see Appendix 7.2), in which System A and System B can be considered to be in a 'system of systems' or part of the larger AB system.

continue (Holmström et al., 2009). However, even if researchers stopped studying such issues, from a practical perspective, the time and effort required to ensure that every practitioner engaged in accident analysis was trained in and used the SAA methods seem prohibitive.

The different factors that affect the method selection of researchers and practitioners are represented in Figure 46.

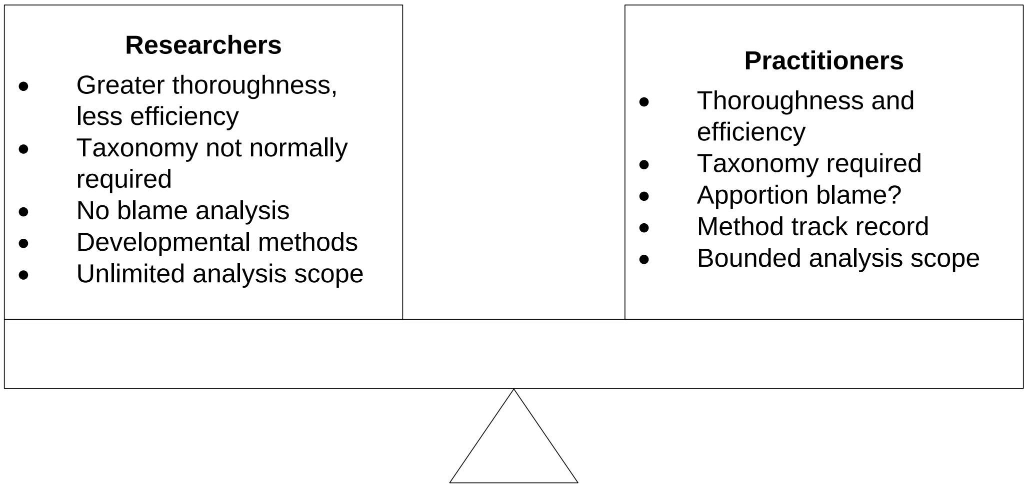

Figure 46 - Researcher and practitioner method selection influences

7.6.2 Bridging vs. closing the SAA research-practice gap

As shown by the discussion in Section 7.6.1, the differing needs of researchers and practitioners indicate that, at present, the SAA methods may be better suited for academic use. It is possible that the requirements of the two communities might become less disparate in the future, e.g. industry track records and taxonomies could be established for the SAA methods. Nevertheless, it seems unlikely that, due to other factors (e.g. the need to apportion blame), the interests of practitioners and researchers will completely coincide and, therefore, that the SAA RPG will be closed.

However, it is arguable that totally closing the gap is not necessary. Researchers in other domains, such as education (Chafouleas and Riley-Tillman, 2005), occupational psychology (Anderson, 2007) and management science (Bansal et al., 2012), suggest that RPGs are to be expected and that the two communities should retain a critical distance from each other.

Reasons for this include: researchers could lose their objectivity and produce practically relevant but methodologically weak ‘popularist’ science if practitioner interests drove the whole research agenda; researchers can continue to examine and develop theory; practitioners are able to address problems and solutions without researcher interference; the gap allows practitioners to prototype, experiment and learn vicariously (Anderson et al., 2001; Bansal et al., 2012; Pfeffer and Sutton, 2006).

Therefore, as the SAA RPG is likely to persist, trying to close the gap risks researchers behaving as practitioners and vice versa (Bansal et al., 2012). Instead, the aim should be to extend bridges (such as those described in Section 7.5) across the common ground that both communities share. This would enable researchers and practitioners to benefit from each other’s strengths whilst retaining their necessarily separate identities, as described in Figure 47.

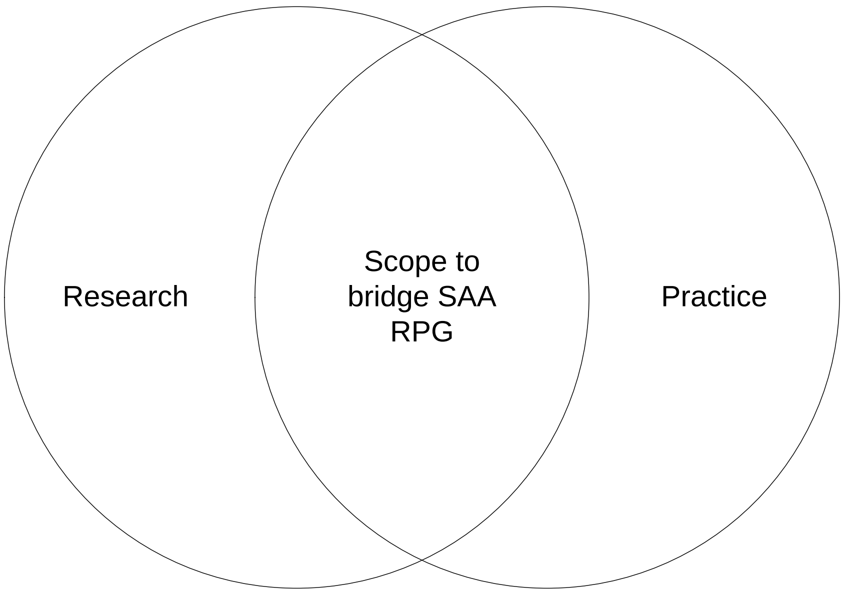

Figure 47 - Scope to bridge the SAA RPG

7.6.3 Is bridging the gap enough?

Even if the practitioner community did adopt the systemic methods it may still be impossible to achieve the ultimate aim of SAA, i.e. the development of more effective safety recommendations. As described in Section 2.2, STS continuously change and develop, due to internal and external forces and demands. The methods that are available to investigate them change at a much slower rate (and usually in a discrete rather than continuous manner) and frequently lag behind reality, often by as much as a decade or two (Hollnagel and Speziali, 2008; Leveson, 2012). In other words, analysis techniques are rarely able to represent or address the actual complexity of industrial systems (Hollnagel, 2008). Therefore, in addition to accident analysis practice lagging behind research, research also lags behind the reality in which practitioners operate. Therefore, regardless of which analysis methods researchers and practitioners use, their analysis processes may already be outdated, as illustrated in Figure 48. Consequently, the safety recommendations produced during an investigation may also be out-dated.

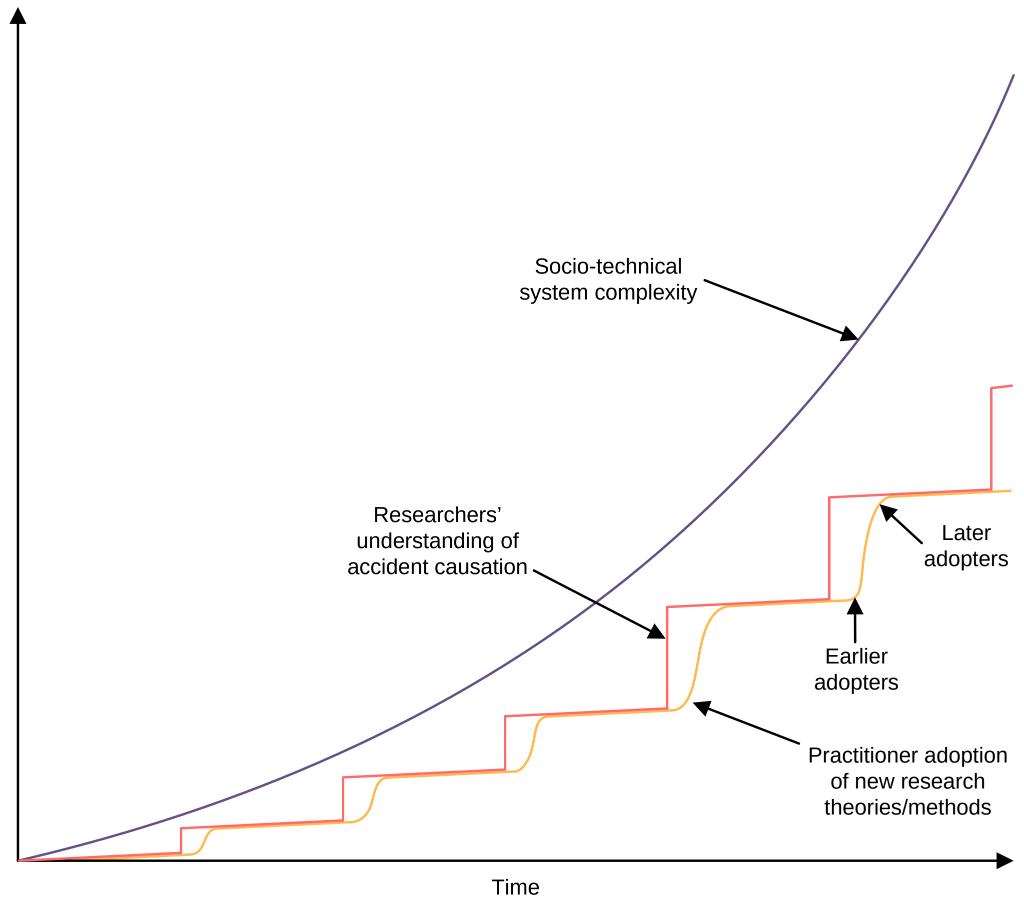

Figure 48 - Lag between reality, research and practice

Furthermore, there are various practical issues which hinder the implementation of safety recommendations, such as: the cost-benefit of the recommendation; the diverse roles and perspectives of stakeholders involved in effecting the recommendation; organisational resistance to change (see

Cedergren, 2013; Lundberg et al., 2010; Lundberg et al., 2012). Given the comprehensive and holistic nature of SAA, implementing all of the recommendations of a systemic analysis is likely to require significant resources and changes in the way organisations operate. Therefore, their application may be less likely, even if they are potentially more effective at reducing the risk of complex STS operations. However, this is not to say that efforts to bridge the SAA RPG should be abandoned. Even if the SAA methods are already obsolete, they are still better at describing complex accidents than many non-systemic techniques and important safety lessons can be gained by implementing them.

7.7 Methodological considerations

The limitations of the individual studies have been discussed within each study chapter (see Chapters 3-6). The remainder of this section describes the strengths and weaknesses of the research as a whole.

7.7.1 Mixed methods and the realism paradigm

A mixed methods approach was utilised for this research, in order to examine different aspects of the SAA RPG, and provided various benefits. For example, comparing the findings of Study 1 and 2 permitted the triangulation of some of the RPG's contributing factors. The use of multiple methods in Study 4 also enabled the triangulation of various aspects of STAMP usage. Furthermore, it is considered that the description of the SAA RPG presented in this thesis would not have been as broad had a single method been employed. The drawbacks of the mixed methods approach described in Section 1.3.2 were, however, experienced to varying degrees. For example, integrating the different types of data collected in Study 4 was challenging, particularly in the case when conflicts in the data were found. Furthermore, it was necessary to learn or improve existing knowledge of a number of methods during the course of the PhD, i.e. questionnaire design, focus group design and execution, thematic analysis etc. However, these issues were overcome and the benefits of the mixed methods approach were realised.

Healy and Perry (2000) describe six criteria with which to judge the quality of realism research (see Table 21). These can be used to evaluate the appropriateness of the paradigm for a given piece of research, as well as attesting to its quality (Williams, 2008). Examples of how the work contained in this thesis meets these requirements are also presented in Table 21, thereby demonstrating some of the strength of the research.

Quality criteria	Criteria description	Example of research
Ontology 1 - ontological appropriateness	Research problem deals with complex social science phenomena involving reflective people	The SAA RPG is a complex, multi-factorial social phenomenon which involves many stakeholders with their own view of the gap
Ontology 2 - contingent validity	Open 'fuzzy boundary' systems involving generative mechanisms rather than direct cause-and-effect. Causal impacts are not fixed but are contingent upon their environment.	The description of the SAA RPG suggests that the factors which can contribute to it will be experienced in different ways (or not at all) by individuals, due to the differing environments (e.g. financial, regulatory) in which they work
Epistemology – multiple perceptions of participants and peer researchers	Neither value-free nor value laden, rather value-aware. Relies on multiple perceptions about a single reality, which involve triangulation of several data sources, and of several peer researchers' interpretations of those triangulations.	Triangulation of data sources provided by mixed methods approach. Peer researchers interpretations gained via journal/conference proceedings review process and personal communication from domain experts (Erik Hollnagel and Nancy Leveson).
Methodology 1 – methodological trustworthiness	The research can be audited	Method selection and usage described in detail. Quotations from interviews and focus group used to present qualitative findings. Various sources of primary data and analysis findings archived, including: audio recordings and transcriptions; NVivo coding information; STAMP workshop analysis outputs and evaluation questionnaires.
Methodology 2 – analytic generalisation	Analytic generalisation (that is, theory building) rather than statistical generalisation (that is, theory-testing)	Data collection and analysis focused on developing an understanding of the nature and extent of the SAA RPG, rather than testing hypotheses regarding it
Methodology 3 – construct validity	How well information about the constructs in the theory being built are measured in the research	Prior knowledge from systems theory, accident analysis and SAA literature used to generate aims of research and triangulation of findings

Table 21 - Quality criteria of realism research. Adapted from Healy and Perry (2000).

7.7.2 Validity of findings

SAA is a dynamic area of research and SAA-related publications have been generated throughout the period of this research (e.g. Hollnagel, 2012; Le Coze, 2013b; Leveson, 2012; Read et al., 2013). Furthermore, there is little to suggest that the level of researcher interest is waning. Therefore, whilst it is considered that this thesis presents a valid description of the SAA RPG, the rapidly expanding literature on the subject may impose a relatively short lifespan on this validity. This situation is exemplified by the findings of Study 1 which, although providing an original contribution to the research literature at the time they were generated, became outdated by subsequent publications (e.g. Hollnagel, 2012; Leveson, 2012; Salmon et al., 2012a) and required the supplementary discussion provided in Section 3.5.3.

7.7.3 Reliability of findings

Given that the data collection and analysis was performed (almost) exclusively by one researcher, the influence of researcher biases will be more prominent. For example, conducting interviews effectively is a skill which requires practice and throughout the data collection phase of Study 2 the interviewing competence of the researcher improved (Robson, 2002 p.290). However, this particular issue was addressed by using a set of pre-defined questions (see Appendix 4.2). Moreover, the systematic approaches used to conduct the four studies and the peer review processes that Studies 1-3 were subjected to (whilst under review for publication) helped to improve the reliability of the research findings.

7.7.4 Generalisation of findings

The research approach provided a strong foundation for the study of the SAA RPG. However, due to the non-representative sample created in Study 2 and the small sample used in Study 4, the findings contained within the thesis should be treated as indicative of the issues associated with the gap, rather than conclusive. It may not be possible to overcome this issue. For example, creating a representative sample of safety experts may be impracticable, given that accident analysis is conducted in numerous industries and countries by a multitude of organisations and individuals. Recruiting a larger sample for Study 4 may improve the generalisation of the study findings for the community of full-time accident investigators. However, due to the differences in the working environments of full- and part-time investigators and SAA researchers (e.g. different levels of training and investigation resources) any additional findings may not help to understand how the wider accident analysis community would view the usage of the SAA techniques. Furthermore, a lack of generalisation may not be problematic, given that efforts to bridge the gap may need to be tailored to a given situation (see Section 7.5.2).

Chapter 8 – Conclusions and future work

8.1 Conclusions

The research contained in this thesis has set out to provide a better understanding of the SAA RPG by examining its contributory factors and the extent of the gap. In summary, an RPG does exist in the field of SAA and is multifaceted in nature. It seems that researchers, in their presentation of SAA and their design of systemic methods, have created an accident analysis innovation that is neither easily communicated to, nor used by, practitioners. Furthermore, various factors stemming from research and practice contribute to the SAA RPG, as well as a general gap within the field of accident analysis. This implies that bridging the gap also requires a multifaceted solution, e.g. improved communication of SAA and development of the systemic methods.

The SAA techniques are able to provide insights into accidents which are not provided by many traditional analysis methods and efforts to bridge the gap should be made. However, in some cases, the RPG may not be as significant as indicated by some proponents of SAA. For example, users of the SCM and its related methods are required to employ various aspects of the systems approach. Furthermore, sequential techniques can still offer an effective solution for the analysis of smaller and/or simpler systems. When considered alongside the fact that practitioners and researchers generally have different requirements of their analysis tools, it seems best to view SAA methods as one part of an analysis toolkit. Therefore, bridging the gap may require integrating the SAA methods with the current analysis practices of accident investigators, rather than replacing every non-systemic technique.

The natural differences between the needs and objectives of the research and practice communities also mean that the SAA RPG should be bridged rather than completely closed. However, even if the gap is bridged, the understanding of system safety provided by the SAA methods may already be outdated due to ever-increasing STS complexity.

8.2 Knowledge contribution

At the time this research began there was no clear description of the SAA RPG, nor an understanding of the extent of the gap or how it could be bridged. The SAA literature and methods had yet to be examined in any great detail and no research had been recently published on the nature of RPGs in accident analysis or investigation.

Therefore, it is considered the work presented in this thesis provides an original and important contribution to the field of accident analysis and the wider RPG literature. This is evidenced by the fact that three of the studies have been converted into peer-reviewed publications.

8.3 Future work

8.3.1 Progression from thesis

A number of possibilities exist for furthering the research contained in the thesis. These ideas are described in the remainder of Section 8.3.1.

8.3.1.1 Progression from Studies 1 and 2

Now that the factors which contribute to the SAA RPG have been identified a natural step would be to examine their relative importance. A more quantitative approach, e.g. an online survey, aimed at recruiting a larger number of participants may be most suitable. The issues of obtaining a representative sample (see Section 7.7.4) would still remain and it may be that a smaller section of the accident analysis community should be targeted, i.e. creating the sample from a given profession, location and/or industry etc. If it is possible to understand the relative impact of the RPG contributory factors then a more strategic approach to bridging the gap could be achieved.

8.3.1.2 Progression from Study 3

A key limitation of Study 3, imposed by resource constraints, was the limited number of analysis methods and accident case studies used to examine the extent of the SAA RPG. An opportunity exists, therefore, to conduct further analyses with the same and/or different SAA and non-systemic techniques and case studies covering a range of industries and accident types, in order to increase the knowledge base of SAA method usage.

8.3.1.3 Progression from Study 4

Whilst the findings of Study 4 provided a useful insight into the use of STAMP by practitioners, there are clear avenues for developing this work. For example, the study could be repeated over multiple training courses to generate a larger set of evaluation data. Other SAA methods could be evaluated and comparisons made with STAMP. Alterations to STAMP, based on the findings of Study 4, could be made and evaluated. Also, collaborative participatory-based research could be conducted with accident investigators to understand how the SAA methods should be developed in order to meet their needs.

8.3.2 Research for the wider SAA research-practice gap context

In addition to the research which could directly follow the studies presented in Chapters 3-6, a number of research topics could be examined, as detailed in the rest of Section 8.3.2.

8.3.2.1 SAA taxonomies

Causal taxonomies for the SAA methods could be developed in collaboration with accident investigators, organisations and regulators to provide a trend analysis capability. In order to maximise their efficacy, such taxonomies would need to be industry-specific and compatible with the outputs generated by the systemic techniques. The outcomes of this research would be most effective if opportunities existed within organisations/regulators to establish new safety databases. An alternative research topic could involve examining current taxonomies and the accident/incident databases used within industry to understand their level of compatibility with SAA outputs. This could inform the redesign of the current databases and/or the SAA methods.

8.3.2.2 Usage guidance

Given that SAA methods provide a generic approach to analysis, an in-depth knowledge of the domain in question is required. Therefore, additional guidance material could be created to provide instructions and/or prompts for conducing SAA in a given industry. This guidance could be extended to cover the analysis of different types of accident. For example, pre-defined STAMP control structure templates or lists of potentially relevant FRAM functions could be devised. This would help to improve the thoroughness, efficiency and reliability of any analysis. However, it would be necessary to design the guidance in such a way as to prevent it from being overly prescriptive, i.e. investigators should still be given flexibility to analyse all of the issues they consider relevant.

8.3.2.3 Examine system complexity threshold

As suggested in Section 7.4, the use of SAA methods may not always be necessary, i.e. non-systemic techniques may still be suitable for the analysis of simpler and/or smaller systems. However, at present there is little guidance for determining when a system is complex enough to require the use of SAA. Furthermore, the information that is available (e.g. Hollnagel (2008) and Hollnagel and Speziali (2008)) is limited. Therefore, analysing these simpler/smaller types of systems, e.g. the domain of general aviation, with SAA methods and comparing the outputs with those generated by non-systemic techniques would help inform the decision making of investigators with regards to the use of the various methods in their ‘analysis toolkit’.

8.3.3 Summary

When considering the various ideas for future SAA research described throughout Section 8.3, it is difficult to prioritise them or suggest an order in which they should be addressed. However, the underlying theme is that future work should be done in collaboration with practitioners, whether it is with the potential end-users of the SAA methods or individuals and/or organisations affected by their use. This infers that, rather than producing all-encompassing solutions to bridge the SAA gap, researchers will need to work with individual organisations to achieve tailored solutions for integrating systemic methods into their analysis practices, as suggested in Section 7.5.2. The suggestions for future work are visually described in Figure 49.

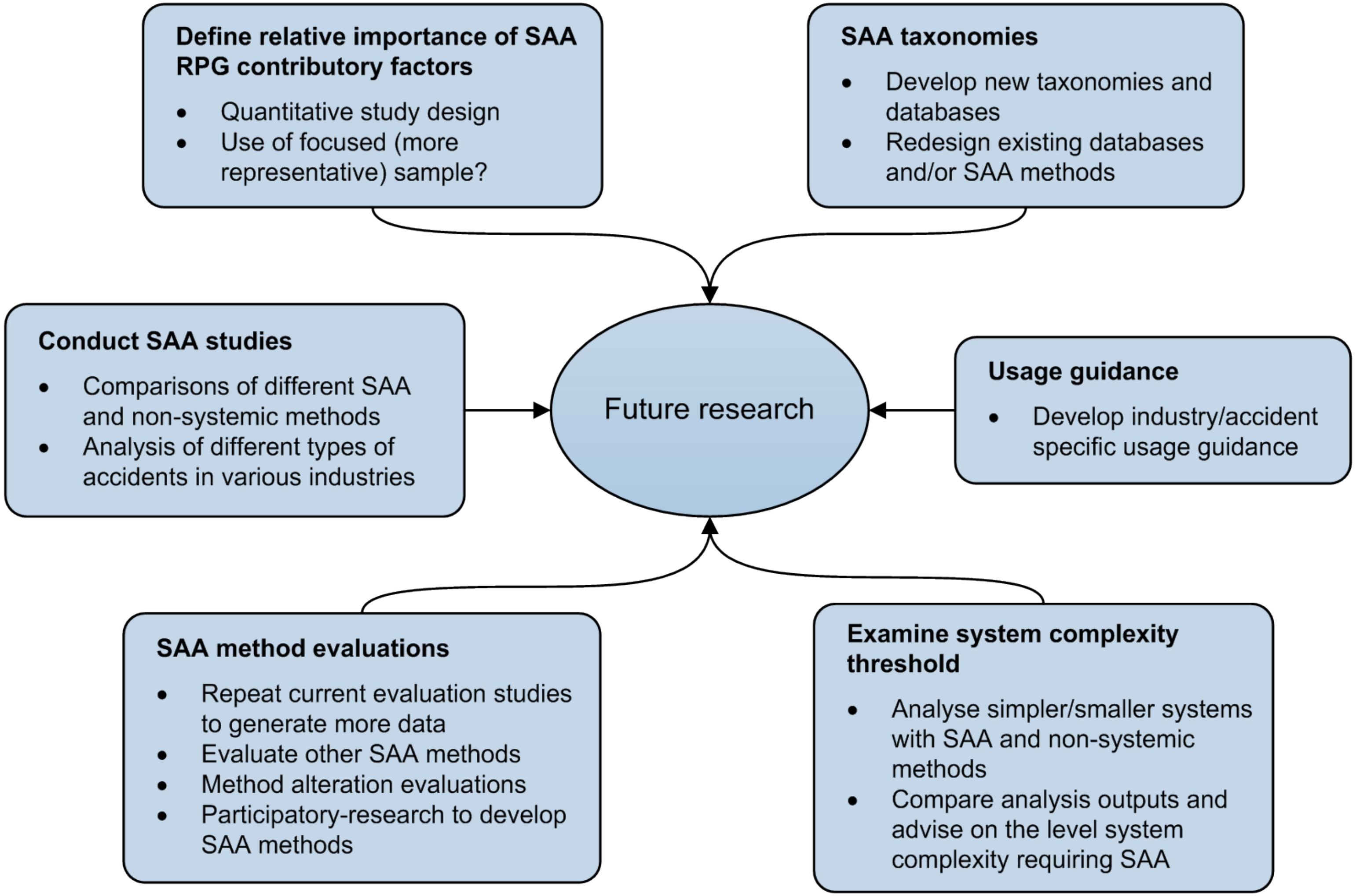

Figure 49 - Future work

References

Abrahamsson, M., Hassel, H. and Tehler, H., 2010. Towards a system-oriented framework for analysing and evaluating emergency response. Journal of Contingencies & Crisis Management, 18(1), pp.14-25.

Agarwal, R. and Prasad, J., 1997. The role of innovation characteristics and perceived voluntariness in the acceptance of information technologies. Decision Sciences, 28(3), pp.557-582.

Aguinis, H. and Lawal, S.O., 2013. eLancing: A review and research agenda for bridging the science–practice gap. *Human Resource Management Review*, 23(1), pp.6-17.

Aini, M.S. and Fakhrul-Razi, A., 2010. Development of socio-technical disaster model. *Safety Science*, 48(10), pp.1286-1295.

Alm, H. and Woltjer, R., 2010. Patient safety investigation through the lens of FRAM. In: eds. D. de Waard, A. Axelsson, M. Berglund, B. Peters and C. Weikert. *Human Factors: A System View of Human, Technology and Organisation*. Shaker Publishing: Maastricht, Netherlands. pp.153-165.

Anderson, N., 2007. The practitioner-researcher divide revisited: Strategic-level bridges and the roles of IWO psychologists. *Journal of Occupational and Organizational Psychology*, 80(2), pp.175-183.

Anderson, N., Herriot, P. and Hodgkinson, G.P., 2001. The practitioner-researcher divide in industrial, work and organizational (IWO) psychology: Where are we now, and where do we go from here? *Journal of Occupational and Organizational Psychology*, 74(4), pp.391-411.

Arendt, J.S. and Lorenzo, D.K., 1991. Investigation of a filter explosion. *Journal of Loss Prevention in the Process Industries*, 4(5), pp.338-343.

Arnold, R., 2009. *A Qualitative Comparative Analysis of SOAM and STAMP in ATM Occurrence Investigation*. MSc. Lund University.

Australian Transport Safety Bureau, 2008. *Analysis, causality and proof in safety investigations*. Aviation Research and Analysis Report AR-2007-053. Australian Transport Safety Bureau: Canberra City, Australia.

Bacchetti, A. and Saccani, N., 2012. Spare parts classification and demand forecasting for stock control: Investigating the gap between research and practice. *Omega*, 40(6), pp.722-737.

Bamber, L., 2003. Risk management: Techniques and practices. In: eds. J.R. Ridley and J. Channing. *Safety at Work*. 6th edn. Butterworth-Heinemann: London, UK. pp.227-262.

Bansal, P., Bertels, S., Ewart, T., MacConnachie, P. and O'Brien, J., 2012. Bridging the research-practice gap. *Academy of Management Perspectives*, 26(1), pp.73-92.

Bass, F.M., 1969. A new product growth for model consumer durables. *Management Science*, 15(5), pp.215-227.

Baysari, M.T., Caponecchia, C. and McIntosh, A.S., 2011. A reliability and usability study of TRACEr-RAV: The technique for the retrospective analysis of cognitive errors – for rail, Australian version. *Applied Ergonomics*, 42(6), pp.852-859.

Belmonte, F., Schoen, W., Heurley, L. and Capel, R., 2011. Interdisciplinary safety analysis of complex socio-technological systems based on the functional resonance accident model: An application to railway traffic supervision. *Reliability Engineering & System Safety*, 96(2), pp.237-249.

Benner, L., 1985. Rating accident models and investigation methodologies. *Journal of Safety Research*, 16(3), pp.105-126.

Bourrier, M., 1996. Organizing maintenance work at two american nuclear power plants. *Journal of Contingencies and Crisis Management*, 4(2), pp.104-112.

Braithwaite, G., 2008. What Can We Learn? In: eds. R. Stone, S. Fager and E. Martinez. *Proceedings of the 39th Annual International Seminar: 'Investigation: The Art and the Science'*. Halifax, Canada, 8 - 11 Sept 2008. International Society for Air Safety Investigators: Stirling, VA, USA. pp.37.

Braithwaite, G., 2004. Re-inventing (with wheels, wings and sails)-A new look at transport accident investigator training. In: eds. S. Fager and E. Martinez. *Proceedings of the 35th Annual International Seminar: 'Investigate-Communicate-Educate'*. Gold Coast, Australia, Aug 30 - Sep 2 2004. ISASI: Stirling, VA, USA. pp.179-183.

Branford, K., 2011. Seeing the big picture of mishap: Applying the AcciMap approach to analyze system accidents. *Aviation Psychology and Applied Human Factors*, 1(1), pp.31-37.

Branford, K., 2007. *An Investigation Into the Validity and Reliability of the AcciMap Approach*. PhD. Australian National University.

Branford, K., Naikar, N. and Hopkins, A., 2009. Guidelines for accimap analysis. In: ed. A. Hopkins. *Learning from High Reliability Organisations*. CCH Australia: Sydney, Australia. pp.193-212.

Brannen, J., 2005. Mixing methods: The entry of qualitative and quantitative approaches into the Research Process. *International Journal of Social Research Methodology*, 8(3), pp.173-184.

Braun, V. and Clarke, V., 2006. Using thematic analysis in psychology. *Qualitative Research in Psychology*, 3(2), pp.77-101.

Brinkman, W., Haakma, R. and Bouwhuis, D.G., 2009. The theoretical foundation and validity of a component-based usability questionnaire. *Behaviour & Information Technology*, 28(2), pp.121-137.

Bronstein, L.R. and Kovacs, P.J., 2013. Writing a mixed methods report in social work research. *Research on Social Work Practice*, 23(3), pp.354-360.

Bryman, A., 2007. Barriers to integrating quantitative and qualitative research. *Journal of Mixed Methods Research*, 1(1), pp.8-22.

Carhart, N. and Yearworth, M., 2010. The Use of System Dynamics Group Model Building for Analysing Event Causality within the Nuclear Industry. In: ed. T. Moon. *28th International Conference of the System Dynamics Society*. Seoul, Korea, 25 - 29 Jul. The System Dynamics Society: Albany, NY, USA.

Cassano-Piche, A., Vicente, K.J. and Jamieson, G.A., 2009. A test of Rasmussen's risk management framework in the food safety domain: BSE in the UK. *Theoretical Issues in Ergonomics Science*, 10(4), pp.283-304.

Cedergren, A., 2013. Implementing recommendations from accident investigations: A case study of inter-organisational challenges. *Accident Analysis & Prevention*, 53, pp.133-141.

Cedergren, A. and Petersen, K., 2011. Prerequisites for learning from accident investigations – A cross-country comparison of national accident investigation boards. *Safety Science*, 49(8-9), pp.1238-1245.

Chafouleas, S.M. and Riley-Tillman, T.C., 2005. Accepting the gap: An introduction to the special issue on bridging research and practice. *Psychology in the Schools*, 42(5), pp.455-458.

Chen, S., Wall, A., Davies, P., Yang, Z., Wang, J. and Chou, Y., 2013. A human and organisational factors (HOFs) analysis method for marine casualties using HFACS-maritime accidents (HFACS-MA). *Safety Science*, 60, pp.105-114.

Choularton, R., 2001. Complex learning: Organizational learning from disasters. *Safety Science*, 39(1-2), pp.61-70.

Chung, A.Z.Q. and Shorrock, S.T., 2011. The research-practice relationship in ergonomics and human factors - surveying and bridging the gap. *Ergonomics*, 54(5), pp.413-429.

Cicek, K. and Celik, M., 2013. Application of failure modes and effects analysis to main engine crankcase explosion failure on-board ship. *Safety Science*, 51(1), pp.6-10.

Coiera, E., 2007. Putting the technical back into socio-technical systems research. *International Journal of Medical Informatics*, 76s, pp.S98-S103.

Cooter, R. and Luckin, B., 1997. Accidents in history: An introduction. In: eds. R. Cooter and B. Luckin. *Accident in History: Injuries, Fatalities and Social Relations*. Rodopi: Amsterdam, Netherlands. pp.1-16.

Crawford, S., Venuti, M.T., Mason, T.K., Walka, J.P., Smith, G.A., Mullins, M.J., Silver, A.E. and Bobrow, B.J., 2010. Pre-hospital chest compression quality is improved with scenario based training and use of novel defibrillator technology. *Resuscitation*, 81(2, Supplement), pp.S12.

Dadashi, N., Wilson, J.R., Golightly, D., Sharples, S. and Clarke, T., 2013. Practical use of work analysis to support rail electrical control rooms: A case of alarm handling. *Journal of Rail and Rapid Transit*, 227(2), pp.148-160.

Damanpour, F. and Schneider, M., 2009. Characteristics of innovation and innovation adoption in public organizations: Assessing the role of managers. *Journal of Public Administration Research and Theory*, 19(3), pp.495-522.

Damodaran, L., 1996. User involvement in the systems design process-a practical guide for users. *Behaviour & Information Technology*, 15(6), pp.363-377.

Davis, M.C., Challenger, R., Jayewardene, D.N.W. and Clegg, C.W., 2013. Advancing socio-technical systems thinking: A call for bravery. *Applied* Ergonomics. DOI: dx.doi.org/10.1016/j.apergo.2013.02.009

de Carvalho, P.V.R., 2011. The use of functional resonance analysis method (FRAM) in a mid-air collision to understand some characteristics of the air traffic management system resilience. *Reliability Engineering & System Safety*, 96(11), pp.1482-1498.

de Carvalho, P.V.R. and Ferreira, B., 2012. Modeling activities in air traffic control systems: Antecedents and consequences of a mid-air collision. *Work: A Journal of Prevention, Assessment and Rehabilitation*, 41, pp.232-239.

Debrincat, J., Bil, C. and Clark, G., 2013. Assessing organisational factors in aircraft accidents using a hybrid reason and AcciMap model. *Engineering Failure Analysis*, 27, pp.52-60.

DeJoy, D.M., Schaffer, B.S., Wilson, M.G., Vandenberg, R.J. and Butts, M.M., 2004. Creating safer workplaces: Assessing the determinants and role of safety climate. *Journal of Safety Research*, 35(1), pp.81-90.

Dekker, S., 2011. *Drift into Failure: From Hunting Broken Components to Understanding Complex Systems*. Ashgate Publishing Company: Farnham, UK.

Dekker, S., 2006. *The Field Guide to Understanding Human Error*. Ashgate Publishing Limited: Aldershot, UK.

Dekker, S., Cilliers, P. and Hofmeyr, J., 2011. The complexity of failure: Implications of complexity theory for safety investigations. *Safety Science*, 49(6), pp.939-945.

Dercon, S. and Christiaensen, L., 2011. Consumption risk, technology adoption and poverty traps: Evidence from Ethiopia. *Journal of Development Economics*, 96(2), pp.159-173.

DeVellis, R.F., 2012. *Scale Development: Theory and Applications*. 3rd edn. Sage Publications Inc.: Thousand Oaks, CA, USA.

Dien, Y., Dechy, N. and Guillaume, E., 2012. Accident investigation: From searching direct causes to finding in-depth causes – problem of analysis or/and of analyst? *Safety Science*, 50(6), pp.1398-1407.

Dobson, K. and Beshai, S., 2013. The theory-practice gap in cognitive behavioral therapy: Reflections and a modest proposal to bridge the gap. *Behavior Therapy*. DOI: dx.doi.org/10.1016/j.beth.2013.03.002

Eason, K., 2007. Local sociotechnical system development in the NHS national programme for information technology. *Journal of Information Technology*, 22(3), pp.257-264.

Emery, F.E., 1959. *Characteristics of socio-technical systems*. Report 527. The Tavistock Institute of Human Relations: London, UK.

Energy Institute, 2008. *Guidance on Investigating and Analysing Human and Organisational Factors Aspects of Incidents and Accidents*. Energy Institute: London, UK.

EUROCONTROL, 2005. *Guidelines on the systemic occurrence analysis methodology (SOAM)*. EAM 2/GUI 8. EUROCONTROL: Brussels, Belgium.

Ferjencik, M., 2011. An integrated approach to the analysis of incident causes. *Safety Science*, 49(6), pp.886-905.

Fichman, R.G., 1992. Information technology diffusion: A review of empirical research. In: eds. J.I. DeGross, J.D. Becker and J.J. Elam. *Proceedings of the Thirteenth International Conference on Information Systems*. Dallas, TX, USA, Dec 13-16 1992. University of Minnesota: Minneapolis, MN, USA. pp.195-206.

Fink, A., 2010. *Conducting Literature Reviews: From the Internet to Paper*. 3rd edn. Sage: London, UK.

Geels, F.W., 2005. *Technological Transitions and System Innovations: A Co-Evolutionary and Socio-Technical Analysis*. Edward Elgar Publishing: Cheltenham, UK.

Ghirxi, K.T., 2010. *The stopping rule is no rule at all: Exploring maritime safety investigation as an emergent process within a selection of IMO Member States*. PhD. World Maritime University.

Goh, Y.M., Brown, H. and Spickett, J., 2010. Applying systems thinking concepts in the analysis of major incidents and safety culture. *Safety Science*, 48(3), pp.302-309.

Goh, Y.M., Love, P.E.D., Brown, H. and Spickett, J., 2012. Organizational accidents: A systemic model of production versus protection. *Journal of Management Studies*, 49(1), pp.52-76.

Goossens, L. and Hale, A., 1997. Risk assessment and accident analysis. *Safety Science*, 26(1–2), pp.21-23.

Gordon, J.E., 1949. The epidemiology of accidents. *American Journal of Public Health*, 39(4), pp.504-515.

Gordon, R., Flin, R. and Mearns, K., 2005. Designing and evaluating a human factors investigation tool (HFIT) for accident analysis. *Safety Science*, 43(3), pp.147-171.

Greenhalgh, T. and Peacock, R., 2005. Effectiveness and efficiency of search methods in systematic reviews of complex evidence: Audit of primary sources. *BMJ*, 331, pp.1064-1065.

Greenhalgh, T., Robert, G., Macfarlane, F., Bate, P. and Kyriakidou, O., 2004. Diffusion of innovations in service organizations: Systematic review and recommendations. *Milbank Quarterly*, 82(4), pp.581-629.

Greenhalgh, T., Robert, G., Macfarlane, F., Bate, P., Kyriakidou, O. and Peacock, R., 2005. Storylines of research in diffusion of innovation: A meta-narrative approach to systematic review. *Social Science & Medicine*, 61(2), pp.417-430.

Groth, K.M. and Swiler, L.P., 2013. Bridging the gap between HRA research and HRA practice: A bayesian network version of SPAR-H. *Reliability Engineering & System Safety*, 115, pp.33-42.

Haddon, W., 1980. Advances in the epidemiology of injuries as a basis for public policy. *Public Health Reports*, 95(5), pp.411-421.

Hale, A.R. and Glendon, A.I., 1987. *Individual Behaviour in the Control of Danger*. Elsevier Science: Oxford, UK.

Hale, A.R. and Hovden, J., 1998. Management and culture: The third age of safety. A review of approaches to organizational aspects of safety, health and environment. In: eds. A. Feyer and A. Williamson. *Occupational Injury: Risk, Prevention and Intervention*. Taylor & Francis Ltd: London, UK. pp.129-166.

Hale, A., 2009. Why safety performance indicators? *Safety Science*, 47(4), pp.479-480.

Hamlin, B., Reidy, M. and Stewart, J., 1998. Bridging the HRD research-practice gap through professional partnerships: A case study. *Human Resource Development International*, 1(3), pp.273-290.

Hanson, D.W., Finch, C.F., Allegrante, J.P. and Sleet, D., 2012. Closing the gap between injury prevention research and community safety promotion practice: Revisiting the public health model. *Public Health Reports*, 127(2), pp.147-155.

Hart, C., 1998. *Doing A Literature Review: Releasing the Social Science Research Imagination*. Sage: London, UK.

Harvey, M.D., 1985. *Models for accident investigation*. Alberta Workers Health, Safety and Compensation: Occupational Health and Safety Division: Edmonton, Canada.

Hayward, B. and Lowe, A., 2004. Safety investigation: Systemic occurrence analysis methods. In: ed. K. Goeters. *Aviation Psychology: Practice and Research*. Ashgate: Aldershot, UK. pp.363-380.

Health and Safety Executive, 2004. *Investigating Accidents and Incidents: A Workbook for Employers, Unions, Safety Representatives and Safety Professionals*. 2nd edn. HSE Books: Sudbury, UK.

Healy, M. and Perry, C., 2000. Comprehensive criteria to judge validity and reliability of qualitative research within the realism paradigm. *Qualitative Market Research: An International Journal*, 3(3), pp.118-126.

Heinrich, H.W., 1931. *Industrial Accident Prevention*. McGraw-Hill: New York, NY, USA.

Herie, M. and Martin, G.W., 2002. Knowledge diffusion in social work: A new approach to bridging the gap. *Social Work*, 47(1), pp.85-95.

Herrera, I.A. and Woltjer, R., 2010. Comparing a multi-linear (STEP) and systemic (FRAM) method for accident analysis. *Reliability Engineering & System Safety*, 95(12), pp.1269-1275.

Hickey, J., 2012. *A System Theoretic Safety Analysis of U.S. Coast Guard Aviation*. MSc. Massachusetts Institute of Technology.

Hodgkinson, G.P. and Rousseau, D.M., 2009. Bridging the rigour–relevance gap in management research: It's already happening! *Journal of Management Studies*, 46(3), pp.534-546.

Hoffman, R. and Militello, L., 2009. *Perspectives on Cognitive Task Analysis: Historical Origins and Modern Communities of Practice*. Taylor and Francis: New York, NY, USA.

Hofmann, S.G., 2013. Bridging the theory-practice gap by getting even bolder with the boulder model. *Behavior Therapy*. DOI: dx.doi.org/10.1016/j.beth.2013.04.006

Holden, R.J., 2009. People or systems? To blame is human. The fix is to engineer. *Professional Safety*, Dec 2009, pp.34-41.

Hollnagel, E., 2013. Human factors/ergonomics as a systems discipline? “The human use of human beings” revisited. *Applied Ergonomics*. DOI: dx.doi.org/10.1016/j.apergo.2013.03.024

Hollnagel, E., 2012. *FRAM – the Functional Resonance Analysis Method*. Ashgate: Farnham, UK.

Hollnagel, E., 2009. *The ETTO Principle: Efficiency-Thoroughness Trade-Off: Why Things that Go Right Sometimes Go Wrong*. Ashgate Publishing Ltd: Farnham, UK.

Hollnagel, E., 2008. The changing nature of risks. *Ergonomics Australia*, 22(1-2), pp.33-46.

Hollnagel, E., 2004. *Barriers and Accident Prevention*. Ashgate Publishing Limited: Aldershot, UK.

Hollnagel, E., 1998. *Cognitive Reliability Engineering Analysis Method: CREAM*. Elsevier Science: Oxford, UK.

Hollnagel, E. and Goteman, Ö, 2004. The Functional Resonance Accident Model. *Cognitive System Engineering in Process Control 2004*. Sendai, Japan, 4 - 5 Nov 2004. CSEPC. pp.155.

Hollnagel, E., Pariès, J., Woods, D.D. and Wreathall, J. (eds), 2011. *Resilience Engineering in Practice: A Guidebook*. Ashgate Publishing Ltd.: Farnham, UK.

Hollnagel, E., Pruchnicki, S., Woltjer, R. and Etcher, S., 2008. Analysis of Comair flight 5191 with the Functional Resonance Accident Model. *8th International Symposium of the Australian Aviation Psychology Association*. Sydney, Australia, 8 - 11 Apr 2008. Australian Aviation Psychology Association: Canberra, Australia.

Hollnagel, E. and Speziali, J., 2008. *Study on developments in accident investigation methods: A survey of the 'state-of-the-art'*. SKI Report 2008:50. Ecole des Mines de Paris: Sophia Antipolis, France.

Hollnagel, E., Woods, D.D. and Leveson, N. (eds), 2006. *Resilience Engineering: Concepts and Precepts*. Ashgate Publishing: Aldershot, UK.

Holmström, J., Ketokivi, M. and Hameri, A., 2009. Bridging practice and theory: A design science approach. *Decision Sciences*, 40(1), pp.65-87.

Hopkins, A., 2013. Issues in safety science. *Safety Science*. DOI: dx.doi.org/10.1016/j.ssci.2013.01.007

Hopkins, A., 2001. Was Three Mile Island a ‘Normal Accident’? *Journal of Contingencies and Crisis Management*, 9(2), pp.65-72.

Hopkins, A., 2000. An AcciMap of the Esso Australia gas plant explosion. In: eds. I. Svedung and G.G.M. Cojazzi. *18th ESReDA Seminar*. Karlstad, Sweden, 14 - 16 Jun 2000. Office for Official Publications for the European Communities: Luxembourg.

Hovden, J., Albrechtsen, E. and Herrera, I.A., 2010. Is there a need for new theories, models and approaches to occupational accident prevention? *Safety Science*, 48(8), pp.950-956.

Hovden, J., Størseth, F. and Tinmannsvik, R.K., 2011. Multilevel learning from accidents – case studies in transport. *Safety Science*, 49(1), pp.98-105.

Hudson, P.T.W., Reason, J.T., Wagenaar, W.A., Bentley, P.D., Primrose, M. and Visser, J.P., 1994. Tripod Delta: Proactive approach to enhanced safety. *Journal of Petroleum Technology*, 46(1), pp.58-62.

Ishimatsu, T., Leveson, N., Thomas, J., Katahira, M., Miyamoto, Y. and Nakao, H., 2010. Modeling and Hazard Analysis Using STPA. *4th Conference of the International Association for the Advancement of Space Safety*. Huntsville, AL, USA. 19 - 21 May 2010.

Jacobsson, A., Sales, J. and Mushtaq, F., 2009. A sequential method to identify underlying causes from industrial accidents reported to the MARS database. *Journal of Loss Prevention in the Process Industries*, 22(2), pp.197-203.

Jenkins, D.P., Salmon, P.M., Stanton, N.A. and Walker, G.H., 2010. A systemic approach to accident analysis: A case study of the Stockwell shooting. *Ergonomics*, 53(1), pp.1-17.

Johansson, B. and Lindgren, M., 2008. A quick and dirty evaluation of resilience enhancing properties in safety critical systems. In: eds. E. Hollnagel, F. Pieri and E. Rigaud. *Third Symposium on Resilience Engineering*. 28 - 30 Oct 2008. École des mines de Paris: Sophia Antipolis, France.

Johnson, C., 2003. *Failure in Safety Critical Systems: A Handbook of Incident and Accident Reporting*. Glasgow University Press: Glasgow, UK.

Johnson, C.W. and de Almeida, I.M., 2008. An investigation into the loss of the Brazilian space programme's launch vehicle VLS-1 V03. *Safety Science*, 46(1), pp.38-53.

Johnson, C.W. and Holloway, C.M., 2003. The ESA/NASA SOHO mission interruption: Using the STAMP accident analysis technique for a software related 'mishap'. *Software: Practice and Experience*, 33(12), pp.1177-1198.

Johnson, R.B. and Onwuegbuzie, A.J., 2004. Mixed methods research: A research paradigm whose time has come. *Educational Researcher*, 33(7), pp.14-26.

Johnson, R.B., Onwuegbuzie, A.J. and Turner, L.A., 2007. Toward a definition of mixed methods research. *Journal of Mixed Methods Research*, 1(2), pp.112-133.

Johnson, W.G., 1973. *The Management Oversight and Risk Tree - MORT: Including systems developed by the Idaho operations office and Aerojet nuclear company*. SAN 821-2. U.S. Government Printing Office: Washington, DC, USA.

Jönsson, H., 2007. *Risk and Vulnerability Analysis of Complex Systems: a basis for proactive emergency management*. Licentiate thesis. Department of Fire Safety Engineering and Systems Safety, Lund University.

Junior, M.M., e Santos, M.S., Vidal, M.C.R. and de Carvalho, P.V.R., 2012. Overcoming the blame game to learn from major accidents: A systemic analysis of an anhydrous ammonia leakage accident. *Journal of Loss Prevention in the Process Industries*, 25(1), pp.33-39.

Kapsali, M., 2011. Systems thinking in innovation project management: A match that works. *International Journal of Project Management*, 29(4), pp.396-407.

Karahanna, E., Straub, D.W. and Chervany, N.L., 1999. Information technology adoption across time: A cross-sectional comparison of pre-adoption and post-adoption beliefs. *MIS Quarterly*, 23(2), pp.183-213.

Katsakiori, P., Sakellaropoulos, G. and Manatakis, E., 2009. Towards an evaluation of accident investigation methods in terms of their alignment with accident causation models. *Safety Science*, 47(7), pp.1007-1015.

Katz, M.L. and Shapiro, C., 1986. Technology adoption in the presence of network externalities. *The Journal of Political Economy*, 94(4), pp.822-841.

Kazaras, K. and Kirytopoulos, K., 2011. Applying STAMP in road tunnels hazard analysis. *6th IET International Conference on System Safety*. 20-22 Sept 2011. IET: London, UK. pp.21.

Kazaras, K., Kirytopoulos, K. and Rentizelas, A., 2012. Introducing the STAMP method in road tunnel safety assessment. *Safety Science*, 50(9), pp.1806-1817.

Kenny, A., Nankervis, K., Kidd, T. and Connell, S., 2012. Models of nursing student employment: An australian action research study. *Nurse Education Today*, 32(5), pp.600-605.

Kirwan, B., 2001. Coping with accelerating socio-technical systems. *Safety Science*, 37(2-3), pp.77-107.

Kjellén, U., 2000. *Prevention of Accidents through Experience Feedback*. Taylor and Francis: London, UK.

Kjellén, U. and Hovden, J., 1993. Reducing risks by deviation control—a retrospection into a research strategy. *Safety Science*, 16(3-4), pp.417-438.

Klein, L., 2013. What do we actually mean by 'sociotechnical'? On values, boundaries and the problems of language. *Applied Ergonomics*. DOI: dx.doi.org/10.1016/j.apergo.2013.03.027

Kletz, T.A., 1983. *HAZOP & HAZAN: Notes on the Identification and Assessment of Hazards*Institution of Chemical Engineers: Rugby.

Klir, G.J., 1969. *An Approach to General Systems Theory*. Nostrand: New York, NY, USA.

Kontogiannis, T. and Malakis, S., 2012. A systemic analysis of patterns of organizational breakdowns in accidents: A case from helicopter emergency medical service (HEMS) operations. *Reliability Engineering & System Safety*, 99, pp.193-208.

Kouabenan, D.R., 2009. Role of beliefs in accident and risk analysis and prevention. *Safety Science*, 47(6), pp.767-776.

Kroes, P., Franssen, M., van de Poel, I. and Ottens, M., 2006. Treating socio-technical systems as engineering systems: Some conceptual problems. *Systems Research & Behavioral Science*, 23(6), pp.803-814.

Kropewnicki, J., Fry, D. and Poyau, J., 2010. Developing an instructor support system for scenario-based training. *Proceedings of the 2010 Spring Simulation Multiconference*. Orlando, FL, USA, 11 - 15 Apr 2010. Society for Computer Simulation International: San Diego, CA, USA.

La Porte, T.R., 1988. The United States air traffic control system: Increasing reliability in the midst of rapid growth. In: eds. R. Mayntz and T. Hughes. *The Development of Large Scale Systems*. Westview Press: Boulder, CO, USA. pp.215-244.

Ladkin, P. and Loer, K., 1998. *Why-Because Analysis: Formal reasoning about incidents*. Technical Report RVS-Bk-98-01. RVS Group, University of Bielefeld: Bielefeld, Germany.

Ladkin, P.B., 2005. *Why-Because Analysis of the Glenbrook, NSW rail accident and comparison with Hopkins's Accimap*. Research Report RVS-RR-05-05. Faculty of Technology, Bielefeld University: Bielefeld, Germany.

Laflamme, L., 1990. A better understanding of occupational accident genesis to improve safety in the workplace. *Journal of Occupational Accidents*, 12(1-3), pp.155-165.

LaPorte, T.R. and Consolini, P.M., 1991. Working in practice but not in theory: Theoretical challenges of "high-reliability organizations". *Journal of Public Administration Research and Theory: J-PART*, 1(1), pp.19-48.

Le Coze, J., 2013a. New models for new times. An anti-dualist move. *Safety Science*, 59, pp.200-218.

Le Coze, J., 2013b. What have we learned about learning from accidents? Post-disasters reflections. *Safety Science*, 51(1), pp.441-453.

Le Coze, J., 2005. Are organisations too complex to be integrated in technical risk assessment and current safety auditing? *Safety Science*, 43(8), pp.613-638.

Leach, P. and Berman, J., 2012. Can the concept of organisational drift help explain the degradation of safety performance that may be observed during re-franchising? In: eds. J.R. Wilson, A. Mills, T. Clarke, J. Rajan and N. Dadashi. *Rail Human Factors Around the World: Impacts on and of People for Successful Rail Operations*. CRC Press: Leiden, Netherlands. pp.94-106.

Lehto, M. and Salvendy, G., 1991. Models of accident causation and their application: Review and reappraisal. *Journal of Engineering and Technology Management*, 8, pp.173-205.

Lenné, M.G., Salmon, P.M., Liu, C.C. and Trotter, M., 2012. A systems approach to accident causation in mining: An application of the HFACS method. *Accident Analysis & Prevention*, 48, pp.111-117.

Leplat, J., 1984. Occupational accident research and systems approach. *Journal of Occupational Accidents*, 6(1-3), pp.77-89.

Leveson, N. 2013a. *Comments on 'Systems Thinking, the Swiss Cheese Model and Accident Analysis: A Comparative Systemic Analysis of the Grayrigg Train Derailment using the ATSB, AcciMap and STAMP Models' paper Published in Accident Analysis & Prevention*. E-mail: personal communication, 27th July 2013.

Leveson, N., 2013b. Drawbacks in using the term 'system of systems'. *Journal of Biotechnology Instrumentation and Technology*, March/April 2013, pp.115-118.

Leveson, N., 2012. *Engineering a Safer World: Systems Thinking Applied to Safety*. The MIT Press: Cambridge, MA, USA.

Leveson, N., 2011. Applying systems thinking to analyze and learn from events. *Safety Science*, 49(1), pp.55-64.

Leveson, N., 2004. A new accident model for engineering safer systems. *Safety Science*, 42(4), pp.237-270.

Leveson, N., 2001. *Evaluating accident models using recent aerospace accidents*. Part I: Event-Based Models. Massachusetts Institute of Technology: Cambridge, MA, USA.

Leveson, N., Daouk, M., Dulac, N. and Marais, K., 2003. *A Systems Theoretic Approach to Safety Engineering* [online]. Available at: http://sunnyday.mit.edu/accidents/external2.pdf [accessed 11 Jan 2011].

Leveson, N., Dulac, N., Marais, K. and Carroll, J., 2009. Moving beyond normal accidents and high reliability organizations: A systems approach to safety in complex systems. *Organization Studies*, 30(2), pp.227-249.

Leveson, N.G., Allen, P. and Storey, M.A., 2002. The analysis of a friendly fire accident using a systems model of accidents. *Proceedings of the 20th International System Safety Conference*. Denver, CO, USA, 5 - 9 Aug 2002. System Safety Society: Unionville, VA, USA. pp.345–357.

Lind, M., 1988. System concepts and the design of man-machine interfaces for supervisory control. In: eds. L.P. Goodstein, H.B. Andersen and S.E. Olsen. *Tasks, Errors and Mental Models*. Taylor & Francis Ltd.: London, UK. pp.269-277.

Lord, S.R., Sherrington, C., Cameron, I.D. and Close, J.C.T., 2011. Implementing falls prevention research into policy and practice in Australia: Past, present and future. *Journal of Safety Research*, 42(6), pp.517-520.

Lucas, M., Laplaze, L. and Bennett, M.J., 2011. Plant systems biology: Network matters. *Plant, Cell and Environment*, 34(4), pp.535-553.

Luna-Reyes, L.F., Zhang, J., Gil-García, J.R. and Cresswell, A.M., 2005. Information systems development as emergent socio-technical change: A practice approach. *European Journal of Information Systems*, 14(1), pp.93-105.

Lundberg, J., Rollenhagen, C. and Hollnagel, E., 2010. What you find is not always what you fix — how other aspects than causes of accidents decide recommendations for remedial actions. *Accident Analysis & Prevention*, 42(6), pp.2132-2139.

Lundberg, J., Rollenhagen, C., Hollnagel, E. and Rankine, A., 2012. Strategies for dealing with resistance to recommendations from accident investigations. *Accident Analysis and Prevention*, 45, pp.455-467.

Macchi, L., Hollnagel, E. and Leonhard, J., 2009. Resilience Engineering approach to safety assessment: an application of FRAM for the MSAW system. *EUROCONTROL Safety R&D Seminar*. Munich, Germany, 21 -22 Oct 2009. EUROCONTROL: France.

Marais, K., Dulac, N. and Leveson, N., 2004. 24 Mar 2004-last update. *Beyond Normal Accidents and High Reliability Organizations: The Need for an Alternative Approach to Safety in Complex Systems* [online]. Available at: http://esd.mit.edu/symposium/pdfs/papers/marais-b.pdf [accessed 9 Nov 2010].

Martinez, E. 2011. Investigation-A Shared Process. *ISASI Forum: Air Safety through Investigation*, 44 (4), pp.7–11.

Mayntz, R., 1997. Chaos in society: Reflections on the impact of chaos theory on sociology. In: eds. C. Grebogi and J.A. Yorke. *The Impact of Chaos on Science and Society*. United Nations University Press: New York, NY, USA. pp.298-323.

Menon, G.M. and Cowger, C.D., 2010. Integrating qualitative and quantitative research methods. In: ed. B. Thyer. *The Handbook of Social Work Research Methods*. 2nd edn. Sage: Thousand Oaks, CA, USA. pp.609-613.

Mesarovic, M.D. and Takahara, Y., 1975. *General Systems Theory: Mathematical Foundations*. Academic Press: New York, NY, USA.

Miles, M.B. and Huberman, A.M., 1994. *Qualitative Data Analysis: An Expanded Sourcebook*. 2nd edn. Sage Publications Ltd.: London, UK.

Millman, M., 1977. *The Unkindest Cut: Life in the Backrooms of Medicine*. Morrow Quill Paperbacks: New York, USA.

Moore, J., Crozier, K. and Kite, K., 2012. An action research approach for developing research and innovation in nursing and midwifery practice: Building research capacity in one NHS foundation trust. *Nurse Education Today*, 32(1), pp.39-45.

Mullai, A., 2004. A risk analysis framework for marine transport of packaged dangerous goods. In: ed. C. Brindley. *Supply Chain Risk*. Ashgate Publishing Ltd: Aldershot, UK. pp.130-159.

Mullai, A. and Paulsson, U., 2011. A grounded theory model for analysis of marine accidents. *Accident Analysis & Prevention*, 43(4), pp.1590-1603.

Nicolescu, B.N. and Petrescu, T.C., 2013. Dynamical systems theory – A powerful tool in the educational sciences. *Procedia - Social and Behavioral Sciences*, 76, pp.581-587.

Noonan, R.K., Sleet, D.A. and Stevens, J.A., 2011. Closing the gap: A research agenda to accelerate the adoption and effective use of proven older adult fall prevention strategies. *Journal of Safety Research*, 42(6), pp.427-430.

Office of Rail Regulation, 2013. *Periodic review 2013: Draft determination of network rail's outputs and funding 2014-19*. Office of Rail Regulation: London, UK.

Ohno, T., 1988. *Toyota Production System: Beyond Large-Scale Production*. Productivity Inc.: Portland, OR, USA.

Okstad, E., Jersin, E. and Tinmannsvik, R.K., 2012. Accident investigation in the Norwegian petroleum industry – common features and future challenges. *Safety Science*, 50(6), pp.1408-1414.

Olson, M.H. and Ives, B., 1981. User involvement in system design: An empirical test of alternative approaches. *Information & Management*, 4(4), pp.183-195.

Ouyang, M., Hong, L., Yu, M. and Fei, Q., 2010. STAMP-based analysis on the railway accident and accident spreading: Taking the China–Jiaoji railway accident for example. *Safety Science*, 48(5), pp.544-555.

Owens, B.D., Herring, M.S., Dulac, N., Leveson, N.G., Ingham, M.D. and Weiss, K.A., 2008. Application of a Safety-Driven Design Methodology to an Outer Planet Exploration Mission. *IEEE Aerospace Conference*. Big Sky, MT, USA, March, 2008.

Peeters, P., 2012. A clear path towards sustainable mass tourism? Rejoinder to the paper 'Organic, incremental and induced paths to sustainable mass tourism convergence' by David B. Weaver. *Tourism Management*, 33(5), pp.1038-1041.

Perrow, C., 1994. The limits of safety: The enhancement of a theory of accidents. *Journal of Contingencies and Crisis Management*, 2(4), pp.212-220.

Perrow, C., 1984. *Normal Accidents: Living with High-Risk Technologies*. Basic Books: New York, NY, USA.

Pfeffer, J. and Sutton, R.I., 2006. *Hard Facts, Dangerous Half-Truths, and Total Nonsense: Profiting from Evidence-Based Management*. Harvard Business School Press: Boston, MA, USA.

Pidgeon, N., 1997. The limits to safety? Culture, politics, learning and man–made disasters. *Journal of Contingencies and Crisis Management*, 5(1), pp.1-14.

Pidgeon, N. and O'Leary, M., 2000. Man-made disasters: Why technology and organizations (sometimes) fail. *Safety Science*, 34(1-3), pp.15-30.

Qureshi, Z.H., 2007. A Review of Accident Modelling Approaches for Complex Socio-Technical Systems. In: ed. T. Cant. *12th Australian Workshop on Safety Related Programmable Systems*. Adelaide, Australia, 30-31 Aug 2007. Australian Computer Society Inc.: Darlinghurst, Australia. pp.47.

Rail Accident Investigation Branch, 2011. *Rail accident report: Derailment at Grayrigg 23 February 2007*. Report 20/2008 v5 July 2011. Rail Accident Investigation Branch, Department for Transport: Derby, UK.

Rail Safety and Standards Board, 2011. *Investigation Guidance Part 3: Practical Support for Accident Investigators*. Rail Safety and Standards Board: London, UK.

Rashid, H.S.J., Place, C.S. and Braithwaite, G.R., 2013. Investigating the investigations: A retrospective study in the aviation maintenance error causation. *Cognition, Technology & Work*, 15(2), pp.171-188.

Rasmussen, B. and Grønberg, C.D., 1997. Accidents and risk control. *Journal of Loss Prevention in the Process Industries*, 10(5–6), pp.325-332.

Rasmussen, J., 1997. Risk management in a dynamic society: A modelling problem. *Safety Science*, 27(2-3), pp.183-213.

Rasmussen, J. and Svedung, I., 2000. *Proactive risk management in a dynamic society*. Swedish Rescue Services Agency: Karlstad, Sweden.

Rathnayaka, S., Khan, F. and Amyotte, P., 2011. SHIPP methodology: Predictive accident modeling approach. Part I: Methodology and model description. *Process Safety and Environmental Protection*, 89(3), pp.151-164.

Read, G.J.M., Salmon, P.M. and Lenné, M.G., 2013. Sounding the warning bells: The need for a systems approach to understanding behaviour at rail level crossings. *Applied Ergonomics*, 44(5), pp.764-774.

Reason, J., 2008. *The Human Contribution: Unsafe Acts, Accidents and Heroic Recoveries*. Ashgate: Farnham, UK.

Reason, J., 1997. *Managing the Risks of Organizational Accidents*. Ashgate Publishing Ltd: Aldershot, UK.

Reason, J., 1990. *Human Error*. Cambridge University Press: Cambridge, UK.

Reason, J., Hollnagel, E. and Paries, J., 2006. *Revisiting the «Swiss cheese» model of accidents*. EEC Note No. 13/06. EUROCONTROL Experimental Centre: Brétigny-sur-Orge, France.

Reiman, T. and Rollenhagen, C., 2011. Human and organizational biases affecting the management of safety. *Reliability Engineering & System Safety*, 96(10), pp.1263-1274.

Richardson, P., 2011. Translating theory into practice (and practice into theory) – does context influence sports injury prevention research? *British Journal of Sports Medicine*, 45(4), pp.369-370.

Robson, C., 2011. *Real World Research: A Resource for Users of Social Research Methods in Applied Settings*. 3rd edn. John Wiley and Sons Ltd: Chichester, UK.

Robson, C., 2002. *Real World Research: A Resource for Social Scientists and Practitioner-Researchers*. 2nd edn. Blackwell Publishing: Oxford, UK.

Rochlin, G.I., La Porte, T.R. and Roberts, K.H., 1987. The self-designing high-reliability organization: Aircraft carrier flight operations at sea. *Naval War College Review*, 40(4), pp.76-90.

Roed-Larsen, S. and Stoop, J., 2012. Modern accident investigation – four major challenges. *Safety Science*, 50(6), pp.1392-1397.

Roelen, A.L.C., Lin, P.H. and Hale, A.R., 2011. Accident models and organisational factors in air transport: The need for multi-method models. *Safety Science*, 49(1), pp.5-10.

Rogers, E.M., 2003. *Diffusion of Innovations*. 5th edn. Free Press: New York, NY, USA.

Rohrbach, L.A., Graham, J.W. and Hansen, W.B., 1993. Diffusion of a school-based substance abuse prevention program: Predictors of program implementation. *Preventive Medicine*, 22(2), pp.237-260.

Rollenhagen, C., Westerlund, J., Lundberg, J. and Hollnagel, E., 2010. The context and habits of accident investigation practices: A study of 108 swedish investigators. *Safety Science*, 48(7), pp.859-867.

Ronza, A., Felez, S., Darbra, R.M., Carol, S., Vilchez, J.A. and Casal, J., 2003. Predicting the frequency of accidents in port areas by developing event trees from historical analysis. *Journal of Loss Prevention in the Process Industries*, 16(6), pp.551-560.

Rosa, E.A., 2005. Celebrating a citation classic—and more symposium on Charles Perrow's normal accidents. *Organization & Environment*, 18(2), pp.229-234.

Royce, D., Thyer, B.A. and Padgett, D.K., 2010. *Program Evaluation: An Introduction*. 5th edn. Wadsworth: Belmont, CA, USA.

Sagan, S.D., 1993. *The Limits of Safety: Organizations, Accidents, and Nuclear Weapons*. Princeton University Press: Princeton, NJ, USA.

Salas, E., 2008. At the turn of the 21st century: Reflections on our science. *Human Factors*, 50(3), pp.351-353.

Saleh, J.H., Marais, K.B., Bakolas, E. and Cowlagi, R.V., 2010. Highlights from the literature on accident causation and system safety: Review of major ideas, recent contributions, and challenges. *Reliability Engineering and System Safety*, 95(11), pp.1105-1116.

Salmon, P., Williamson, A., Lenné, M., Mitsopoulos-Rubens, E. and Rudin-Brown, C.M., 2010a. Systems-based accident analysis in the led outdoor activity domain: Application and evaluation of a risk management framework. *Ergonomics*, 53(8), pp.927-939.

Salmon, P.M., Cornelissen, M. and Trotter, M.J., 2012a. Systems-based accident analysis methods: A comparison of Accimap, HFACS, and STAMP. *Safety Science*, 50(4), pp.1158-1170.

Salmon, P.M., Lenné, M.G. and Stephan, K., 2010b. Applying systems based methods to road traffic accident analysis: The barriers to application in an open, unregulated system. *Proceedings of the 9th International Symposium of the Australian Aviation Psychology Association: Managing Safety–Maximising Performance*. Sydney, Australia, 18 - 22 Apr 2010. Australian Aviation Psychology Association: Canberra, Australia.

Salmon, P.M., McClure, R. and Stanton, N.A., 2012b. Road transport in drift? Applying contemporary systems thinking to road safety. *Safety Science*, 50(9), pp.1829-1838.

Salmon, P.M., Read, G.J.M., Stanton, N.A. and Lenné, M.G., 2013. The crash at Kerang: Investigating systemic and psychological factors leading to unintentional non-compliance at rail level crossings. *Accident Analysis & Prevention*, 50, pp.1278-1288.

Salmon, P.M., Stanton, N.A., Lenné, M., Jenkins, D.P., Rafferty, L. and Walker, G.H., 2011. *Human Factors Methods and Accident Analysis: Practical Guidance and Case Study Applications*. Ashgate Publishing Ltd.: Farnham, UK.

Samaras, G.M., 2012. Reducing latent errors, drift errors, and stakeholder dissonance. *Work: A Journal of Prevention, Assessment and Rehabilitation*, 41, pp.1948-1955.

Saurin, T.A. and Carim Júnior, G.C., 2011. Evaluation and improvement of a method for assessing HSMS from the resilience engineering perspective: A case study of an electricity distributor. *Safety Science*, 49(2), pp.355-368.

Sawaragi, T., Horiguchi, Y. and Hina, A., 2006. Safety analysis of systemic accidents triggered by performance deviation. *SICE-ICASE International Joint Conference 2006*. Busan, Korea, 18 - 21 Oct 2006. ICASE: Korea. pp.1778-1781.

Schnall, R., Cimino, J.J. and Bakken, S., 2012. Development of a prototype continuity of care record with context-specific links to meet the information needs of case managers for persons living with HIV. *International Journal of Medical Informatics*, 81(8), pp.549-555.

Schröder-Hinrichs, J.U., Baldauf, M. and Ghirxi, K.T., 2011. Accident investigation reporting deficiencies related to organizational factors in machinery space fires and explosions. *Accident Analysis & Prevention*, 43(3), pp.1187-1196.

Schwaninger, M., 2006. System dynamics and the evolution of the systems movement. *Systems Research and Behavioral Science*, 23(5), pp.583-594.

Seising, R., 2010. Cybernetics, system(s) theory, information theory and fuzzy sets and systems in the 1950s and 1960s. *Information Sciences*, 180(23), pp.4459-4476.

Senge, P.M., 2006. *The Fifth Discipline: The Art and Practice of the Learning Organization*. 2nd edn. Random House: London, UK.

Sgourou, E., Katsakiori, P., Goutsos, S. and Manatakis, E., 2010. Assessment of selected safety performance evaluation methods in regards to their conceptual, methodological and practical characteristics. *Safety Science*, 48(8), pp.1019-1025.

Shorrock, S., Young, M., Faulkner, J. and Braithwaite, G., 2004. Who Moved My (Swiss) Cheese? The (R)Evolution of Human Factors In Transport Safety Investigation. In: eds. R. Stone, S. Fager and E. Martinez. *Proceedings of the 35th Annual International Seminar: 'Investigate—Communicate—Educate'*. Gold Coast, Australia, 30 Aug - 2 Sept 2004. International Society for Air Safety Investigators: Stirling, VA, USA. pp.141-144.

Shrivastava, S., Sonpar, K. and Pazzaglia, F., 2009. Normal accident theory versus high reliability theory: A resolution and call for an open systems view of accidents. *Human Relations*, 62(9), pp.1357-1390.

Siemieniuch, C.E. and Sinclair, M.A., 2013. Extending systems ergonomics thinking to accommodate the socio-technical issues of systems of systems. *Applied Ergonomics*. DOI: dx.doi.org/10.1016/j.apergo.2013.03.017

Sinclair, M.A., 2007. Ergonomics issues in future systems. *Ergonomics*, 50(12), pp.1957-1986.

Sklet, S., 2004. Comparison of some selected methods for accident investigation. *Journal of Hazardous Materials*, 111, pp.29-37.

Skyttner, L., 2005. *General Systems Theory: Problems, Perspectives, Practice*. 2nd edn. World Scientific Publishing Ltd.: London, UK.

Smit, E.S., Vries, H. and Hoving, C., 2013. Determinants of practice nurses' intention to implement a new smoking cessation intervention: The importance of attitude and innovation characteristics. *Journal of Advanced Nursing*. DOI: 10.1111/jan.12153

Snape, D. and Spencer, L., 2003. The foundations of qualitative research. In: eds. J. Ritchie and J. Lewis. *Qualitative Research Practice: A Guide for Social Science Students and Researchers*. Sage Publications Ltd.: London, UK. pp.1-23.

Solomon, D.J., Laakso, M. and Björk, B., 2013. A longitudinal comparison of citation rates and growth among open access journals. *Journal of Informetrics*, 7(3), pp.642-650.

Song, T., Zhong, D. and Zhong, H., 2012. A STAMP Analysis on the China-Yongwen Railway Accident. In: eds. F. Ortmeier and P. Daniel. *SAFECOMP 2012*. 25 Sep 2012. Springer-Verlag: Berlin, Germany. pp.376-387.

Stanton, N.A., Rafferty, L.A. and Blane, A., 2012. Human factors analysis of accidents in systems of systems. *Journal of Battlefield Technology*, 15(2), pp.23-30.

Steele, K. and Pariès, J., 2006. The process of tailoring models for a priori safety and risk management for use within industry. In: eds. E. Hollnagel and E. Rigaud. *Second Resilience Engineering Symposium*. Antibes-Juan-Les-Paris, 8 - 10 Nov 2006. Mines Paris. pp.294-295.

Stringfellow Herring, M., Owens, B.D., Leveson, N., Ingham, M. and Weiss, K.A., 2007. *A safety-driven, model-based system engineering methodology, part I*. MIT Technical Report. Massachusetts Institute of Technology: Cambridge, MA, USA.

Stringfellow, M.V., 2010. *Accident Analysis and Hazard Analysis for Human and Organizational Factors*. PhD. Massachusetts Institute of Technology.

Sundström, G.A. and Hollnagel, E., 2011. The importance of functional interdependencies in financial services systems. In: eds. E. Hollnagel, J. Pariès, D.D. Woods and J. Wreathall. *Resilience Engineering in Practice*. Ashgate: Farnham, UK. pp.171-190.

Svedung, I. and Rasmussen, J., 2002. Graphic representation of accident scenarios: Mapping system structure and the causation of accidents. *Safety Science*, 40(5), pp.397-417.

Svenson, O., Lekberg, A. and Johansson, A.E.L., 1999. On perspective, expertise and differences in accident analyses: Arguments for a multidisciplinary integrated approach. *Ergonomics*, 42(11), pp.1561-1571.

Szeremeta, M., Janica, J.R., Niemcunowicz-Janica, A. and Pepinski, W., 2013. Fatal drowning as a result of an airplane crash - case report. *Forensic Science International*, 226(1–3), pp.e12-e15.

Tai, B., Straus, M.M., Liu, D., Sparenborg, S., Jackson, R. and McCarty, D., 2010. The first decade of the national drug abuse treatment clinical trials network: Bridging the gap between research and practice to improve drug abuse treatment. *Journal of Substance Abuse Treatment*, 38(Supplement 1), pp.S4-S13.

Thomas, C. and Bevan, N., 1996. *Usability context analysis: A practical guide*. Version 4.04. National Physical Laboratory: Teddington, UK.

Tornatzky, L.G. and Klein, K.J., 1982. Innovation characteristics and innovation adoption-implementation: A meta-analysis of findings. *IEEE Transactions on Engineering Management*, EM-29(1), pp.28-45.

Trist, E., 1981. The evolution of socio-technical system: A conceptual framework and an action research program. *Occasional Paper*, 2(June).

Trist, E.L., 1959. *Socio-technical systems*. Report 572. The Tavistock Institute of Human Relations: London, UK.

Turner, B.A., 1978. *Man-made Disasters*. Wykeham: London, UK.

Underwood, P. and Waterson, P., 2013a. Systemic accident analysis: Examining the gap between research and practice. *Accident Analysis & Prevention*, 55, pp.154-164.

Underwood, P. and Waterson, P., 2013b. Systems thinking, the Swiss Cheese Model and accident analysis: A comparative systemic analysis of the Grayrigg train derailment using the ATSB, AcciMap and STAMP models. *Accident Analysis & Prevention*. DOI: dx.doi.org/10.1016/j.aap.2013.07.027

Underwood, P. and Waterson, P., 2012a. A Critical Review of the STAMP, FRAM and AcciMap Systemic Accident Analysis Models. In: ed. AHFE. *International Conference on Applied Human Factors and Ergonomics*. San Francisco, 21 - 25 July 2012. The Printing House: Stoughton, WI, USA. pp.1709-1718.

Underwood, P. and Waterson, P., 2012b. A critical review of the STAMP, FRAM and AcciMap systemic accident analysis models. In: ed. N.A. Stanton. *Advances in Human Aspects of Road and Rail Transportation*. CRC Press: Boca Raton, FL, USA. pp.385-394.

Underwood, P. and Waterson, P., 2012c. A Review of Systemic Accident Analysis Models. In: ed. M. Anderson. *Contemporary Ergonomics and Human Factors 2012*. Blackpool, UK, 16-19 April 2012. CRC Press: London, UK. pp.364-365.

US Nuclear Regulatory Commission, 1975. *Reactor safety study: An assessment of accident risks in US commercial nuclear power plants*. NUREG-75/014. National Research Council: Washington, DC, USA.

van Aken, J.E., 2005. Management research as a design science: Articulating the research products of mode 2 knowledge production in management. *British Journal of Management*, 16(1), pp.19-36.

Vaughan, D., 1996. *The Challenger Launch Decision: Risky Technology, Culture, and Deviance at NASA.* University of Chicago Press: Chicago, IL, USA.

Vestrucci, P., 2013. On the “post-dictive use” of the fault tree method for accident investigation to aid judicial procedures. *Safety Science*, 53, pp.240-247.

Vicente, K.J., 1999. *Cognitive Work Analysis: Toward Safe, Productive, and Healthy Computer-Based Work*. Lawrence Erlbaum Associates: Mahwah, NJ, USA.

Viitanen, J., Hyppönen, H., Lääveri, T., Vänskä, J., Reponen, J. and Winblad, I., 2011. National questionnaire study on clinical ICT systems proofs: Physicians suffer from poor usability. *International Journal of Medical Informatics*, 80(10), pp.708-725.

von Bertalanffy, L., 1950. An outline of general system theory. *British Journal for the Philosophy of Science*, 1(2), pp.134-165.

Wagenaar, W.A. and van der Schrier, J., 1997. The goal, and how to get there. *Safety Science*, 26(1-2), pp.25-33.

Wahlström, B., 1988. On the use of models in human decision-making. In: eds. L.P. Goodstein, H.B. Andersen and S.E. Olsen. *Tasks, Errors and Mental Models*. Taylor & Francis Ltd.: London, UK. pp.161-170.

Wandersman, A., Duffy, J., Flaspohler, P., Noonan, R., Lubell, K., Stillman, L., Blachman, M., Dunville, R. and Saul, J., 2008. Bridging the gap between prevention research and practice: The interactive systems framework for dissemination and implementation. *American Journal of Community Psychology*, 41(3), pp.171-181.

Waterson, P., 2009a. A critical review of the systems approach within patient safety research. *Ergonomics*, 52(10), pp.1185-1195.

Waterson, P., 2009b. A systems ergonomics analysis of the Maidstone and Tunbridge Wells infection outbreaks. *Ergonomics*, 52(10), pp.1196-1205.

Waterson, P. and Jenkins, D.P., 2011. Lessons learnt from using AcciMaps and the Risk Management Framework to analyse large-scale systemic failures. In: ed. M. Anderson. *Contemporary Ergonomics and Human Factors 2011: Proceedings of the International Conference on Ergonomics & Human Factors*. Stoke Rochford, UK, 12-14 Apr 2011. CRC Press: London, UK. pp.6-13.

Waterson, P.E. and Anderson, J., 2013. Bridging the research practice gap in healthcare human factors and ergonomics. In: ed. M. Anderson. *Contemporary Ergonomics and Human Factors 2013: Proceedings of the International Conference on Ergonomics and Human Factors 2013*. Cambridge, UK, 15-18 Apr 2013. Taylor & Francis: Abingdon, UK. pp.285-286.

Waterson, P.E. and Jenkins, D.P., 2010. Methodological considerations in using AcciMaps and the Risk Management Framework to analyse large-scale systemic failures. *5th IET International Conference on System Safety*. Manchester, UK, 18 - 20 Oct 2010. IET Conference Publications. pp.1-6.

Watson, H.A., 1961. *Launch control safety study*. Section VII, Volume I. Bell Laboratories: Murray Hill, NJ, USA.

Wiegmann, D.A. and Shappell, S.A., 2003. *A Human Error Approach to Aviation Accident Analysis: The Human Factors Analysis and Classification System*. Ashgate Publishing Ltd: Burlington, VT, USA.

Williams, C., 2008. *In search of ergonomics expertise*. PhD. Loughborough University.

Wilson, J.R., 2013. Fundamentals of systems ergonomics/human factors. *Applied Ergonomics*. DOI: dx.doi.org/10.1016/j.apergo.2013.03.021

Wolfe, B.E., 2012. Healing the research–practice split: Let's start with me. *Psychotherapy*, 49(2), pp.101-108.

Woltjer, R., 2006. A Systemic Functional Resonance Analysis of the Alaska Airlines Flight 261 Accident. In: ed. C. Weikert. *Swedish Human Factors Network (HFN) Conference*. Linköping, Sweden, 5 - 7 Apr 2006. Swedish Human Factors Network. pp.83-93.

Woltjer, R., Smith, K. and Hollnagel, E., 2006. Constraint Recognition and State Space Representation in Collaborative Distributed Command and Control. In: ed. C. Weikert. *Swedish Human Factors Network (HFN) Conference*. Linköping, Sweden, 5 - 7 Apr 2006. Swedish Human Factors Network. pp.72-82.

Woo, D.M. and Vicente, K.J., 2003. Sociotechnical systems, risk management, and public health: Comparing the North Battleford and Walkerton outbreaks. *Reliability Engineering & System Safety*, 80(3), pp.253-269.

Woodcock, K., Drury, C.G., Smiley, A. and Ma, J., 2005. Using simulated investigations for accident investigation studies. *Applied Ergonomics*, 36, pp.1-12.

Woods, D.D. and Cook, R.I., 2002. Nine steps to move forward from error. *Cognition, Technology & Work*, 4, pp.137-144.

Xing, K., Ness, D. and Lin, F., 2013. A service innovation model for synergistic community transformation: Integrated application of systems theory and product-service systems. *Journal of Cleaner Production*, 43, pp.93-102.

Xue, L., Fan, J., Rausand, M. and Zhang, L., 2013. A safety barrier-based accident model for offshore drilling blowouts. *Journal of Loss Prevention in the Process Industries*, 26(1), pp.164-171.

Yang, C., Jing, W., Daemen, J.J.K., Zhang, G. and Du, C., 2013. Analysis of major risks associated with hydrocarbon storage caverns in bedded salt rock. *Reliability Engineering & System Safety*, 113, pp.94-111.

Zaltman, G., Duncan, R. and Holbek, J., 1973. *Innovations and Organizations*. Wiley: New York, NY, USA.

Zhang, G. and Tang, M., 1993. The investigation of a devastating accident — an accidental explosion of 40 tons of TNT. *Journal of Hazardous Materials*, 34(2), pp.225-233.

Zio, E. and Ferrario, E., 2013. A framework for the system-of-systems analysis of the risk for a safety-critical plant exposed to external events. *Reliability Engineering & System Safety*, 114, pp.114-125.

Appendices

Appendix 1.1 – Underwood and Waterson (2012a)

Appendix 1.2 – Underwood and Waterson (2013a)

Appendix 1.3 – Underwood and Waterson (2013b)

Appendix 2.1 – Research-practice gap literature search criteria and results

Appendix 3.1 – Study 1 literature search

Appendix 4.1 – Study 2 sample demographics

Appendix 4.2 – Study 2 interview questions

Appendix 4.3 – Study 2 analysis model awareness table

Appendix 5.1 – RAIB (2011) investigation findings

Appendix 6.1 – STAMP workshop material

Appendix 6.2 – STAMP evaluation questionnaire

Appendix 6.3 – STAMP workshop outputs

Appendix 6.4 – STAMP evaluation questionnaire individual responses

Appendix 7.1 – Examples of research-practice knowledge transfer events

Appendix 7.2 – System of systems definition

Appendix 1.1

Underwood and Waterson (2012a)

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Appendix 1.2

Underwood and Waterson (2013a)

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Systemic accident analysis: Examining the gap between research and practice

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Abstract

The systems approach is arguably the dominant concept within accident analysis research. Viewing accidents as a result of uncontrolled system interactions, it forms the theoretical basis of various systemic accident analysis (SAA) models and methods. Despite the proposed benefits of SAA, such as an improved description of accident causation, evidence within the scientific literature suggests that these techniques are not being used in practice and that a research–practice gap exists. The aim of this study was to explore the issues stemming from research and practice which could hinder the awareness, adoption and usage of SAA. To achieve this, semi-structured interviews were conducted with 42 safety experts from ten countries and a variety of industries, including rail, aviation and maritime. This study suggests that the research–practice gap should be closed and efforts to bridge the gap should focus on ensuring that systemic methods meet the needs of practitioners and improving the communication of SAA research.

1. Introduction

The systems approach is arguably the dominant paradigm in accident analysis and human factors research (e.g. Salmon et al., 2012a; Stanton et al., 2012). It views socio-technical system accidents as the result of unexpected, uncontrolled relationships between a system's constituent parts.

This requires the study of systems as whole entities, rather than considering their parts in isolation. Many complex system accidents, e.g. space shuttle Columbia and Comair flight 5191, have not simply resulted from catastrophic equipment failure or an unsafe human action, as required according to traditional cause-effect accident models; instead accidents emerge as complex phenomena within the normal operational variability of a system (de Carvalho, 2011). Therefore, describing accidents in a sequential (cause-effect) fashion is arguably inadequate, as it is unable to sufficiently explain the non-linear complexity of modern-day socio-technical system accidents (Hollnagel, 2004; Lindberg et al., 2010). It can also lead to equipment or humans at the 'sharp end' of a system being incorrectly blamed for an accident. This represents a missed opportunity to learn important lessons about system safety and, therefore, develop more effective safety recommendations. Use of the systems approach, via systemic accident analysis (SAA), supposedly avoids these limitations and it has been used as the conceptual foundation for various SAA methods and models, e.g. Systems Theoretic Accident Modelling and Processes model (STAMP) (Leveson, 2004), the Functional Resonance Analysis Method (FRAM) (Hollnagel, 2004) and Accimap (Rasmussen, 1997).

1.1. Systemic accident analysis in research

A number of studies have compared SAA methods with established non-systemic analysis techniques, such as Fault Tree Analysis (e.g. Belmonte et al., 2011) and the Sequentially Timed Events Plotting method (e.g. Herrera and Woltjer, 2010). These studies and others like them (e.g. Ferjencik, 2011) suggest that, whilst the non-systemic methods are suitable for describing what happened in an accident, the SAA techniques provide a deeper understanding of how dynamic, complex system behaviour contributed to the event.

Furthermore, Leveson (2011, p. 349) comments that most accident reports are written from the perspective of cause-effect models and that the analysis frequently stops prematurely. Some studies exemplify this by stating that additional insights were achieved using SAA methods, when compared with the findings of official investigation reports (e.g. Jenkins et al., 2010; Johnson and de Almeida, 2008). The improved understanding of accident causation provided by SAA should, therefore, allow the development of more effective safety recommendations.

1.2 Systemic accident analysis in practice

Despite the proposed advantages of SAA, there is evidence within the scientific literature to suggest that methods and tools employing a systemic perspective are not being adopted in practice. For example, some researchers (e.g. Carhart and Yearworth, 2010; Leveson, 2011) comment that the most widely used accident analysis tools are based on sequential, reductionist models of systems and causality. Other researchers also suggest that SAA techniques are yet to gain acceptance outside of the research community (e.g. Okstad et al., 2012; Salmon et al., 2012a). These observations are supported by the sequential understanding of accident causation presented within various elements of the practitioner-focused safety literature (e.g. Energy Institute, 2008; Health and Safety Executive, 2004; Rail Safety Standards Board, 2011).

1.3. The gap between research and practice

The different analysis approaches taken by the researcher and practitioner communities suggest that a research–practice gap exists in the domain of SAA. Various aspects of the research–practice gap in accident analysis have been previously studied, both from a general perspective and within the context of SAA. Generic factors which can influence a practitioner's approach to accident analysis have been identified, such as investigator bias and resource constraints (e.g. Johnson, 2003; Lundberg et al., 2010). These influences can arguably lead practitioners away from the theoretical ideal of accident investigation and therefore contribute to a research–practice gap (Lundberg et al., 2010). Other studies (e.g. Salmon et al., 2012a; Underwood and Waterson, 2012) have examined how the characteristics of several systemic analysis models impact on the ability of an individual to successfully perform SAA, such as the lack of method reliability caused by their qualitative nature.

Despite the presence of such a research–practice gap there is evidence to suggest that a desire to adopt SAA exists within sections of the practitioner community. For example, accident investigators within aviation have begun to recognise the need to look beyond sequential analysis methods (e.g. Martinez, 2011, p. 8). Further-more, Steele and Pariès (2006) suggest that many practitioners acknowledge the limitations of traditional models and are keen to apply new techniques. Given that a demand to apply SAA seems to exist in both the researcher and practitioner communities, the research–practice gap needs to be examined in more depth.

1.4. Study aims

Whilst some of the research-based factors contributing to the SAA research–practice gap have been identified in previous studies (e.g. Underwood and Waterson, 2012), it is believed that practitioner-related influences, such as those described by Lundberg et al. (2010), require further examination within the context of SAA. Therefore, the following aims for the study were established:

- Understand how the awareness of, and need for, SAA within the practitioner community could inhibit the adoption and use of SAA.
- Understand how the factors influencing current analysis approaches may hinder the adoption and use of SAA.
- Follow up and probe deeper into the issues stemming from research which may impede the diffusion of SAA into practice.

2. Methods

The use of semi-structured interviews was selected as the most appropriate method to achieve the aims of the study for a number of reasons. Firstly, the lack of information regarding SAA within the practitioner literature prevented the use of document analysis alone. Secondly, previous studies focused on the SAA research–practice gap have used methods such as thematic analysis of the scientific literature (e.g. Underwood and Waterson, 2012) and user evaluations of SAA methods (e.g. Salmon et al., 2012a). Consequentially, interview data was viewed as the most suitable form of information to supplement the existing findings. Finally, semi-structured interviews provide the ability to examine topics of interest in varying degrees of depth; an approach which suited the exploratory nature of this study (Robson, 2002).

2.1. Sampling strategy

Due to the study resource constraints, it was not possible to create a statistically representative sample. Therefore a convenience sample, considered to be indicative of the accident investigation community, was created. The sample included participants employed as full-time accident investigators, health and safety professionals (e.g. company safety managers), human factors specialists and accident analysis researchers. However, these participant categories were not mutually exclusive, e.g. some practitioners had research experience. Therefore, participants were allocated to the category associated with their current role as it was felt that their role would have the most influence on their analysis approach, e.g. due to resource constraints. Also, gaining a detailed understanding of how a participant's background influenced their analysis approach was beyond the study scope.

Human factors experts were recruited as they are often employed on a consultancy basis to provide input into accident investigations or safety-critical system design. The views of researchers were also sought to enable a comparison with the practitioners' perspectives and further explore the research-based factors that may influence the SAA research–practice gap.

Participants were required to have experience of investigating accidents and/or performing risk assessments within at least one safety-critical industry. No specific inclusion criteria were set regarding the level of their experience. Participant recruitment was halted when an appropriate level of thematic data saturation was judged to have been achieved.

2.2. Participants

Interviews were conducted with 42 participants (age range: 28–79 years; mean age: 46.4 years) based in ten countries. The nine full time accident investigators (AI), 17 health and safety professionals (HS), ten human factors specialists (HFE) and six researchers (R) had experience of working in at least one of 25 industries. Of these industries, those that had been worked in by at least five participants included: rail, aviation, maritime, oil and gas, defence, healthcare, nuclear power and manufacturing. The interviews lasted between 28 and 128 min (mean interview length: 70 min).

2.3. Interview question design

The interview questions were designed to understand the following topics: (1) the participants' knowledge of SAA and accident causation, (2) the analysis methods and processes they currently use and (3) the barriers they feel prevent information flowing between the research and practice communities. In order to provide a comprehensive deductive analysis framework, the interview questions were based on these topics, the questions employed by Lundberg et al. (2010) and the findings of previous studies (e.g. Underwood and Waterson, 2012) (see Appendix A for interview questions).

In addition to the interview questions, participants were asked to complete an analysis model awareness table (see Appendix B) which was specifically designed to assess their level of awareness and usage of well-known systemic and non-systemic techniques. The STAMP, FRAM and Accimap methods were included as they have been identified as the most frequently cited systemic analysis tools (Underwood and Waterson, 2012). The Swiss Cheese model (Reason, 1997) and Fault Tree Analysis (Watson, 1961) were also included as they are examples of traditional techniques commonly mentioned in the scientific literature (e.g. Katsakiori et al., 2009; Qureshi, 2007; Sklet, 2004).

2.4. Data collection and analysis

Five pilot interviews were conducted and analysed. The inter-view schedule was reviewed and amended, where necessary, after each interview. The main interview study was subsequently performed with a minor iteration of the interview schedule generated halfway through the process (wording of two questions was changed). Upon the conclusion of the data collection phase a theoretic (i.e. deductive) and inductive thematic analysis, as described by Braun and Clarke (2006), was performed on the interview transcriptions using NVivo 9.

2.5. Research–practice gap evaluation framework

Research–practice gaps signify the impairment of transferring new information between the research and practice communities. The transference process itself, sometimes termed the 'diffusion of innovation', has been the focus of a number of studies which have produced a range of theories and models (e.g. Greenhalgh et al., 2004; Rogers, 2003). Rohrbach et al. (1993) summarised the stages involved in achieving long-term commitment to new ideas which arguably relate to transferring SAA from research into practice. Firstly, the awareness of an innovation, e.g. SAA, is created within the practitioner community. The second and third steps involve practitioners committing to adopt and subsequently implementing the new systemic techniques. These steps were used as a frame-work to evaluate whether issues discovered in the data could affect a given stage and therefore contribute to the formation of a gap.

3. Findings

3.1. Key themes

The themes which were considered to be key issues, i.e. topics that were mentioned by at least 20% of the participants, are presented in Table 1.

Theme (relevant article section)	Percentage of participants				
	Accident investigator	Health and safety professional	Human factors expert	Researcher	Total
1. Requirement for accountability influences analysis approach (3.3.3)	56	41	30	67	45
2. Model not practitioner focused (3.3.1)	33	24	80	50	43
3. Empirical validation requirements (3.3.4)	11	35	60	50	38
4. Analyst chooses a technique that suits the situation (3.4.1 and 3.6.1)	56	35	30	17	36
5. Previous experience and training affects analysis (3.4.2)	67	18	30	50	36
6. Model suits user's way of thinking (3.3.2)	22	24	30	67	31
7. Research considered too conceptual (3.2.5)	56	12	30	17	26
8. Analysis time requirements (3.4.1)	44	6	40	33	26
9. Company policy affects analysis (3.5.1)	22	18	50	17	26
10. Amount of training given (3.2.3)	33	24	30	0	24
11. User's previous training and experience affects model preference (3.3.2)	11	24	20	50	24
12. Lack of communication between researcher and practitioner communities (3.2.5)	56	18	10	0	21

Table 1 – Key themes

Whilst the number of participant comments indicates the importance of a given theme, the non-representative nature of the sample means that this cannot be meaningfully tested (see Section 5 for more information). Therefore, the key themes listed in Table 1 are described alongside others that were deemed to influence SAA awareness, adoption and usage and contribute to the research–practice gap.

3.2. SAA awareness

3.2.1. Current level of SAA awareness

The scientific literature presented in Section 1 describes a general lack of systemic analysis model usage with industry. This situation does not necessarily stem from low levels of SAA aware-ness and comments from several senior practitioners indicate that awareness is growing within industry:

"*Lots and lots of people talk about this [systemic analysis approach] and it's very current in a lot of the safety and high-hazard industry community.*" (Health and safety professional)

Furthermore, notable remarks from two participants provide evidence that systemic models are currently employed in certain industry sectors. One individual commented that both Accimap and FRAM are used within their national transport accident investigation agency. A second participant with a background in human factors described the Accimap training provided by their organisation to accident investigators within the rail industry.

However, the analysis model awareness table responses obtained from the participants suggest that the majority of practitioners remain unaware of the most frequently cited systemic analysis models, i.e. STAMP, FRAM and Accimap (see Fig. 1) (Underwood and Waterson, 2012).

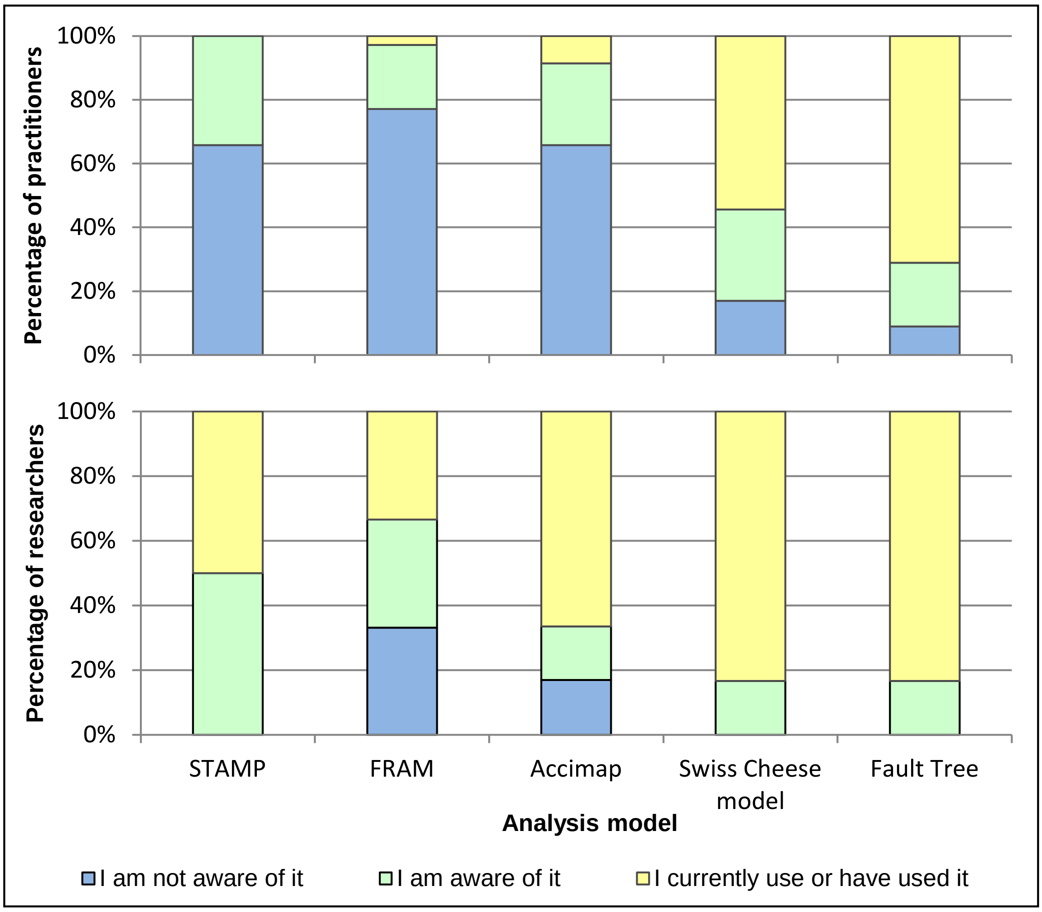

Figure 1 - Analysis model awareness

This is in contrast to the responses of the researchers who were interviewed and indicates that knowledge and use of these models is greater within the scientific community. The research-based participants only accounted for 14% of the sample and therefore this comparison must be made tentatively. However, it is indicative of the lack of SAA model usage within industry portrayed in the scientific literature and provides further evidence that a research–practice gap exists.

In addition, a different understanding of SAA seems to exist between the two communities. When asked to provide a description of the 'systems approach to accident analysis', the two most common characteristics mentioned by participants referred to 'component interactions' and 'analysing the whole system', which are key elements of SAA. However, relatively fewer practitioners (AI = 22%, HS = 27%, HFE = 30%) referred to 'component interactions' compared with the researchers (67%). The 'analysing the whole system' feature was also referred to by relatively fewer practitioners (AI = 22%, HS = 20%, HFE = 40%) compared with the researchers (50%). Five practitioners described SAA as a 'systematic' approach, rather than providing examples of 'systemic' analysis characteristics, which suggests a degree of confusion may exist regarding SAA terminology. Furthermore, five practitioners were unable to provide a definition.

3.2.2. The demand for SAA information

Whilst there is a clear theoretical argument for the use of SAA (see Section 1), various factors exist which may negate the need or opportunity for a practitioner to seek out a systemic analysis tool. Some practitioners simply have no desire to change their current approach and therefore have no need for new information:

"*I can't say that I've actively gone and looked at the new techniques that are out there as the ones I've always used have worked.*" (Health and safety professional)

Additionally, day-to-day workload demands were considered by some individuals to restrict their learning opportunities:

"*I don't have nearly enough time to keep up with the [research] paperwork in this area; hardly any at all. That's a problem that most practitioners have; they're so busy doing investigations it's very difficult to keep up with the theoretical side.*" (Accident investigator)

These comments highlight factors which inhibit the search for SAA-related information. However, should a practitioner decide to use a systemic analysis technique, they are still faced with obstacles associated with accessing and utilising the relevant research.

3.2.3. Extent of training impacts awareness

An individual's awareness of analysis methods is dictated, at least in part, by the level of training they receive. The extent of training received has clear implications with regards to the opportunity to increase awareness of SAA and comments from participants indicate that levels of training are role-dependent. Full-time investigators, for example, sometimes receive extensive training via university-level courses:

"*After you join, the first two years is spent doing a diploma, through a university here, in accident investigation.*" (Accident investigator)

However, it may also be the case that other practitioners with varying degrees of involvement with accident investigation receive less training:

"*We had analytical investigation methods training which was a week-long course. The course started as a week but latterly I think it went down to one and a half days.*" (Human factors expert)

Several participants with experience in the rail and nuclear sectors remarked that individuals with lower levels of responsibility for accident investigation may not have received any relevant training.

3.2.4. Accessibility of SAA information

Individuals who are not provided with SAA training can find gaining access to the relevant information problematic, which may limit their awareness. The time and costs associated with the acquiring the necessary training, for example, may be excessive:

"*A lot of time, when you hear about courses, it costs a lot of money to go which dissuaded me from going.*" (Health and safety professional)

Furthermore, an accident investigator, a health and safety professional and a human factors expert all remarked that the cost of purchasing scientific journal articles and attending conferences may prohibit access to SAA information.

As well as cost, intellectual property rights can form another barrier to acquiring scientific research information:

"*The academic community is very competitive. There's intellectual property rights problems in industry too but normally if there's a buck in it, or a common benefit, you'll collaborate and create an alliance. I find it very hard to get an alliance of academics.*" (Health and safety professional)

3.2.5. Communication of SAA information

Each participant was asked to list the sources of information they utilise in order to keep their knowledge up-to-date. 40 participants provided answers, which are summarised in Table 2.

Source of information	Percentage of participants				
	Accident investigator (n = 9)	Health and safety professional (n = 16)	Human factors expert (n=10)	Practitioner total	Researcher (n = 5)
Colleagues and network contacts	56	44	60	51	60
Conferences	33	50	40	43	20
Internet searches	22	13	10	14	0
Investigation reports	11	19	0	11	0
Online forums and networks	11	19	0	11	0
Practitioner literature and professional institutes	33	44	70	49	20
Research literature	22	6	50	23	100
Research projects	0	19	10	11	60
Textbooks	22	6	10	11	0
Training and experience	44	31	20	31	20
Does not search for information	0	6	0	3	0

Table 2 - Sources of information

Table 2 indicates that the three most popular sources of new information for practitioners, in general, are speaking with colleagues and members of their extended networks, attending conferences and consulting industry literature and professional institutes. In comparison, Table 2 suggests that the majority of researchers tend to gain new knowledge via the scientific literature and by conducting research projects, as well as consulting colleagues. The data in Table 2 also suggests that most practitioners do not consult the scientific literature.

Moreover, some of the practitioners specifically remarked on a general lack of communication between the research and practice communities:

“*I’m not aware of any real liaison between the two [communities].*” (Human factors expert)

“*We hardly ever meet people on the theoretical side; it’s once in a blue moon.*” (Accident investigator)

When practitioners do engage with the research community the information presented is considered by some practitioners to be too conceptual and provides little or no practical benefit:

“*I know some accident investigators that have been to international conferences where there were lots of academics putting forward papers on approaches to accident investigation. The practitioners in the audience said ‘this is actually meaningless and we don’t use it.*’” (Accident investigator)

Consequently practitioners can develop a sense of disregard for researchers which could further influence the apparent lack of SAA communication:

“*There is a mentality within practitioners where academics are seen as people sitting in an ivory tower and haven’t had any real expe-rience of accident investigation so [practitioners think] ‘how can they comment on investigations?’*” (Accident investigator)

3.3. SAA adoption

3.3.1. Practicality of analysis method

Even if sufficient awareness of research is obtained, barriers to its adoption may arise from a lack of consideration for practitioner requirements. The features of an analysis method desired most by participants referred to aspects of usability, such as the simplicity of using a method (see Fig. 2).

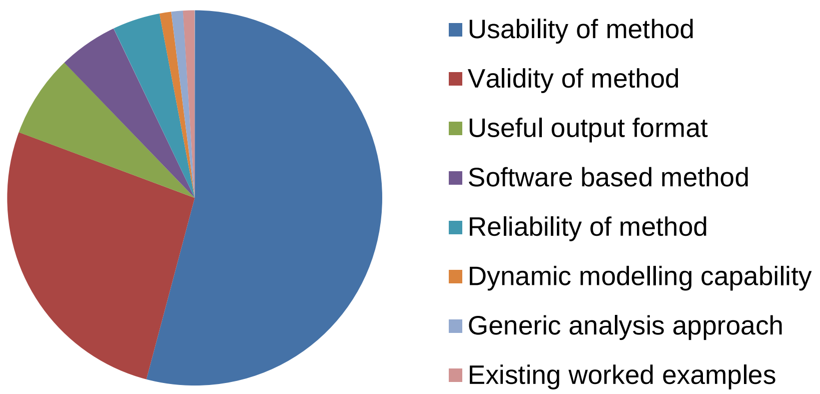

Figure 2 – Preferred features of an analysis method

The importance of designing a usable technique was reflected in the comments of several individuals:

"*I think if you make it simple, people will use it. If it's complicated, they won't and it becomes another job that's too difficult to do and it gets put on the shelf.*" (Health and safety professional)

Other practicality-related issues which may inhibit the adoption of research were also referred to by participants. Several accident investigators, for example, commented on a possible lack of appreciation for the practicalities of their role in the design of analysis methods. The potentially excessive cost of implementing research was also highlighted by a human factors expert.

3.3.2. Personal adoption criteria

In addition to the practicalities of using an analysis technique, adoption may also be influenced by a number of factors based on an individual's personal preference and experience. A person's decision to adopt a method may be, for example, based on how well it suits their way of thinking:

"*When I think of the Swiss Cheese model, I can really think of those barriers being broken and trying to find out why they have been broken. For me it's a very natural way of investigating. Some people really hate it but for me it works.*" (Accident investigator)

The preference for a given model can also be influenced by an individual's previous experience and training:

“*If I had trained with other people I would probably have a very different default model that I use. I think it’s mostly my [educational] upbringing that makes it very difficult to think of anything else.*” (Researcher)

Experience gained by analysis method usage was specifically highlighted by several participants who remarked that their decision to adopt a technique was based upon the outcome of an initial trial period.

3.3.3. Accountability influences analysis approach

The analysis approach taken by a practitioner can be influenced by their need to assign liability for an accident. Some individuals remarked that they prefer or are mandated to avoid seeking blame in favour of focusing on safety improvements, as per the systems approach. However, other practitioners who are more concerned with the commercial and legal implications of accidents may seek to apportion blame:

“*The way the analysis was set up was really to assist with legal proceedings. That was the main driver. . . [it was] not always to find out what the root cause was. It would be more to do with whether a prosecution was likely to be successful or not.*” (Human factors expert)

This is particularly evident when those who are conducting an investigation may be deemed culpable and are incentivised to apportion liability elsewhere:

“*Because it’s the manager that carries out the industry’s own investigation they’re not really going to look at themselves and they’re certainly not going to look at their own management chain because that puts them in a threatening position.*” (Accident investigator)

In addition to the influence on SAA adoption, the need to demonstrate liability can also influence the use of an analysis technique. One health and safety professional, for example, referred to the occasions where he was instructed by clients to use their analysis tools in particular ways in order to avoid ‘black spots’ on their safety records.

3.3.4. Model validation

The extent of an analysis model’s empirical validation was considered by many practitioners to be a key influence on their adoption decision. Several participants commented on the need for extensive validation to demonstrate that a method has been ‘proven’ and can be ‘trusted’:

“*Has it been tried and tested? Does it add value? We have to ask these questions when we implement something.*” (Health and safety professional)

A number of individuals who provide consultancy services in accident investigation and risk analysis specifically commented on the importance of a method’s track record when attempting to establish the credibility of their work with clients. However, less consideration was given to the extent of a method’s conceptual validity:

“*Validity comes very much down the line. I think it’s very much about quickness and whether the technique is understood in the community, if I’m brutally honest.*” (Health and safety professional)

3.4. SAA usage

3.4.1. Usage resource constraints

The level of effort invested in an analysis will be based, at least in part, by the resources available to the investigation team:

“*There’s a 14 out of 15 chance that we’re not going to go to an investigation that we should do and that’s simply because of funding.*” (Accident investigator)

Consequently this can affect whether an individual employs more complex analysis techniques, such as those based on the systems approach:

“*[Name of method] is something that I’ve been trained in but I’d only use it if there had been a major incident, whereas the 5 Whys method (Ohno, 1988) is probably a starting point for a nice and simple easy one. I think the more complex the incident you’d pull in more of the techniques to give you the answer.*” (Health and safety professional)

In addition to whether an analysis method is used, the time and financial constraints involved in accident investigation can also affect how it is used. Several participants, for example, remarked that the depth of analysis they can achieve with their preferred technique is limited by the time available to them.

3.4.2. Model reliability

If a systemic analysis technique is adopted by a practitioner there are factors related to reliability which will affect its usage. A number of participants remarked on the influence that an individual's background and experience has on their analysis approach and how this can produce variation in investigation findings. Open discussions and analysis reviews which result in a consensus on the investigation findings can help minimise the biasing effects of individuals' backgrounds; a process which is common with full-time investigators:

"*The inspector will do a very structured presentation to a group of inspectors where we challenge what he's done, what he's said and what evidence he's got that's sufficient to make the conclusions that he's drawing together.*" (Accident investigator)

However, several participants commented on how the qualitative nature of the systemic analysis tools could increase the difficulty of reaching such an agreement:

"*If you turned up with an Accimap and said 'the system is safe because I've analysed it in an Accimap' you'd just get laughed out of the room. They'd pick it to pieces because it's far more subjective.*" (Human factors expert)

3.4.3. Data requirements of SAA

Several factors relating to the data requirements of SAA were considered by participants to impact on their ability to use the systemic analysis methods. For example, the system-wide data needed to perform SAA is not always available:

"*If I were to go and work in industry now I think I would have to revert back to more simple accident analysis methods just because the data wouldn't be there to support them [the SAA methods].*" (Researcher)

Some practitioners mentioned that the accident information databases they are required to use employ coding taxonomies which reflect the theoretical (cause-effect) underpinnings of sequential techniques. This may influence the type of data that is collected and one individual observed that, even if they gather data relevant to SAA, they must transpose their findings into a non-systemic format.

These issues appear to stem, in part, from the fact that researchers and practitioners have fundamentally different approaches to analysis and therefore different data requirements:

"*Sometimes I do feel there is an important division between how practitioners and some academics treat accident investigation. We're always looking at specifics and therefore evidence will some-times take us down a very specific path and we don't need to consider the wider aspects and vulnerabilities of the system.*" (Accident investigator)

3.5. Organisational influences on the research–practice gap

3.5.1. Organisational policy

Some individuals have the freedom to choose which analysis technique they adopt and use. However, in many cases, organisational policy dictates which methods are used:

"*We tend to find that when people come here [for investigation training] they want to know all about the models and how to use all of them but often they go back to an organisation that says 'this is what we use' so they don't really get the opportunity.*" (Researcher)

Practitioners who provide investigation services on a consultancy basis also commented that requests from some clients to use in-house analysis techniques can produce similar barriers to analysis tool usage. Organisational policy can also impact on the resources available for practitioners to learn and use new analysis methods and therefore create the issues described in Sections 3.2.3 and 3.4.1.

A link between safety culture and organisational policy was referred to by several individuals who observed that their analysis approaches were, in part, dictated by the senior management and the safety culture they instilled. A number of participants also commented that safety-related changes they recommended to senior management teams, such as introducing new accident investigation policies, sometimes needed to be presented in cost-benefit, rather than safety improvement, terms:

"*When I turned up at [company name] there was no health and safety. They didn't care about which safety regulation said they had to do risk assessments. What I had to do was sell them the cost-effectiveness [of safety]. When I put it into a dollar sign they understood it and then their attitude became 'this is good for the company and it prevents reputational damage as well.'*" (Health and safety professional)

3.6. Industry influences on the research–practice gap

3.6.1. Regulatory requirements

The degree of regulation within a given industry can have a large influence on what type of analysis techniques are used in accident investigation and risk assessments:

"*Regulators [in the nuclear industry] dictate exactly what methods need to be used and they're very slow to update their opinions on these things.*" (Human factors expert)

"*There is a degree of flexibility. No one is telling me that I have to use the Swiss Cheese model and that is it. This is an International Maritime Organisation resolution, don't forget, and is not mandatory.*" (Accident investigator)

The comments of many practitioners indicated that SAA-based regulation is not in place across industry in general. This may be due to a lack of SAA awareness at the regulatory level, rather than a decision to reject it:

"*The regulation probably doesn't recognise [the systems approach] or encourage it at the minute. I don't know about the military or anyone like that but certainly in the railway industry it doesn't seem to.*" (Health and safety professional)

3.6.2. Industry characteristics

In addition to the regulatory environment of an industry, the suitability of performing SAA within a given industry may depend on a range of domain characteristics, e.g. degree of operational complexity:

"*If you look at highly dynamic, very complex systems then the systems approach is more appropriate. If you're looking at things like the manufacturing industry, it's probably less appropriate, and things like the Bowtie method or something a bit more linear is probably more suitable.*" (Human factors expert)

"*If you are in a highly defined, highly automated environment requiring software reliability, for instance in medical systems, then it makes absolute sense to use the STAMP technique. It's an issue of horses for courses.*" (Health and safety professional)

3.6.3. Resistance to change

The effort and cost of implementing an innovation, such as SAA, within an organisation or throughout an industry by means of new regulations can create resistance to change. This inertia can increase with the level of regulation:

"*Once you get a nuclear power plant licensed you don't ever want to change it because you've spent so much money. So, by its very nature, a very heavily regulated industry cannot be innovative.*" (Health and safety professional)

"*I would say changing anything in healthcare at a national level is really, really difficult. It takes a long time and there's a lot of consultation involved. If we were going to change the way we work, there's huge numbers of people who have a stake in what we do.*" (Human factors expert)

4. Discussion

The topics presented in Section 3 describe a wide range of issues that can affect if, and how, research is applied by practitioners. When considering all of these factors together they can be viewed as providing a wider context in which the research practice-gap is played out. Whilst not an exhaustive list, it is believed that the range of themes included in Section 3 is comprehensive enough to provide an adequate representation of the gap. The findings are graphically summarised in Fig. 3, which is based on the evaluation framework derived from the work of Rohrbach et al. (1993) (see Section 2.5).

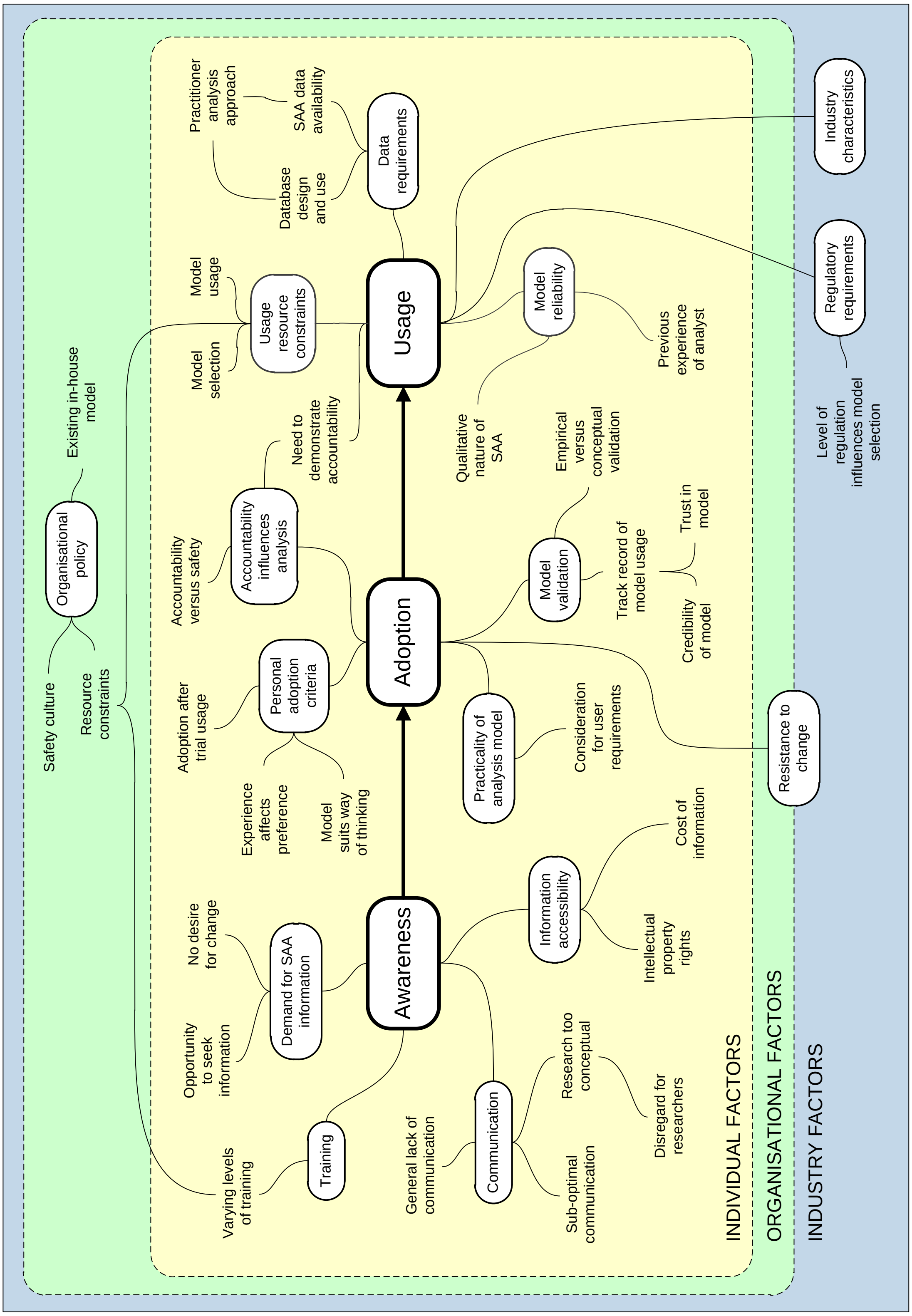

Figure 3 – The SAA research-practice gap

Discussion on the features of the gap and the implications for SAA is provided in the remainder of Section 4.

4.1. Issues associated with the research–practice gap

The majority of issues raised by participants may contribute, at least in part, to a general gap between accident analysis research and practice. Therefore, these factors could hinder the success of any new analysis method, regardless of its theoretical under-pinning. What then are the characteristic features of the SAA research–practice gap? This question is explored further within the context of SAA awareness, adoption and usage in the rest of Section 4.1.

4.1.1. SAA awareness

The opportunity to learn about new analysis techniques, e.g. via training (see Section 3.2.3), access to and the communication of the relevant information (see Sections 3.2.4 and 3.2.5) will affect a practitioner's awareness of any technique. However, it is worth commenting on how these issues relate to SAA. It is acknowledged within the literature that SAA requires extensive theoretical and domain knowledge, training and for-mal education (e.g. Hollnagel and Speziali, 2008; Johansson and Lindgren, 2008; Salmon et al., 2012a; Sklet, 2004).

It is therefore conceivable that practitioners will only be made aware of systemic analysis tools in the more in-depth training courses. In addition, it is the belief of the authors that the majority of SAA information is presented via the scientific literature and at conferences. SAA has been presented at conferences (e.g. Kazaras and Kirytopoulos, 2011; Underwood and Waterson, 2012), however, as conferences appear to be the third most popular source of information for practitioners (see Table 2), it is arguable that SAA is not being promoted in the most effective way.

The cost of training, scientific literature and conference proceedings can limit SAA awareness. However, information regarding SAA is freely available on the internet from sources such as Google Scholar, Nancy Leveson's MIT website (http://sunnyday.mit.edu/) and Erik Hollnagel's FRAM related website (http://www.functionalresonance.com/). This suggests that it is the issues surrounding SAA communication (see Section 3.2.5) that may be a more significant influence on awareness. Given that practitioners can lose interest in research that is too conceptual it is possible that the considerable amount of accident causation theory present in the systems approach literature may dissuade them from learning more about SAA.

4.1.2. SAA adoption

As with the awareness of SAA, there are several factors related to the adoption of an analysis technique which are influenced by features of the systems approach.

The importance of an analysis method's usability was reflected in the comments of practitioners (see Section 3.3.1). Whilst there is varying opinion within the literature with regard to the usability of the systemic analysis techniques their use has been viewed in some cases as time-consuming (e.g. Ferjencik, 2011; Johansson and Lindgren, 2008; Salmon et al., 2011). This issue can become increasingly problematic for individuals whose main responsibilities do not include the investigation of accidents, as they may have less time to conduct analyses. SAA may not be suited to and, therefore, adopted by them.

The notion that more effective safety recommendations can be devised by the avoidance of blaming a suitable culprit is well established in the SAA literature (e.g. Leveson, 2004) and was echoed in the comments of several participants (see Section 3.3.3). How-ever, searching for human error makes it easier to find out who is responsible for an accident and various practitioners emphasised that demonstrating accountability, particularly from a legal or commercial perspective, is still an objective of accident investigation (Reiman and Rollenhagen, 2011). Therefore, practitioners may be incentivised to use non-systemic analysis techniques to ease the identification of culpable personnel (Underwood and Waterson, 2012).

Most practitioners in safety-oriented businesses tend to prefer well established methods; a point which was raised by the participants (Johansson and Lindgren, 2008). Although STAMP, FRAM and Accimap have been applied across a variety of safety-critical domains this has mainly taken place within an academic context, e.g. accident analysis case studies (e.g. Salmon et al., 2012a). The comments of participants, therefore, suggest that SAA methods will require considerable empirical validation within an industrial set-ting if they are to gain acceptance from practitioners (see Section 3.3.4).

4.1.3. SAA usage

If a practitioner takes the decision to adopt a systemic analysis method they are faced with several issues which can hinder the application of SAA.

SAA is not a simple endeavour and requires significant analyst effort and access to various subject matter experts (Salmon et al., 2012b). SAA may, therefore, only be suited to major accident investigations where funding, time and personnel are sufficient to obtain the amount of information required for SAA. Indeed, both Leveson (2004) and Salmon et al. (2012b) suggest that the data requirements of STAMP and Accimap are only typically met via the comprehensive reports produced after a large scale accident.

Furthermore, individuals may not be able to gain access to the data required for SAA. For example, such information may exist outside of the organisation 'affected' by the accident (e.g. commercially sensitive documentation from an equipment supplier) or an individual may be in the 'wrong' position within an organisation to address the whole scope of an accident (e.g. unable to interview senior managers) (Dien et al., 2012). In addition to the varying levels of information access, the type of data that is collected can also influence the application of SAA. Accident data is reported, collected and compiled in databases over time in line with national regulations and established codification systems (Mullai, 2004; Mullai and Paulsson, 2011). However, in some cases these databases and coding schemes are not based around the systems approach (e.g. they just focus on local events at the 'sharp end' of a system) and the information required to populate them is, there-fore, unlikely to enable thorough SAA (Roelen et al., 2011; Salmon et al., 2012b).

4.1.4. Organisational and industry issues

A significant influence on a practitioner's selection of a model is the safety culture of their organisation. The comments of a number of participants (see Section 3.5.1) reflect the findings of Lundberg et al. (2012), who suggest that four aspects of safety culture can influence the decision to implement safety-related changes: institutionalised low safety standards, prioritisation of safety, the decision making criteria to adopt changes and the level of resources allocated to implement them. These factors clearly apply to the implementation of any new analysis method. However it is arguable that, in some cases, obtaining organisational (or regulatory) commitment to making a fundamental shift to employ SAA may be harder than implementing a modification of an existing sequential technique.

The comments from practitioners (see Section 3.6.2) indicate that, depending on the industry in question, the use of SAA may not always be appropriate. This notion is supported by Hollnagel and Speziali (2008) who suggest that systemic models are best suited to accidents within highly complex, intractable systems, e.g. nuclear power plants. Therefore, whilst the generic nature of the systemic models means that they can be applied in any domain, the notion that ‘one size does not fit all’ means that the resulting ‘competition’ from other analysis techniques represents a further barrier to SAA adoption (Mullai and Paulsson, 2011; Salmon et al., 2012a).

However, although new models often criticise or even disqualify older ones, in reality these different techniques can complement each other due to their own strengths and weaknesses (Jacobsson et al., 2009). This issue has been examined in studies which combined systemic and non-systemic techniques (e.g. Ferjencik, 2011; Kontogiannis and Malakis, 2012) and suggest that a more insightful analysis is achieved compared to that when using a single model. This indicates that aspects of SAA may be successfully utilised in many industries, regardless of their complexity.

4.2. Does the SAA research–practice gap need to be closed?

So far, this article has described and discussed a number of features that may prevent the use of SAA techniques by practitioners. An important question that naturally follows this discourse is ‘does the SAA research–practice gap need to be closed?’

The proposed benefits of SAA presented in Section 1, i.e. gaining an improved understanding of accidents which may lead to more effective recommendations, suggest that it should be. Research that has compared SAA methods with non-systemic analysis techniques indicates that these benefits can be achieved and, therefore, that SAA should be promoted throughout safety critical domains (see Section 1.1). Whilst sequential techniques may remain effective in certain circumstances, e.g. the analysis of less complex systems or of sub-systems/components, the ever-rising complexity of socio-technical systems suggests that the use of SAA will become increasingly important in the future (Hollnagel and Speziali, 2008; Salmon et al., 2011).

However, the difference between SAA and the current practices of some accident investigators seems to be a subtle one. The Swiss Cheese model (SCM), which has been widely adopted in various industries (e.g. healthcare and aviation) is described as a sequential technique by some researchers (e.g. Hollnagel, 2012; Leveson, 2011). However, it does provide a holistic multi-level analysis approach, as per SAA, and later versions of the model (see Reason, 1997) also take account of the fact that 'active failures' are not required for an accident to occur. Additionally, a number of organisations have purposely neutralised the language used in their SCM-based models to avoid attributing blame, such as the Australian Transport Safety Bureau and EUROCONTROL. Even within the research community, confusion exists over whether the SCM is a systemic technique, as exemplified by researchers who cite it (and methods based on it) as such (e.g. Salmon et al., 2012a; Stanton et al., 2012). Therefore, acknowledging the existence of a SAA research–practice gap seems to depend on which view of accident causation is taken by an individual.

Despite this ambiguity, what seems clear is that SAA methods are theoretically capable of providing useful insights into complex socio-technical system accidents which are not generated by many traditional analysis techniques. Therefore, efforts to increase practitioner awareness, adoption and usage of SAA should be made.

4.3. Bridging the SAA research–practice gap

Whilst one of the factors presented in Section 3 may be sufficient to prevent a practitioner from conducting SAA, it is more likely that they all, to a greater or lesser extent, combine to inhibit the application of the systems approach. So, if the SAA research–practice gap is to be closed, which of issues presented in Section 3 should be tackled? An initial step in answering this question can be made by considering the key themes contained in Table 1. The majority of these themes focus on two aspects: ensuring that the SAA methods meet the needs of the practitioners (themes 2–4, 8); communicating SAA research in a more effective manner (themes 5, 7, 9–12).

In order to meet the analysis needs of practitioners, it must be established if, and how, the systemic methods need to be adapted to meet the demands of live investigations and accident trend analysis. This process has begun and discussions between the two communities are taking place, e.g. the annual STAMP and FRAM workshops organised respectively by Nancy Leveson and Erik Hollnagel. However, to the authors' knowledge, practitioner feedback has yet to be widely publicised. Therefore, further efforts should be made to establish whether the SAA methods can be effectively applied in industry. Ideally, this work would involve recruiting accident investigators to use, evaluate and help refine the systemic techniques; a process that was also involved in successfully establishing other analysis methods, such as HFACS (Shappell and Wiegmann, 2000) and Tripod Delta (Hudson et al., 1994). As indicated by the data presented in Fig. 2, the evaluations should initially focus on the methods' usability, validity and the usefulness of their outputs. This process would bring the added advantage of providing a degree of empirical validation and help create the 'track record' desired by various elements of the practitioner community. Given that there may be reluctance to trial a new technique in live investigations, the use of high-fidelity simulated investigations would provide a suitable alternative. Research should also be conducted into developing industry-specific taxonomies for classifying contributing systemic factors to improve the reliability of the SAA methods and their suitability for multiple accident case analysis (Salmon et al., 2012a).

Achieving more effective communication of SAA research to practitioners can be accomplished via a number of routes. Table 2 suggests that, along with continued presentation of research at conferences, promoting SAA within the practitioner literature and professional institutes would increase the awareness of many practitioners. Steele and Pariès (2006) comment that successful communication of 'less traditional' perspectives on accident causality to practitioners target the layperson, convincingly summarise such ideas and make them seem like common sense. Information created for the practitioner-focused literature should be produced to meet these criteria. This may be particularly relevant for practitioners who only have a part-time involvement in accident investigation. Increasing the amount of SAA information provided in accident analysis training offers another important option for increasing awareness and adoption of systemic methods. Ideally this training would be conducted strategically to maximise its impact. As a starting point, the training should be provided to accident investigation trainers. This would utilise an existing net-work of professional trainers that can act as effective and efficient interface between the researcher and practitioner communities. Ideally, industry regulators and senior safety managers should also be trained in SAA. If the regulators and organisations formally adopt SAA then the need/requirement for individuals to employ systemic techniques in accident analysis will increase. However, until a SAA track record can be established in industry, it is unlikely that regulators and organisations will commit to formally adopt and use the systemic analysis techniques. Therefore, achieving this commitment is likely to be a long-term aim of bridging the research–practice gap.

4.4. Can the SAA research–practice gap be closed?

Whilst the proposed solutions described in Section 4.3 offer a means of bridging the research–practice gap, it may not be possible to completely close it. A number of researchers (e.g. Dekker, 2011; Stanton et al., 2012; Zio and Ferrario, 2013) are continuing to explore the nature of systemic accidents by considering the behaviour of ever-larger 'systems of systems'. For example, the drift into failure concept proposed by Dekker (2011) promotes looking 'up and out' at various factors which operate at a global level, such as sociological and political conditions, and how they affect system safety. Investigating and rectifying such issues is likely to remain beyond the scope of accident investigation, at least in the short term, due to a variety of issues such as resource constraints. There-fore, whilst is it is the role of the research community to further the understanding of systemic accidents, some of this knowledge may not be practicable to apply. However, efforts should still be made to bridge the research–practice gap so that SAA knowledge can be utilised when possible.

5. Study limitations

Given that this study utilised a non-representative convenience sample, as indicated in Section 3.1, a number of limitations were placed on the findings. For example, statistically testing the relative importance of themes identified by the participants or the differences observed across roles, industries and countries would not produce results that could be generalised. This means that the representation of the research–practice gap in Fig. 3 can only present the contributing factors, rather than their relative influence. However, the use of a convenience sample resulted from the resource constraints of the study rather than a lack of consideration of sample design. Given the number of people who are involved in accident analysis, achieving a representative sample from which results could be generalised would be a significant challenge. Despite the limitations imposed by the nature of the sample, the authors believe that the findings of this study offer some useful insights and direction for future work.

6. Conclusions

The systems approach is arguably the dominant concept within accident analysis research. Its application, via systemic accident analysis (SAA), supposedly provides an improved description of accident causation, avoids the incorrect apportioning of blame for an accident and helps inform more effective safety recommendations. However, despite the suggested benefits of SAA, evidence within the scientific literature indicates that systemic analysis models and methods are not being widely used in practice. This implies that a research–practice gap exists which impacts on the awareness, adoption and usage of SAA.

This study examined various issues stemming from both the research and practice communities which may hinder the application of SAA. Some of these factors are indicative of a general research–practice gap in accident analysis. However, others are more pertinent to SAA, such as its lack of track record within industry and the possible incentive to use non-systemic techniques to facilitate the attribution of liability. The benefits of SAA suggest that the research–practice gap should be closed. Efforts to bridge the gap should focus on ensuring that SAA methods meet the needs of practitioners and improving the communication of SAA research.

Appendix A

Interview questions

Background information

1. What is your age?
2. What is your current job title?
3. What are the main duties of your current role?
4. As a percentage, how much of your time is spent analysing accidents?
5. How many years of experience do you have of analysing accidents?
6. How many accidents have you analysed?
7. What types of accidents have you analysed?
8. Which industries did these accidents occur in?
9. When would you be called into perform an analysis/risk assessment?
10. In your opinion, what is the main reason why major accidents within the industry you work in?

    10.1 Why?

The systems approach

11. Have you heard of the systems approach?
12. What is your understanding of the systems approach to accident analysis?

    12.1 How did you gain this understanding?

13. Do you apply a systems approach to accident analysis?

    13.1 How do you apply it?

14. What do you think the benefits of using the systems approach are?

15. What are the drawbacks of using the systems approach?

The current approach

16. When you perform an analysis, what steps do you go through?

17. How much time is spent on analysing the data compared with its collection and report writing?

18. What method(s) do you currently use to analyse accidents?

19. What made you choose that specific method?

20. What are the benefits of the method?

21. What are the drawbacks of the method? 22.

What other methods did you consider?

23. Why is your current method better than the alternatives?

24. When selecting a method what consideration do you give to:

    24.1 Validity and reliability?

    24.2 Usability?

    24.3 How it helps you generate recommendations?

25. If I asked you to write a wish list of the features that your ideal analysis technique would possess, what would you write?

Research–practice gap

26. How do you keep up-to-date with new analysis theories and methods?

27. What sort of input would you value from the researcher/practitioner community?

28. What are the barriers which prevent the application of accident analysis research? 29. How do you think those barriers could be removed?

Appendix B

Analysis tool	I have never heard of it	I have heard of it but don't I know how it works	I understand how it works but I have never used it	I have used it before but do not use it currently	I currently use it
STAMP					
FRAM					
Accimap					
Swiss Cheese					
MORT					
Fault Tree Analysis					
Domino model					

STAMP: Systems-Theoretic Accident Model and Processes

FRAM: Functional Resonance Accident Model

MORT: Management Oversight and Risk Tree

References

Belmonte, F., Schoen, W., Heurley, L., Capel, R., 2011. Interdisciplinary safety analysis of complex socio-technological systems based on the functional resonance accident model: an application to railway traffic supervision. Reliability Engineering & System Safety 96 (2), 237–249.

Braun, V., Clarke, V., 2006. Using thematic analysis in psychology. Qualitative Research in Psychology 3 (2), 77–101.

Carhart, N., Yearworth, M., 2010. The use of system dynamics group model building for analysing event causality within the nuclear industry. In: Moon, T. (Ed.), 28th International Conference of the System Dynamics Society. 25–29 July 2010, The System Dynamics Society.

de Carvalho, P.V.R., 2011. The use of functional resonance analysis method (FRAM) in a mid-air collision to understand some characteristics of the air traffic management system resilience. Reliability Engineering & System Safety 96 (11), 1482–1498.

Dekker, S., 2011. Drift into Failure: From Hunting Broken Components to under-standing Complex Systems. Ashgate Publishing Company, Farnham.

Dien, Y., Dechy, N., Guillaume, E., 2012. Accident investigation: from searching direct causes to finding in-depth causes—problem of analysis or/and of analyst? Safety Science 50 (6), 1398–1407.

Energy Institute, 2008. Guidance on Investigating and Analysing Human and Orga-nisational Factors Aspects of Incidents and Accidents. Energy Institute, London.

Ferjencik, M., 2011. An integrated approach to the analysis of incident causes. Safety Science 49 (6), 886–905.

Greenhalgh, T., Robert, G., Macfarlane, F., Bate, P., Kyriakidou, O., 2004. Diffusion of innovations in service organizations: systematic review and recommendations. Milbank Quarterly 82 (4), 581–629.

Health and Safety Executive, 2004. Investigating Accidents and Incidents: A Work-book for Employers, Unions, Safety Representatives and Safety Professionals, 2nd edn. HSE Books, Sudbury.

Herrera, I.A., Woltjer, R., 2010. Comparing a multi-linear (STEP) and systemic (FRAM) method for accident analysis. Reliability Engineering & System Safety 95 (12), 1269–1275.

Hollnagel, E., 2012. FRAM—The Functional Resonance Analysis Method. Ashgate, Farnham. Hollnagel, E., 2004. Barriers and Accident Prevention. Ashgate Publishing Limited, Aldershot.

Hollnagel, E., Speziali, J., 2008. Study on developments in accident investigation methods: a survey of the state-of-the-art. SKI Report 2008:50. École des Mines de Paris, Sophia Antipolis, France.

Hudson, P.T.W., Reason, J.T., Wagenaar, W.A., Bentley, P.D., Primrose, M., Visser, J.P., 1994. Tripod delta: proactive approach to enhanced safety. Journal of Petroleum Technology 46 (1), 58–62.

Jacobsson, A., Sales, J., Mushtaq, F., 2009. A sequential method to identify underlying causes from industrial accidents reported to the MARS database. Journal of Loss Prevention in the Process Industries 22 (2), 197–203.

Jenkins, D.P., Salmon, P.M., Stanton, N.A., Walker, G.H., 2010. A systemic approach to accident analysis: a case study of the Stockwell shooting. Ergonomics 53 (1), 1–17.

Johansson, B., Lindgren, M., 2008. A quick and dirty evaluation of resilience enhancing properties in safety critical systems. In: Hollnagel, E., Pieri, F., Rigaud, E. (Eds.), Third Symposium on Resilience Engineering. 28–30 October 2008, École des mines de Paris.

Johnson, C., 2003. Failure in Safety Critical Systems: A Handbook of Incident and Accident Reporting. Glasgow University Press, Glasgow.

Johnson, C.W., de Almeida, I.M., 2008. An investigation into the loss of the Brazilian space programme's launch vehicle VLS-1 V03. Safety Science 46 (1), 38–53.

Katsakiori, P., Sakellaropoulos, G., Manatakis, E., 2009. Towards an evaluation of acci-dent investigation methods in terms of their alignment with accident causation models. Safety Science 47 (7), 1007–1015.

Kazaras, K., Kirytopoulos, K., 2011. Applying stamp in road tunnels hazard analysis. In: 6th IET International Conference on System Safety, 20–22 September 2011, IET, pp. 1–6.

Kontogiannis, T., Malakis, S., 2012. A systemic analysis of patterns of organizational breakdowns in accidents: a case from helicopter emergency medical service (HEMS) operations. Reliability Engineering & System Safety 99, 193–208.

Leveson, N., 2011. Engineering a Safer World: Systems Thinking Applied to Safety. The MIT Press, London.

Leveson, N., 2004. A new accident model for engineering safer systems. Safety Science 42 (4), 237–270.

Lindberg, A., Hansson, S.O., Rollenhagen, C., 2010. Learning from accidents—what more do we need to know? Safety Science 48 (6), 714–721.

Lundberg, J., Rollenhagen, C., Hollnagel, E., 2010. What you find is not always what you fix—how other aspects than causes of accidents decide recommendations for remedial actions. Accident Analysis & Prevention 42 (6), 2132–2139.

Lundberg, J., Rollenhagen, C., Hollnagel, E., Rankine, A., 2012. Strategies for deal-ing with resistance to recommendations from accident investigations. Accident Analysis and Prevention 45, 455–467.

Martinez, E., 2011. Investigation—a shared process. ISASI Forum: Air Safety through Investigation 44 (4), 7–11.

Mullai, A., 2004. A risk analysis framework for marine transport of packaged dangerous goods. In: Brindley, C. (Ed.), Supply Chain Risk. Ashgate Publishing Ltd., Aldershot, pp. 130–159.

Mullai, A., Paulsson, U., 2011. A grounded theory model for analysis of marine acci-dents. Accident Analysis & Prevention 43 (4), 1590–1603.

Ohno, T., 1988. Toyota Production System: Beyond Large-scale Production. Produc-tivity Inc., Portland.

Okstad, E., Jersin, E., Tinmannsvik, R.K., 2012. Accident investigation in the Nor-wegian petroleum industry—common features and future challenges. Safety Science 50 (6), 1408–1414.

Qureshi, Z.H., 2007. A review of accident modelling approaches for complex socio-technical systems. In: Cant, T. (Ed.), 12th Australian Workshop on Safety Related Programmable Systems. 2007, Australian Computer Society, pp. 47–59.

Rail Safety Standards Board, 2011. Investigation Guidance Part 3: Practical Support for Accident Investigators. Rail Safety and Standards Board, London.

Rasmussen, J., 1997. Risk management in a dynamic society: a modelling problem. Safety Science 27 (2-3), 183–213.

Reason, J., 1997. Managing the Risks of Organizational Accidents. Ashgate Publishing Ltd., Aldershot.

Reiman, T., Rollenhagen, C., 2011. Human and organizational biases affecting the management of safety. Reliability Engineering and System Safety 96, 1263–1274.

Robson, C., 2002. Real World Research: A Resource for Social Scientists and Practitioner–Researchers, 2nd edn. Blackwell Publishing, Oxford.

Roelen, A.L.C., Lin, P.H., Hale, A.R., 2011. Accident models and organisational factors in air transport: the need for multi-method models. Safety Science 49 (1), 5–10.

Rogers, E.M., 2003. Diffusion of Innovations, 5th edn. Free Press, New York.

Rohrbach, L.A., Graham, J.W., Hansen, W.B., 1993. Diffusion of a school-based substance abuse prevention program: predictors of program implementation. Preventive Medicine 22 (2), 237–260.

Salmon, P.M., Cornelissen, M., Trotter, M.J., 2012a. Systems-based accident analysis methods: a comparison of Accimap, HFACS, and STAMP. Safety Science 50 (4), 1158–1170.

Salmon, P.M., McClure, R., Stanton, N.A., 2012b. Road transport in drift? Applying contemporary systems thinking to road safety. Safety Science 50 (9), 1829–1838.

Salmon, P.M., Stanton, N.A., Lenné, M., Jenkins, D.P., Rafferty, L., Walker, G.H., 2011. Human Factors Methods and Accident Analysis: Practical Guidance and Case Study Applications. Ashgate Publishing Ltd., Farnham.

Shappell, S., Wiegmann, D., 2000. The Human Factors Analysis and Classification System—HFACS. DOT/FAA/AM-00/7. U.S. Department of Transportation, Federal Aviation Administration, Washington, DC.

Sklet, S., 2004. Comparison of some selected methods for accident investigation. Journal of Hazardous Materials 111, 29–37.

Stanton, N.A., Rafferty, L.A., Blane, A., 2012. Human factors analysis of accidents in systems of systems. Journal of Battlefield Technology 15 (2), 23–30.

Steele, K., Pariès, J., 2006. The process of tailoring models for a priori safety and risk management for use within industry. In: Hollnagel, E., Rigaud, E. (Eds.), Second Resilience Engineering Symposium. 8–10 November 2006, Mines Paris.

Underwood, P., Waterson, P., 2012. A critical review of the STAMP, FRAM and Accimap systemic accident analysis models. In: Stanton, N.A. (Ed.), Advances in Human Aspects of Road and Rail Transportation. CRC Press, Boca Raton, pp. 385–394.

Watson, H.A., 1961. Launch Control Safety Study. Section VII, vol. I. Bell Laboratories, Murray Hill.

Zio, E., Ferrario, E., 2013. A framework for the system-of-systems analysis of the risk for a safety-critical plant exposed to external events. Reliability Engineering & System Safety 114, 114–125.

Appendix 1.3

Underwood and Waterson (2013b)

Underwood, P. and Waterson, P., 2013b. Systems thinking, the Swiss Cheese Model and accident analysis: A comparative systemic analysis of the Grayrigg train derailment using the ATSB, AcciMap and STAMP models. *Accident Analysis & Prevention*. DOI: dx.doi.org/10.1016/j.aap.2013.07.027

Systems thinking, the Swiss Cheese Model and accident analysis: A comparative systemic analysis of the Grayrigg train derailment using the ATSB, AcciMap and STAMP models

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Keywords: Systems thinking, Accident analysis, Swiss Cheese Model, ATSB, AcciMap, STAMP

Abstract

The Swiss Cheese Model (SCM) is the most popular accident causation model and is widely used throughout various industries. A debate exists in the research literature over whether the SCM remains a viable tool for accident analysis. Critics of the model suggest that it provides a sequential, oversimplified view of accidents. Conversely, proponents suggest that it embodies the concepts of systems theory, as per the contemporary systemic analysis techniques. The aim of this paper was to consider whether the SCM can provide a systems thinking approach and remain a viable option for accident analysis. To achieve this, the train derailment at Grayrigg was analysed with an SCM-based model (the ATSB accident investigation model) and two systemic accident analysis methods (AcciMap and STAMP). The analysis outputs and usage of the techniques were compared. The findings of the study showed that each model applied the systems thinking approach. However, the ATSB model and AcciMap graphically presented their finding sin a more succinct manner, whereas STAMP more clearly embodied the concepts of systems theory. The study suggests that, whilst the selection of

an analysis method is subject to trade-offs that practitioners and researchers must make, the SCM remains a viable model for accident analysis.

1. Introduction

The systems thinking approach to understanding socio-technical system accidents is arguably the dominant paradigm within accident analysis research (e.g. Salmon et al., 2012; Stanton et al., 2012). It views accidents as the result of unexpected, uncontrolled relationships between a system's constituent parts with the requirement that systems are analysed as whole entities, rather than considering their parts in isolation (Underwood and Waterson, 2013).

Traditional cause–effect accident models suggest that complex systems accidents are caused by events such as catastrophic equipment failure or an unsafe human action. However, as system complexity has increased over time, many accidents (e.g. space shuttle Columbia; Comair flight 5191) have not simply resulted from such trigger events. Instead these accidents emerge as complex phenomena within the normal operational variability of a system (de Carvalho, 2011). Describing accidents in a sequential (cause–effect) fashion is, therefore, arguably inadequate. It can also lead to equipment or humans at the 'sharp end' of a system being incorrectly blamed for an accident. This represents a missed opportunity to learn important lessons about system safety and how to prevent accident recurrence.

The use of the systems thinking approach, via systemic accident analysis (SAA), attempts to avoid these limitations and it has been used as the conceptual foundation for various SAA methods and models, such as: AcciMap (Rasmussen, 1997); Functional Resonance Analysis Method (FRAM) (Hollnagel, 2004); Systems Theoretic Accident Modelling and Processes model (STAMP) (Leveson, 2004); systems dynamics simulation (e.g. Cooke, 2003);causal loop diagrams (e.g. Goh et al., 2010, 2012). A number of studies have compared SAA methods with established non-systemic analysis techniques, such as the Sequentially Timed Events Plotting method (e.g. Herrera and Woltjer, 2010) and Fault Tree Analysis (e.g. Belmonte et al., 2011). These studies and others like them (e.g. Ferjencik,

2011) suggest that the SAA techniques do indeed provide a deeper understanding of how dynamic, complex system behaviour contributes to accidents.

The academic debate on accident models is, however, a lengthy one with new models often criticising or even disqualifying older ones (Ghirxi, 2010; Jacobsson et al., 2009). A notable case in point can be found when considering the Swiss Cheese Model (SCM) (Reason, 1990, 1997).

1.1. SAA vs. the SCM

Undoubtedly the most popular accident causation model, the SCM has been widely adopted in various industries (e.g. aviation and healthcare) (Salmon et al., 2012). Classified by some (e.g. Hollnagel, 2004) as an ‘epidemiological’ model, the SCM suggests that longstanding organisational deficiencies can create the necessary conditions for a frontline ‘active failure’ to trigger an accident. The presence of these conditions and events in the system represent the inadequacy/absence of defensive barriers (e.g. physical protection, training and procedures) designed to prevent accidents. The defences within a system and their associated inadequacies are graphically represented by layers of and holes in Swiss cheese (see Fig. 1). When the ‘holes’ in a system’s defences align, an accident trajectory can pass through the defensive layers and result in a hazard causing harm to people, assets and the environment, as depicted in Fig. 1 (Reason, 2008, p.101).

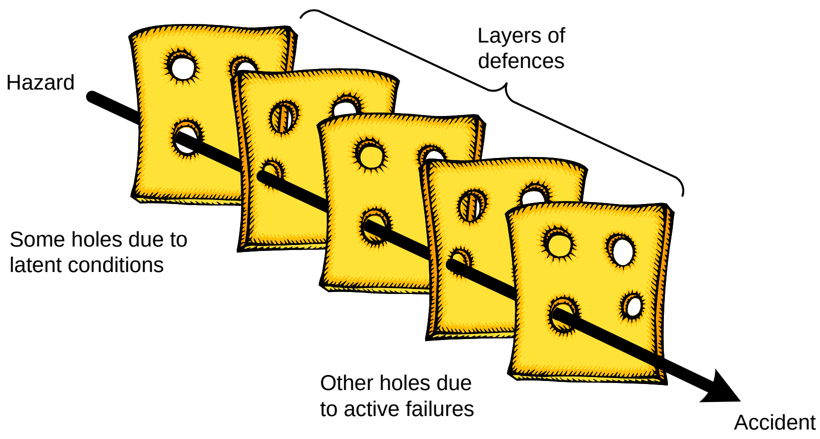

Figure 1 – Swiss Cheese Model (adapted from Reason (2008))

The SCM has drawn criticism from a number of researchers (e.g. Dekker, 2006, p.89; Hollnagel, 2012, p.14; Leveson, 2012, p.19) who describe it as a sequential technique which oversimplifies accident causation by not considering the complex interaction of system components. In addition, some authors (e.g. Dekker, 2006, p.89; Hickey, 2012, p.19) suggest that the sequential nature of accident causation is portrayed in the signature image of the SCM (see Fig. 1). The implication is that the SCM no longer provides an appropriate description of accident causation.

Other criticisms of the SCM focus on its application. For example, some researchers comment on the model's lack of specificity about a number of its features, e.g. how the holes in the layers of cheese line up and how this affects its ease of use (e.g. Le Coze, 2013; Wiegmann and Shappell, 2003). Furthermore, Shorrock et al. (2004) suggest that an overly prescriptive application of the SCM can lead to accidents being entirely (and incorrectly) attributed to senior management, i.e. overlooking the contribution of individuals at the frontline.

1.2. Performing SAA with the SCM?

The perceived drawbacks of the SCM (see Section 1.1) only represent one side of the academic debate, however. In contrast to the idea that the SCM is a sequential model, Reason et al. (2006, p.9) state that it describes accident causation as the ‘unlikely and often unforeseeable conjunction of several contributing factors arising from different levels of the system’. In other words, events and/or conditions happen together to produce an accident. As per SAA, the SCM provides a holistic multi-level analysis approach and later versions of the model also take account of the fact that ‘active failures’ are not required for an accident to occur (see Reason, 1997,p.17). Furthermore, the connection made by the SCM between normative serialisation (i.e. cause–effect) and the temporal orderliness of events that occurred is entirely unintended (Reason et al., 2006,p.16).

The SCM is underspecified but Reason et al. (2006, p.21) state that it was never intended to be a used as a detailed accident analysis model and that criticising it for a lack of specificity seems unjustified. Regardless, this issue has been resolved by the various methods which have been developed to operationalise its concepts such as HFACS (Wiegmann and Shappell, 2003) and Tripod-Delta (Hudson et al., 1994). Additionally, a number of organisations (e.g. the Australian Transport Safety Bureau (ATSB) and EUROCONTROL) have purposely neutralised the language used in their SCM-based models to avoid attributing blame, an important aspect of SAA.

Whist the development of accident models has been required to explain the increasing complexity of socio-technical systems, the introduction of a new model does not necessarily mean that existing ones become obsolete (Hollnagel and Speziali, 2008, p.37; Reason et al., 2006, p.21). Indeed, the SCM (and methods based on it) is still used by researchers to perform accident analysis (e.g. Szeremeta et al., 2013; Xue et al., 2013) with some suggesting that it offers a systemic view of accidents (e.g. Salmon et al., 2012; Stanton et al., 2012). However, if the critiques of the SCM are justified then the continued use of this (arguably outdated) model means accident investigations may not achieve the necessary understanding of major accidents to prevent recurrence. Given that the SCM is in widespread use throughout various industries and SAA methods are yet to be widely adopted by practitioners (see Underwood and Waterson, 2013), the outcome of this debate has clear ramifications with regards to improving safety. Therefore, it is important to understand whether or not the SCM can provide a systems thinking approach and remain a viable option for accident analysis.

1.3. Study objectives

The aim of this paper is to consider whether the SCM can provide a systems thinking approach to accident analysis. In order to achieve this aim, the paper has three main objectives:

1. Analyse a major accident (the train derailment at Grayrigg) using three techniques: an SCM-based model developed and used by practitioners (the ATSB investigation analysis model) and two SAA methods predominantly used by the research community (AcciMap and STAMP).

2. Compare the outputs and application processes of the models, via an evaluation framework, in order to examine their theoretical and usage characteristics.

3. Reflect on the similarities and differences between the models and the implications for applying the systems thinking approach in theory and practice.

The intention is to examine this issue within an applied context, rather than a purely conceptual one. By giving a practical example of how the SCM compares to SAA techniques, it is hoped that the paper will be able to demonstrate whether the SCM does apply the systems thinking approach or not. An overview of the three analysis tools, a description of the Grayrigg accident, details of the analysis processes and the model evaluation criteria used in the study are provided in Sections 2, 3, 4.1 and 4.2 respectively.

2. The analysis methods

2.1. ATSB investigation analysis model

The ATSB investigation analysis model (referred to hereafter as the ‘ATSB model’) is a modified version of the SCM. As per the SCM, the ATSB model provides a general framework that can be used to guide data collection and analysis activities during an investigation (ATSB, 2008, p.36). However, various alterations to the original SCM were made by the ATSB to improve its usability and the identification of potential safety issues. Such changes include an enhanced ability to combine technical issues into the overall analysis, the use of neutral language and emphasising the impact of preventative, as well as reactive, risk controls. To highlight the changes made, the ATSB (2008) presented a latter version of the SCM (see Fig. 2) and their adaptation of it (see Fig. 3).

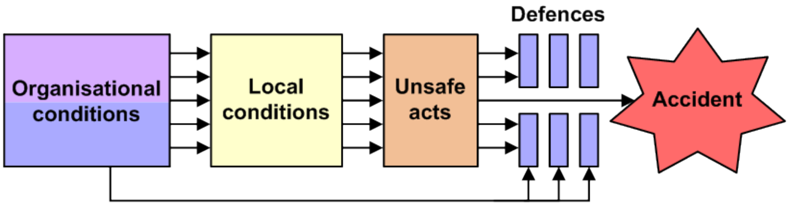

Figure 2 – Latter version of the SCM (adapted from ATSB (2008))

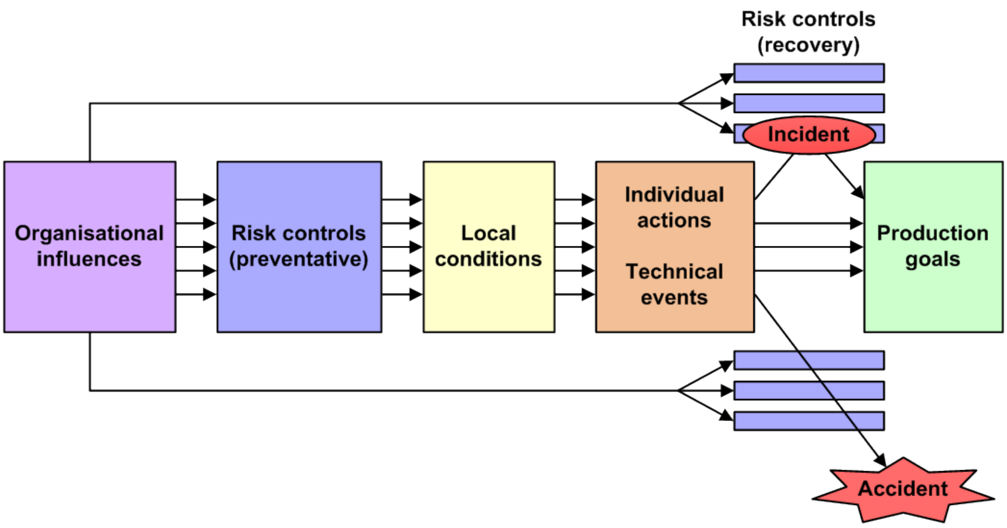

Figure 3 – ATSB adaptation of the SCM (adapted from ATSB (2008))

As indicated by Fig. 3, the ATSB model views organisations as goal seeking systems whose performance can become unsafe from the result of interacting events and conditions. In this situation, risk controls are required to prevent an accident from occurring or minimise the severity of its consequences (ATSB, 2008, p.36). These risk controls are akin to the layers of defences portrayed in Fig. 1.Whereas Fig. 3 highlights some of the changes that the ATSB made to the SCM, the official representation of the ATSB model which is used during investigations is presented in Fig. 4.

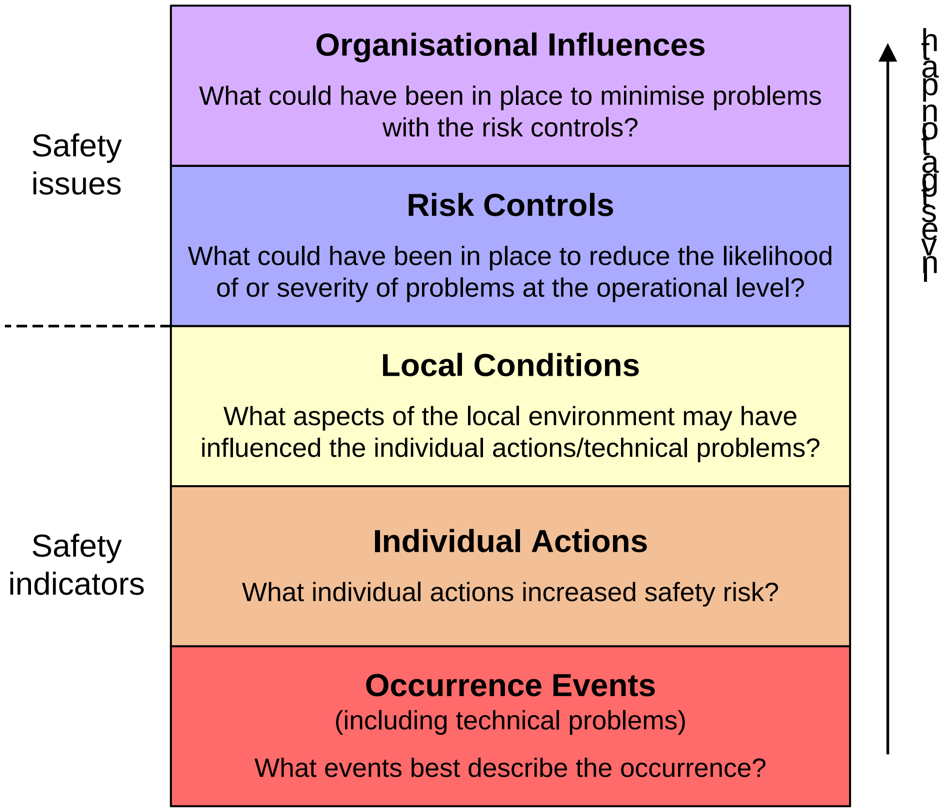

Figure 4 – The ATSB Investigation Analysis Model (adapted from ATSB (2008))

The model represents the operation of a system via five levels of 'safety factors', where a safety factor is an event or condition that increases safety risk (ATSB, 2008). The first three levels correspond to 'safety indicators', i.e. safety factors dealing with the individual or local aspects of an accident. The upper two levels address 'safety issues', i.e. safety factors associated with organisational or systemic issues.

The ATSB model was selected for use in this study for a number of reasons. Firstly, although modified, it is based on the SCM and therefore, according to various SAA researchers (see Section 1.1), can be classed as a sequential model. Secondly, the model has been used in transport accident investigations by the ATSB since 2002 (ATSB, 2008). As such, the model has been empirically validated by a governmental investigation agency, which is highly regarded within the accident investigation community (ATSB, 2008). Therefore, the ATSB model represents a 'tried and tested' analysis technique used by investigation experts. Furthermore, a publically available description of the model and its use is provided by the ATSB (2008), thereby enhancing the reliability of its usage in this study.

2.2. AcciMap

The AcciMap, developed by Rasmussen (1997) and Svedung and Rasmussen (2002) was designed to take a control theory-based systems thinking approach to accident analysis. Consequently, accidents are considered to result from the loss of control over potentially harmful physical processes. According to Rasmussen (1997), every organisational level in a system affects the control of these hazards and a vertically integrated view of system behaviour is required. The dynamic nature of socio-technical systems means that an accident is likely to be prepared over time by the normal efforts of many individuals throughout a system and that a normal variation in somebody's behaviour can 'release' an accident (Rasmussen, 1997). The AcciMap was developed as a means of analysing the series of interacting events and decision-making processes which occurred throughout a socio-technical system and resulted in a loss of control (Branford et al., 2009). To do so, it combines the classic cause-consequence chart and the Risk Management Framework (Rasmussen, 1997), which depicts the control of socio-technical systems over six organisational levels (see Fig. 5).

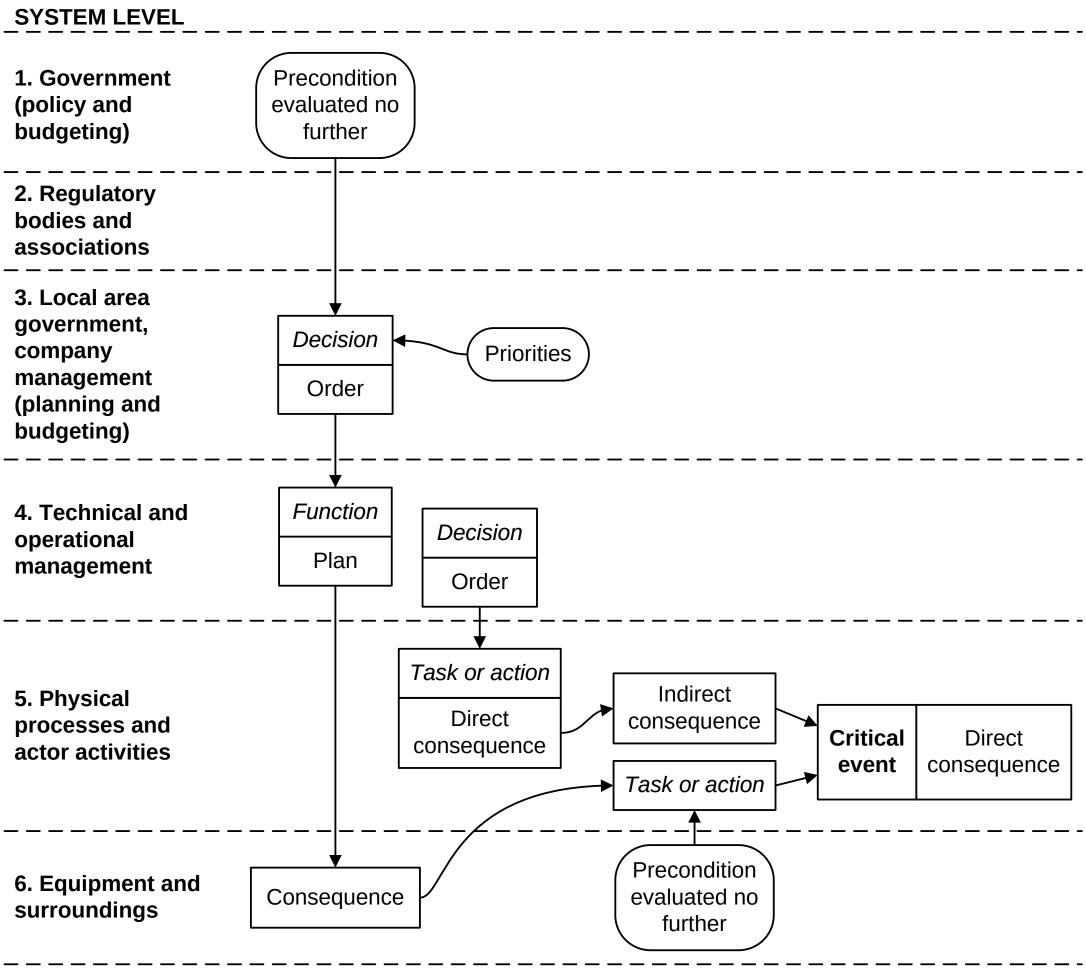

Figure 5 – AcciMap diagram format (adapted from Svedung and Rasmussen (2002))

Although the AcciMap forms part of a broader risk management process, it has been used independently of this approach to analyse individual accidents (e.g. Salmon et al., 2012; Stanton et al., 2012) (Branford et al., 2009). The method was selected for use in this study for this reason and because: it is one of the most popular SAA methods; it has been used previously to analyse rail accidents (e.g. Branford et al., 2009; Salmon et al., 2013); guidance material is available which would improve the reliability of the analysis (see Svedung and Rasmussen, 2002; Underwood and Waterson, 2012).

2.3. STAMP

The STAMP model, based on systems and control theory, focuses on safety as a control problem (as per the AcciMap approach). Emergent system properties (e.g. safety) are controlled by imposing constraints on the behaviour and interaction of system components (Leveson, 2012). Three basic constructs are used by STAMP to determine why control was ineffective and resulted in an accident: safety constraints, hierarchical safety control structures and process models.

Safety constraints can be passive, which maintain safety by their presence (e.g. a physical barrier), or active, which require some action to provide protection (i.e. detection, measurement, diagnosis or response to a hazard). Accidents occur only when system safety constraints are not enforced. Hierarchical safety control structures are used by STAMP to describe the composition of systems (see Fig. 6).

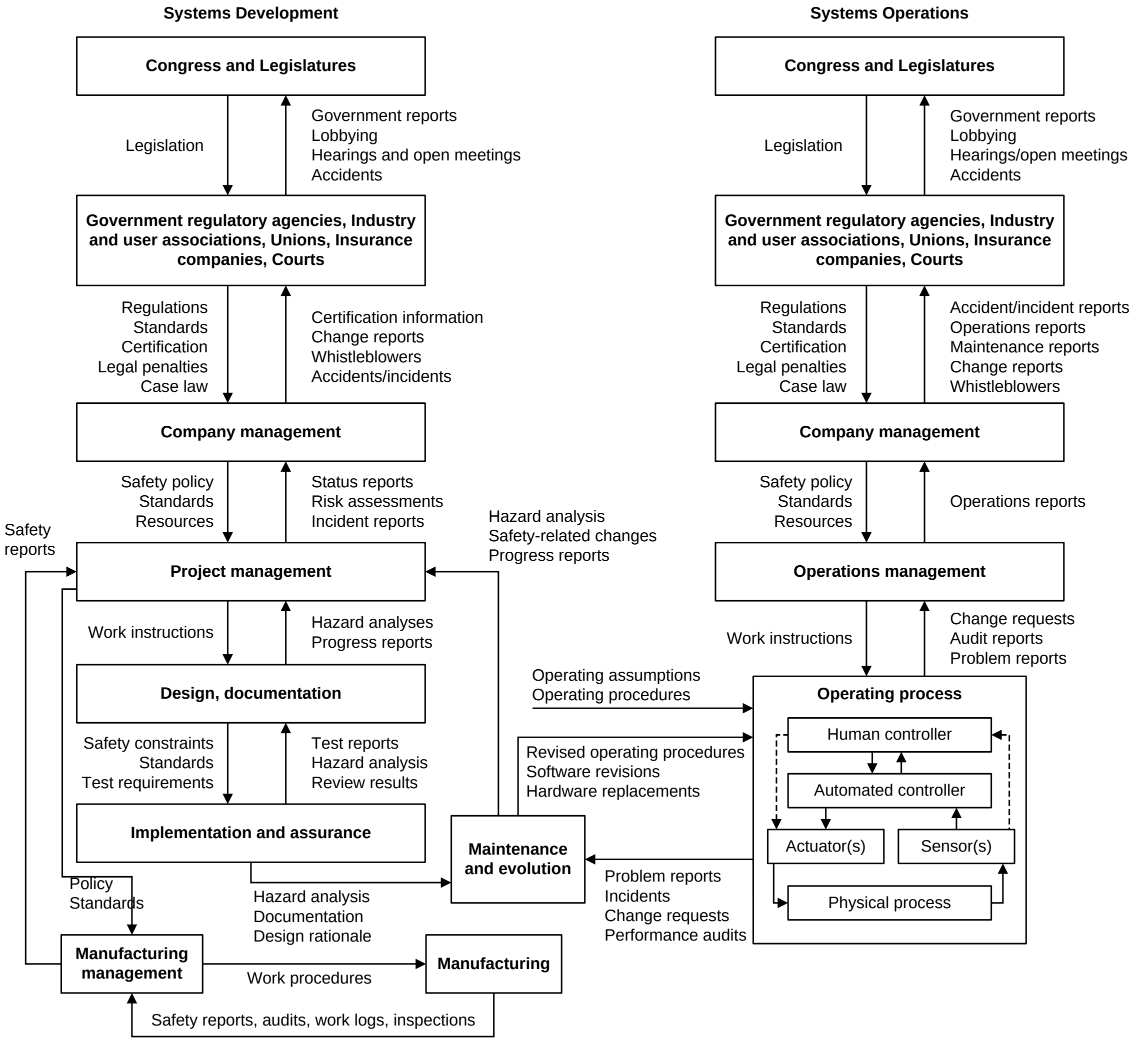

Figure 6 – General socio-technical system hierarchical safety control structure (adapted from Leveson (2011))

Each hierarchical level of a system imposes constraints on and controls the behaviour of the level beneath it. Control (two-way communication) processes operate between system levels to enforce the safety constraints. Process models are incorporated into STAMP as any human or automated controller requires a model of the process they are responsible for controlling, if they are to control it effectively (Leveson, 2012).The STAMP model was selected for comparison with the ATSB model and AcciMap for several reasons. It is the most frequently cited SAA model and has been used previously to analyse rail accidents and incidents (e.g. Ouyang et al., 2010; Song et al., 2012) (Underwood and Waterson, 2012). In addition, detailed guidance on the application of STAMP is provided by Leveson (2012) and, therefore, would enhance the reliability of the analysis.

3. The Grayrigg accident

3.1. Case study selection

The train derailment at Grayrigg was selected as the analysis case study for various reasons. Firstly, the event represented a major accident on the UK rail network; a complex system with many stakeholders, including infrastructure controllers, train and freight operating companies and maintenance contractor organisations. Therefore, it was appropriate to utilise systems thinking concepts to analyse the event. Furthermore, the rail industry in the UK is currently expanding and creating an increased usage demand on the network and continued pressure to reduce costs (Office of Rail Regulation, 2013). With these conditions, it is clear that safety research within this industry is an on-going requirement. This is evidenced by the current rail-based research within and outside of the UK (e.g. Dadashi et al., 2013; Read et al., 2013; Salmon et al., 2013; Wilson, 2013). The accident garnered significant media coverage and resulted in Network Rail (the organisation that manages the rail infrastructure in the UK) receiving the largest fine imposed since the Office of Rail Regulation was established. As such, the derailment represents one of the highest profile accidents in UK rail history. Finally, the event resulted in a full investigation by the Rail Accident

Investigation Branch (RAIB), the independent railway accident investigation organisation for the UK. The RAIB investigated a wide range of factors across various parts of the rail network system, e.g. the activities of frontline staff, management teams and regulatory inspectors. Therefore, the scope of the investigation and the comprehensiveness of the final report (RAIB, 2011) provided a suitable data source for a systemic analysis.

3.2. Description of the accident

On 23 February 2007 an express passenger train derailed as it entered the points (known as Lambrigg 2B points) located near Grayrigg in Cumbria, UK (RAIB, 2011). Points are an assembly of two movable (switch) rails and two fixed (stock) rails which are used to divert vehicles from one track to another (see Fig. 7). For a detailed description of points components and operation see RAIB (2011, p.210–214).

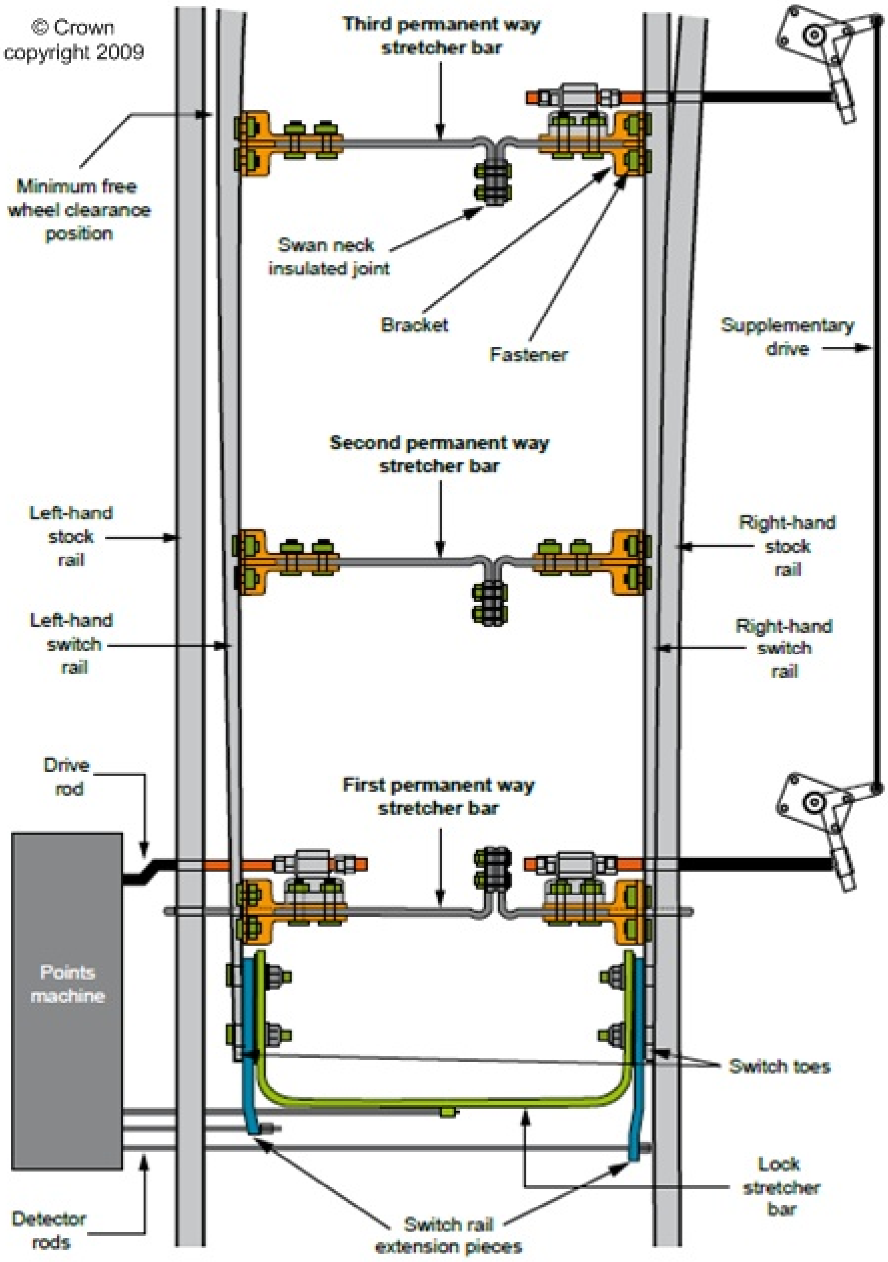

Figure 7 – Layout of points showing switch and stock rails and stretcher bars (from RAIB (2011))

All nine vehicles of the train derailed, eight of which subsequently fell down an embankment with five turning onto their sides (see Fig. 8). The train was carrying four crew and at least 105 passengers at the time of the accident. One passenger was fatally injured; 28 passengers, the train driver and one other crew member received serious injuries and 58 passengers received minor injuries (RAIB, 2011).

Figure 8 – Aerial view of the derailed train (numbers represent train vehicle number) (from RAIB (2011))

The subsequent investigation determined that the train derailed as it passed over 2B points, which were in an unsafe state that allowed the left-hand switch rail to move towards the left-hand stock rail. The left-hand wheels of the leading vehicle were subsequently forced into the reducing width between the switch rails and derailed by climbing over the rails. All the other vehicles derailed as a consequence. The RAIB concluded that various operational and environmental aspects (e.g. the actions of the driver, the condition of the train, the weather) had no bearing on the accident (RAIB, 2011, p.14). Therefore, the derailment was a maintenance related accident.

The unsafe state of the points was caused by successive failures of all three permanent way stretcher bar (PWSB) assemblies and the lock stretcher bar assembly. Three factors were deemed to have combined to create this situation: (1) the failure of the joint connecting the third PWSB to the right-hand switch rail which, together with (2) excessive residual switch opening (the gap between the rail heads of adjacent switch and stock rails on the closed side of points), caused the left-hand switch rail to be struck by passing train wheels. The resultant large cyclic forces caused rapid deterioration and the eventual failure of the remaining stretcher bars and their fasteners. (3) An inspection, scheduled for18 February 2007, which should have detected the degradation, was not performed.

The omitted inspection was due to be undertaken by the local track section manager (TSM), who had volunteered to perform a routine visual check of the track. The RAIB concluded that restricted track access (resulting from a change in access policies in 2005 and the reduced daylight hours in winter) and limited staff availability contributed to the decision of the TSM to combine his own supervisory inspection with a basic visual inspection. The TSM, however, forgot to complete the points inspection. This omission was not identified in the maintenance review meeting on the following day and the maintenance records were incorrectly updated to show that the inspection had been completed. These events, which reduced the likelihood of any corrective action being taken, were also considered by the RAIB to have contributed to the accident.

A number of ‘underlying’ factors (which the RAIB associates with the overall management systems, organisational arrangements or the regulatory structure) were considered to have influenced the derailment. Examples include: (1) an incomplete understanding within Network Rail of points maintenance requirements, which resulted in an absence of clear, properly briefed standard for maintaining loose PWSB fasteners and residual switch opening; (2) the performance measurement of points was not based on a thorough understanding of risk and control measures; (3) underestimating the risks associated with the design of points with non-adjustable stretcher bars (as per the points involved in the derailment), which adversely affected inspection regimes, reporting of faults and maintenance activity.

4. Methods

4.1. Accident analysis process

The ATSB model and STAMP analyses of the Grayrigg derailment was performed by the first researcher (Underwood), as per the processes described in Sections 4.1.1 and 4.1.3. The AcciMap analysis of the accident was performed by the second researcher (Waterson) in accordance with the process described in Section 4.1.2. Both individuals (human factors researchers) have experience of applying accident analysis methods in various domains (e.g. rail, aerospace, healthcare) and used the RAIB (2011) investigation report as the data source for the analysis activities. The report was imported into NVivo 9 and the text contained within the document, considered relevant to each analysis, was qualitatively coded (see Sections 4.1.1–4.1.3 for further details). This coded information was subsequently used to create the various analysis diagrams to ensure a direct link between the text in the report and the analysis outputs. Upon completion of the analyses, the researchers exchanged and reviewed the outputs and any discrepancies or disagreements were resolved through discussion until consensus was reached, as per the approach taken by Salmon et al. (2012). As the researchers were familiar with all three methods and their application processes prior to commencing the study, it was judged that the cross-checking process was sufficiently robust. Only pre-derailment events were analysed due to study resource limitations.

4.1.1. ATSB model analysis process

The guidance provided by the ATSB (2008) on the use of the ATSB model refers to its application within live investigations. Therefore, no specific guidance was available with regards to its use for the analysis of completed investigations. The analysis process consisted of applying the ATSB safety factor definitions, as a coding framework, to the information in the RAIB (2011) report (see ATSB, 2008, p.38–42). When a given piece of information was identified as a safety factor the text was coded with NVivo 9 and subsequently captioned, colour-coded and mapped on to the relevant section of an analysis chart, as per the format used by the ATSB (see ATSB, 2008, p.46). Relationships between the safety factors were represented by arrows to indicate the direction of influence, as per the ATSB (2008) approach.

4.1.2. AcciMap analysis process

AcciMap analyses have been conducted in various formats since the method’s creation. This prompted Branford et al. (2009) to develop a standardised application process for the method, aimed at improving the consistency of its usage. However, it was judged that this process was too far removed from the original format introduced by Rasmussen (1997), which has been used in more contemporary research (e.g. Stanton et al., 2012; Salmon et al., 2013).Therefore the guidance offered by Svedung and Rasmussen (2002)was selected for use in this study. Information within the investigation report was coded with NVivo if it described: (1) the topography of the accident scene; (2) a decision/action taken by an actor in the system; (3) a direct/indirect consequence; (4) a precondition requiring no further evaluation. This information was subsequently captioned, mapped on to the relevant sections of an AcciMap diagram and linked by arrows to represent the influence a given factor had on another, as per the format in Fig. 5.

4.1.3. STAMP analysis process

The process of applying STAMP to analyse an accident consists of nine stages and is defined by Leveson (2012, p.349) as the CAST (Causal Analysis based on STAMP) approach. The stages of CAST are summarised below:

1. Identify the system(s) and hazard(s) involved in the loss.

2. Identify the system safety constraints and system requirements associated with the hazard.

3. Document the control structure in place to control the hazard and enforce the safety constraints.

4. Determine the proximal events leading to the loss.

5. Analyse the loss at the physical system level.

6. Analyse the higher levels of the control structure.

7. Examine the overall coordination and communication contributors to the loss.

8. Determine the dynamics and changes to the system and its control structure over time.

9. Generate recommendations.

The first eight steps of the CAST process were completed in order, although this was not a necessity, as noted by Leveson (2012, p.350). The final stage, i.e. generating recommendations, was not performed as this was outside the scope of the study. The information required for each stage of CAST was used as a coding framework to facilitate the identification of relevant data within the RAIB (2011) report. For example, once a higher-system level component had been identified, text was coded if it described the component's: safety-related responsibilities; unsafe decisions and control actions; the reasons for the unsafe decisions/actions; relevant contextual information (as per stage 6 of the CAST process).

4.2. Analysis model evaluation

The analysis techniques were evaluated against two topics of interest: (1) coverage of systems theory concepts and (2) usage characteristics. When considering whether a model actually applies systems thinking, it is necessary to operationalise the key concepts of systems theory (Read et al., 2013). Furthermore, using analysis techniques underpinned by systems theory does not necessarily mean that the systems thinking approach can be applied successfully, i.e. other characteristics of the methods which affect their usage must be considered. These systems theory concepts and usage characteristics are described in Sections 4.2.1 and 4.2.2 and are graphically summarised in Fig. 9.

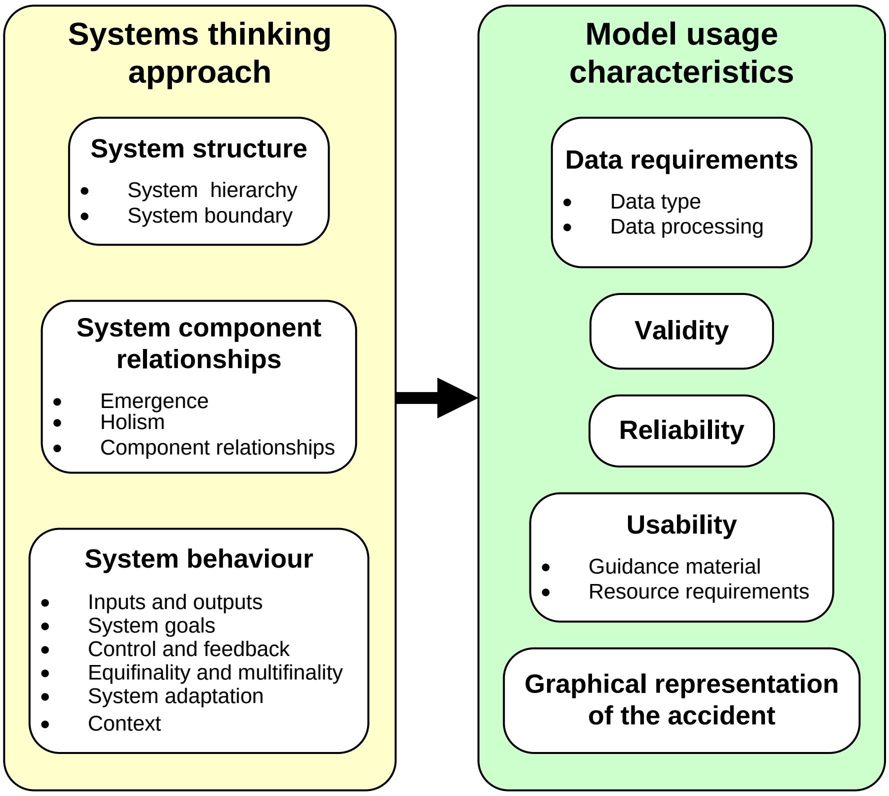

Figure 9 – Evaluation framework

This diagram represents the evaluation framework used to assess the outputs and usage of the models.

The outputs and usage of the models were assessed by both analysts in relation to the components of the evaluation framework in order to facilitate a systematic comparison. As per the accident analysis, any disagreements in the evaluations were resolved through discussion until consensus was reached.

4.2.1. The components of system thinking within accident analysis

Systems thinking has been advocated in accident analysis research at least since the 1980s (e.g. Leplat, 1984). Defining the core components of the systems thinking approach, however, is difficult task as there appears to be no firm agreement amongst researchers (Waterson, 2009). Nevertheless, some broad interrelated themes can be identified within the literature.

4.2.1.1. System structure

Systems are generally based on a hierarchy of subsystems which are formed in order to perform specific functions (Skyttner, 2005). In order to understand a system, it is necessary to examine each relevant hierarchical level and its relationship with adjacent levels. Moving up the hierarchy provides a deeper understanding of a system’s goals, whereas examining lower levels reveals how a system functions to meet those objectives (Vicente, 1999). Furthermore, determining the boundary of a system, i.e. distinguishing between what is part of the system and what is part of the environment, is an important aspect of specifying its hierarchy (Jönsson, 2007, p.41).

4.2.1.2. System component relationships

The interaction of system components results in emergent behaviour, e.g. safety (Leveson, 2012). Therefore, socio-technical systems will display characteristics and operate in ways not expected or planned for by their designers (Wilson, 2013). Such behaviour cannot be explained by studying system components in isolation: the whole is greater than the sum of its parts. A system must be studied holistically, i.e. all components, human and technical, need to be considered as well as the relationships between them (Read et al., 2013).

4.2.1.3. System behaviour

Inputs are converted into outputs, via transformation processes, in order to achieve system goals, e.g. safe operations. System components must be controlled via feedback mechanisms when deviations in behaviour occur if system goals are to be reached and safety maintained (Skyttner, 2005). Dynamic system behaviour means that a goal can be achieved from a variety of initial starting conditions (equifinality). Alternatively, systems can produce a range of outputs from an initial starting point (multifinality). This dynamic behaviour also means that systems can adapt over time to changing conditions and may migrate towards a state of increased risk and drift into failure (Dekker, 2011; Leveson, 2011). Furthermore, system components do not operate in a vacuum and their performance must be placed within context, i.e. how local goals, resources and environmental conditions influenced their behaviour.

4.2.2. Model usage characteristics

Establishing whether a given analysis technique is theoretically underpinned by systems thinking concepts is only one factor that will determine if an individual can effectively perform SAA. A number of researchers have identified a range of other issues which can hinder the usage of analysis methods (e.g. Benner, 1985; Stanton et al., 2012; Underwood and Waterson, 2013).

4.2.2.1. Data requirements

The output of any analysis is defined, in part, by the ability of a method to analyse and incorporate a given piece of evidence (e.g. photographic, documentary, witness testimony, etc.). Furthermore, the information that a method requires to produce a thorough analysis (e.g. data related to technical failures, human factors, organisational practices, etc.) can impact on the evidence collection process in an investigation. The importance of how a method processes information and its data requirements has been recognised in previous method evaluation studies (e.g. Herrera and Woltjer, 2010; Stanton et al., 2012; Waterson and Jenkins, 2010).

4.2.2.2. Validity and reliability

The closely related issues of validity and reliability are important factors in successfully applying any type of analysis method. Previous studies have acknowledged this significance by including validity and reliability (and topics related to them) as method evaluation criteria (e.g. Benner, 1985; Stanton et al., 2012; Wagenaar and van der Schrier, 1997). The need for valid and reliable methods was also identified as a requirement of practitioners, who are engaged in accident analysis, by Underwood and Waterson (2013).

4.2.2.3. Usability

The usability of an SAA technique will clearly affect whether an analysis is performed effectively and efficiently and, therefore, it must be easy to understand and apply. The availability and clarity of guidance material as well as the training and resources required to use SAA methods have all been cited as factors which can influence their usability (e.g. Branford et al., 2009; Johansson and Lindgren, 2008; Stanton et al., 2012).

4.2.2.4. Graphical representation of the accident

The graphical output of a method also affects the ability of an individual (or team of investigators) to successfully perform an analysis. Graphically representing an accident has been considered to be useful by both researchers (e.g. Sklet, 2004; Svedung and Rasmussen, 2002) and practitioners (e.g. ATSB, 2008) for a number of reasons. For example, it can be easier to see the relationships between system components and identify gaps/weaknesses in the analysis. Charting an accident can also be useful for communicating the findings of complex investigations (ATSB, 2008).

5. Findings

5.1. Applying the analysis models to the Grayrigg accident

5.1.1. ATSB model analysis output

The analysis chart produced by the ATSB model analysis is presented in Fig. 10.

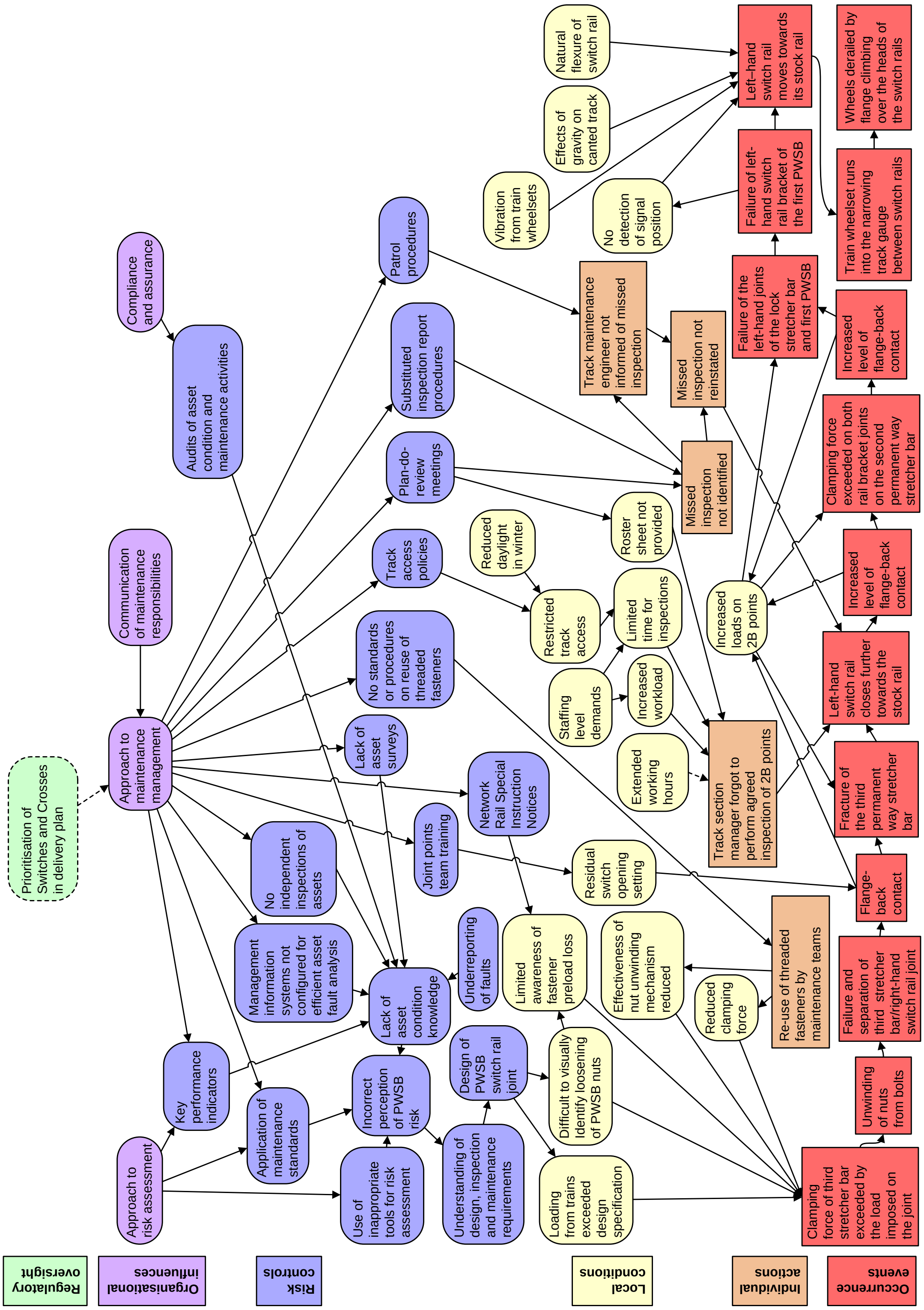

Figure 10 – Chart of the safety factors associated with the Grayrigg accident (dashed lines indicate a possible but not probable factor/relationship)

The derailment of the wheels of the leading vehicle was the single occurrence event attributed to the accident. However, various technical issues were included in the analysis chart to represent the gradual deterioration and failure of the points which led to the derailment. These technical problems were also incorporated to more clearly describe the multiple interactions between them and the individual actions and local conditions associated with the accident. The chart shows that there were few, albeit important, individual actions/inactions that contributed to the accident, such as the missed inspection of the points by the TSM. Conversely, a larger number of local conditions and inadequate risk controls were identified as factors which negatively affected the work of the maintenance staff and condition of the points. However, as showman Fig. 10, some of the local conditions resulted from technical problems and individual actions.

Few organisational influences were classified during the analysis. However, these factors were shown to have a wide ranging adverse influence on numerous risk controls. In particular, Network Rail's approach to maintenance management was identified as a significant influence on the ineffectiveness of many risk controls. The analysis chart shows six levels of safety factors to account for the role that regulatory oversight played in the accident. Although this sixth 'regulatory' level goes beyond the official format of the ATSB model (see Fig. 4), charting the influence of the regulators has occurred in previous ATSB investigations (ATSB, 2008, p.46). Therefore, given that the RAIB investigated the actions of the regulator, it was deemed acceptable to incorporate the additional safety factor level. However, as indicated on the analysis chart, the actions of the regulator were not considered to have a significant impact on Network Rail's maintenance management.

5.1.2. AcciMap analysis output

The AcciMap diagram resulting from the analysis is presented in Fig. 11.

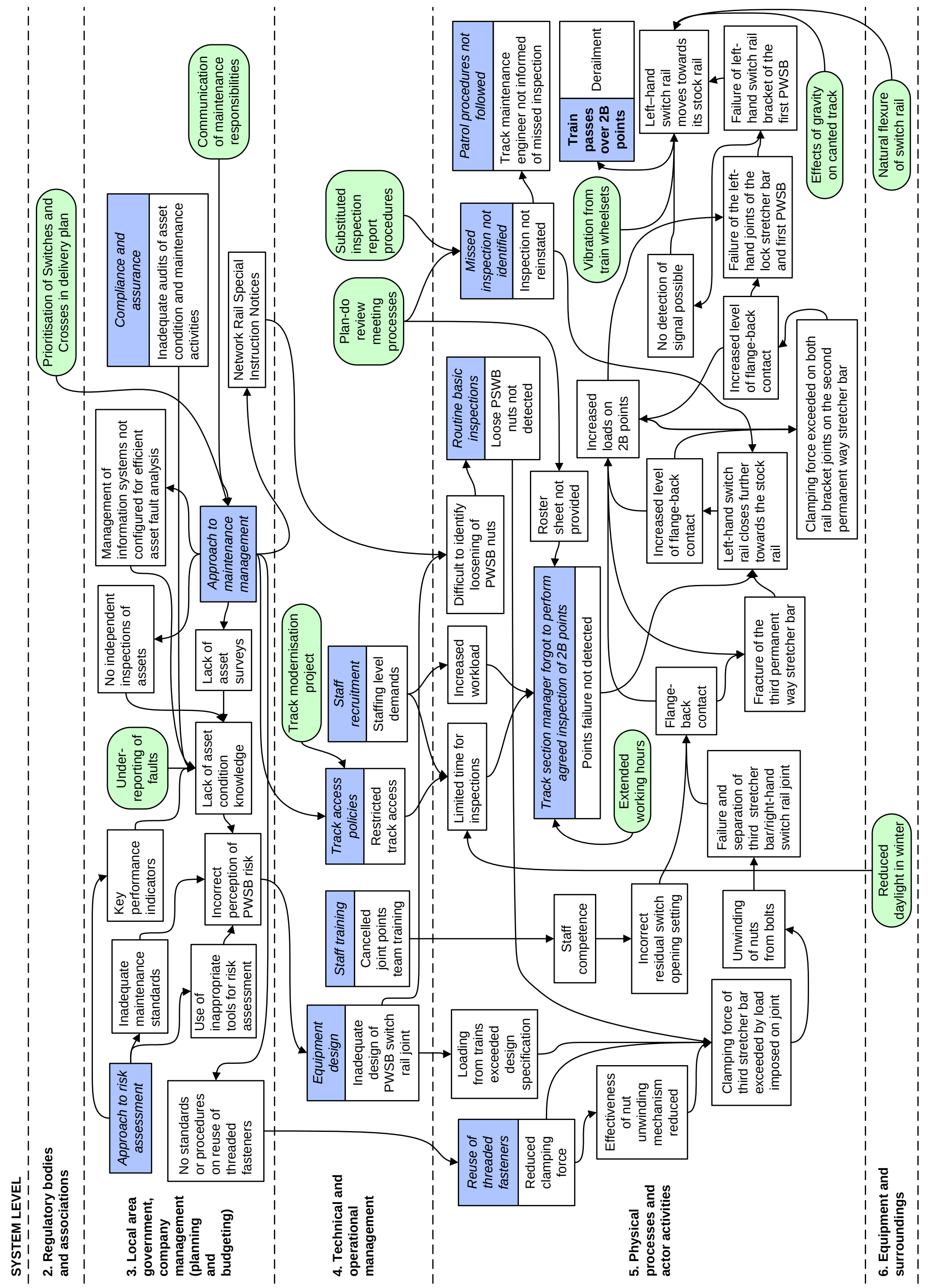

Figure 11 – AcciMap diagram of the Grayrigg accident

Similarly to the ATSB model analysis, the train passing over the failed 2B points and derailing were considered to be the critical event and its direct consequence respectively. Only two ‘equipment and surroundings’ related issues were identified during the analysis. However, they both influenced two key factors in the accident, i.e. the missed inspection by the TSM and the movement of left-hand switch rail, which contributed to the points being impassable. Five human actor activities were included in Level 5 of the AcciMap diagram and focused on two important activities: (1) the reuse of threaded fasteners and (2) the undetected physical faults. These actor activities either directly or indirectly contributed to the physical processes associated with the points' degradation. For example, the reuse of threaded fasteners directly contributed to the inability of the points to withstand the physical loads from rail traffic. Furthermore, the missed TSM inspection indirectly contributed to the failure of the points, as an opportunity to identify the required maintenance was missed. A relatively higher number of physical processes, in comparison with actor activities, were incorporated into the analysis diagram to describe the gradual deterioration and failure of the points. A number of influential decisions taken at Level 4 of the system, i.e. technical and operational management, were identified. These decisions had direct consequences which subsequently affected the physical processes and actor activities linked with the derailment, e.g. local track access policies restricted the time available to conduct inspections. Conversely, the risk assessment and maintenance management decisions attributed to the higher-level company management influenced numerous direct and indirect consequences. These consequences, in turn, either directly or indirectly influenced activities at the lower system levels, as shown on the analysis chart. The AcciMap diagram did not include Level 1 of the system, i.e. national government, as no information was available in the report to populate this section of the chart. Adapted from RAIB (2011, p.123–124).

5.1.3. STAMP analysis output

The first stage of the STAMP analysis, as described in Section 4.1.3, required the identification of the system and hazard involved in the accident. These were defined as the 'UK railway' and 'train derailment due to failed points' respectively. Two system safety constraints were subsequently associated with controlling the hazard: (1) the physical points components must operate within design limits; (2) maintenance and repair activities must correct any points defects. The hierarchical control structure, as it existed at the time of the accident, consisted of multiple organisational functions which had a responsibility for ensuring safety on the railway (see Fig. 12).

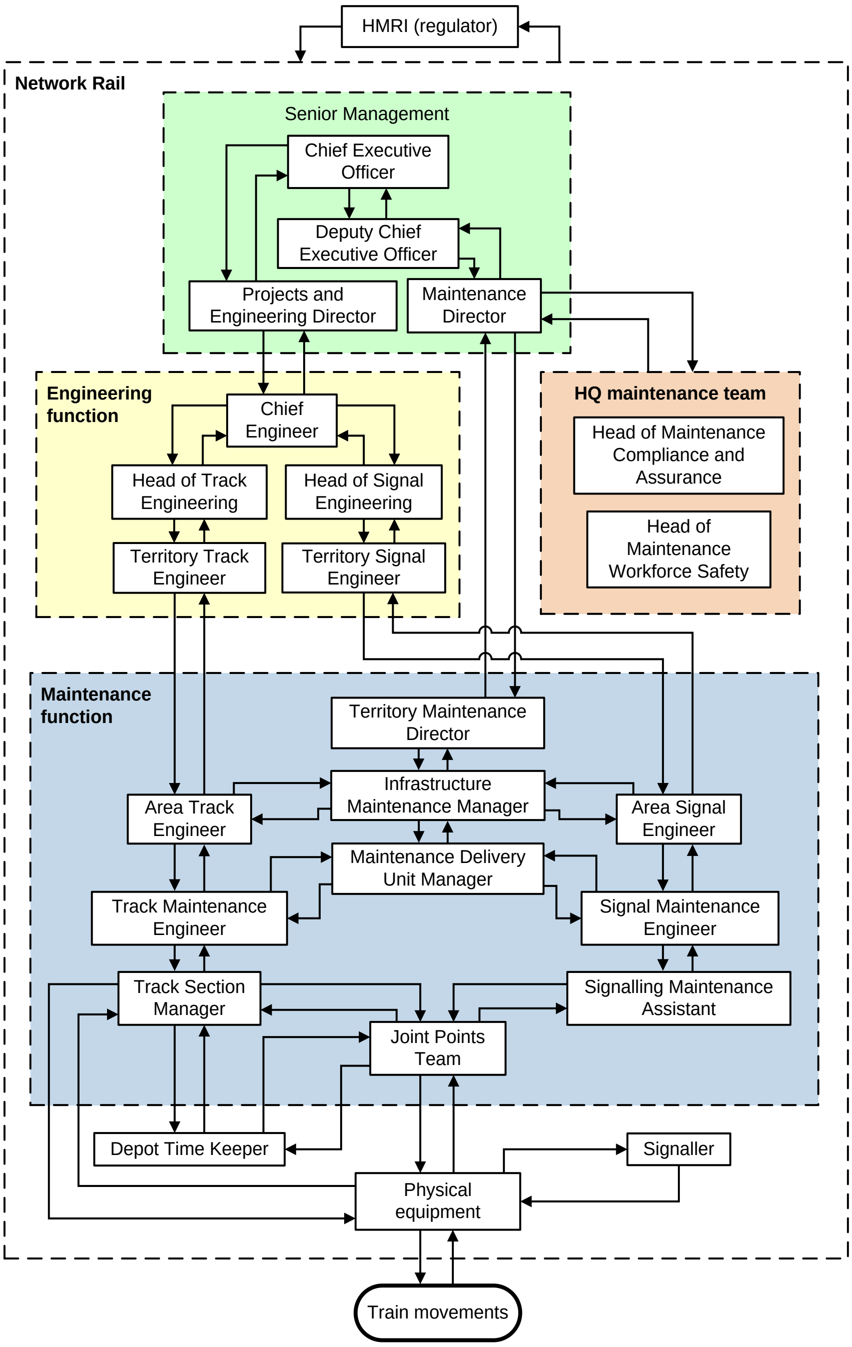

Figure 12 – The control structure in place at the time of the Grayrigg accident

Defining the control structure involves describing the roles and responsibilities of each component in the system, as well as the controls and feedback available to them. However, for the sake of clarity and because some of this information was not available in the RAIB (2011) report, this description has not been included in Fig. 12. The proximate events leading up to the accident are described, in terms of the condition of the points and the maintenance activities, in Table 1.

Date	Event
1st December 2006	Supervisor's inspection identified loose check rail bolts on crossing of 2B points
6th-7th January 2007	Overnight repair of defects identified on 1st December 2006
7th January 2007	Basic visual inspection identifies third PWSB right-hand bracket joint fasteners had failed and were renewed
8th January - 12th February 2007	Third PWSB right-hand bracket failed again, third PWSB subsequently fractures
14th January 2007	Routine patrol reported no defects
21st January 2007	Routine patrol reported no defects
25th January 2007	Supervisor's inspection identified alignment defects with rectification required within six months
28th January 2007	Routine basic visual inspection reported no defects
4th February 2007	Routine basic visual inspection reported no defects
11th February 2007	Routine basic visual inspection reported no defects
11th-21st February 2007	Second PWSB joints failed and PWSB missing from points
18th February 2007	Missed basic visual inspection
21st-23rd February 2007	First PWSB and lock stretcher bar failed
23rd February 2007	Derailment

Table 1 – The proximal events leading to the Grayrigg accident (adapted from RAIB (2011 p. 123 -124)) (PWSB = permanent way stretcher bar)

These events, e.g. the missed inspection on 18 February 2007, acted as reference points to begin the analysis of the derailment at the physical system level and the lower levels of the control structure. The subsequent analysis of the system components, considered to have had the most influence on the accident, is presented in Figs. 13 and 14.

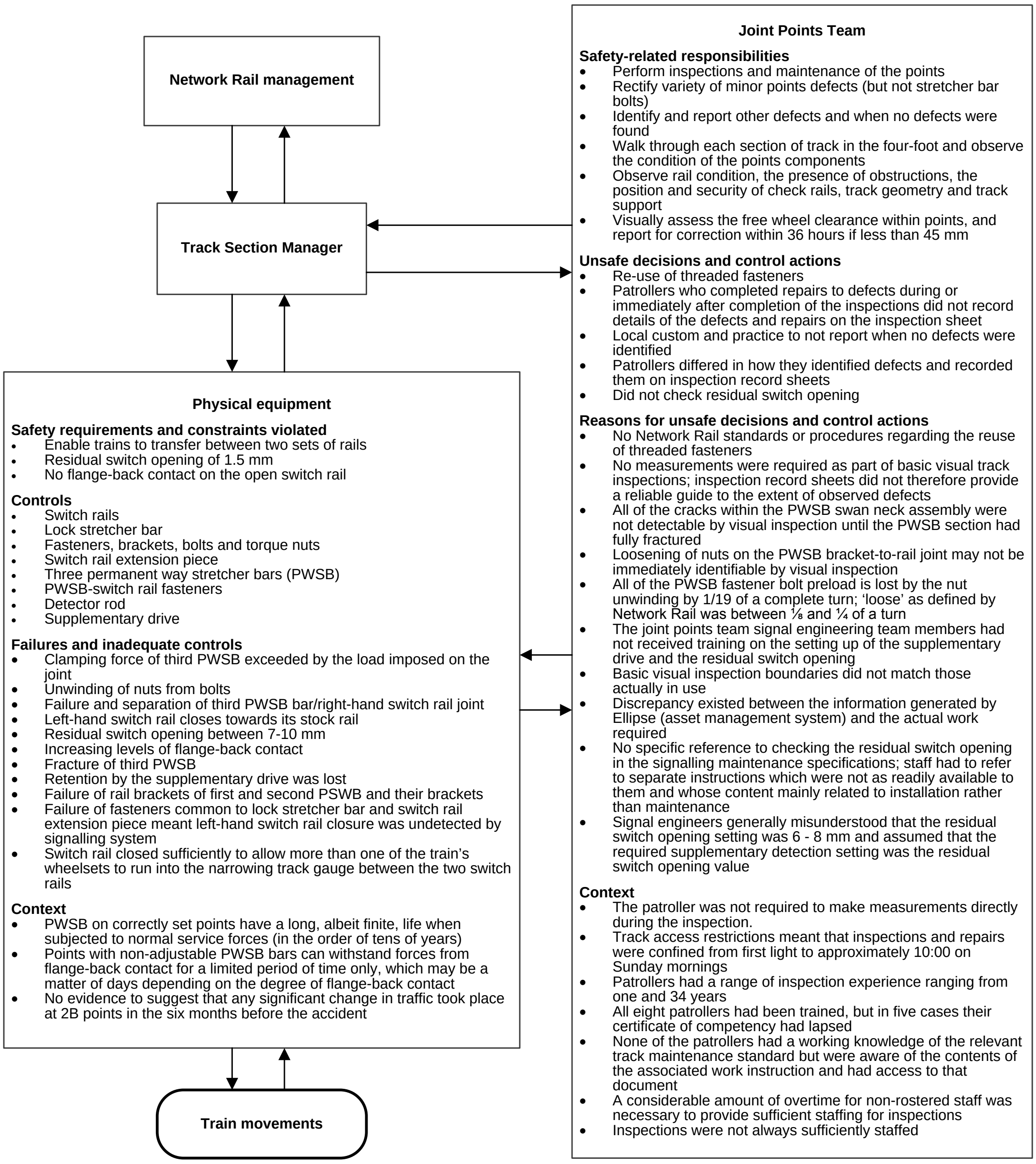

Figure 13 – STAMP analysis of lower-level system components

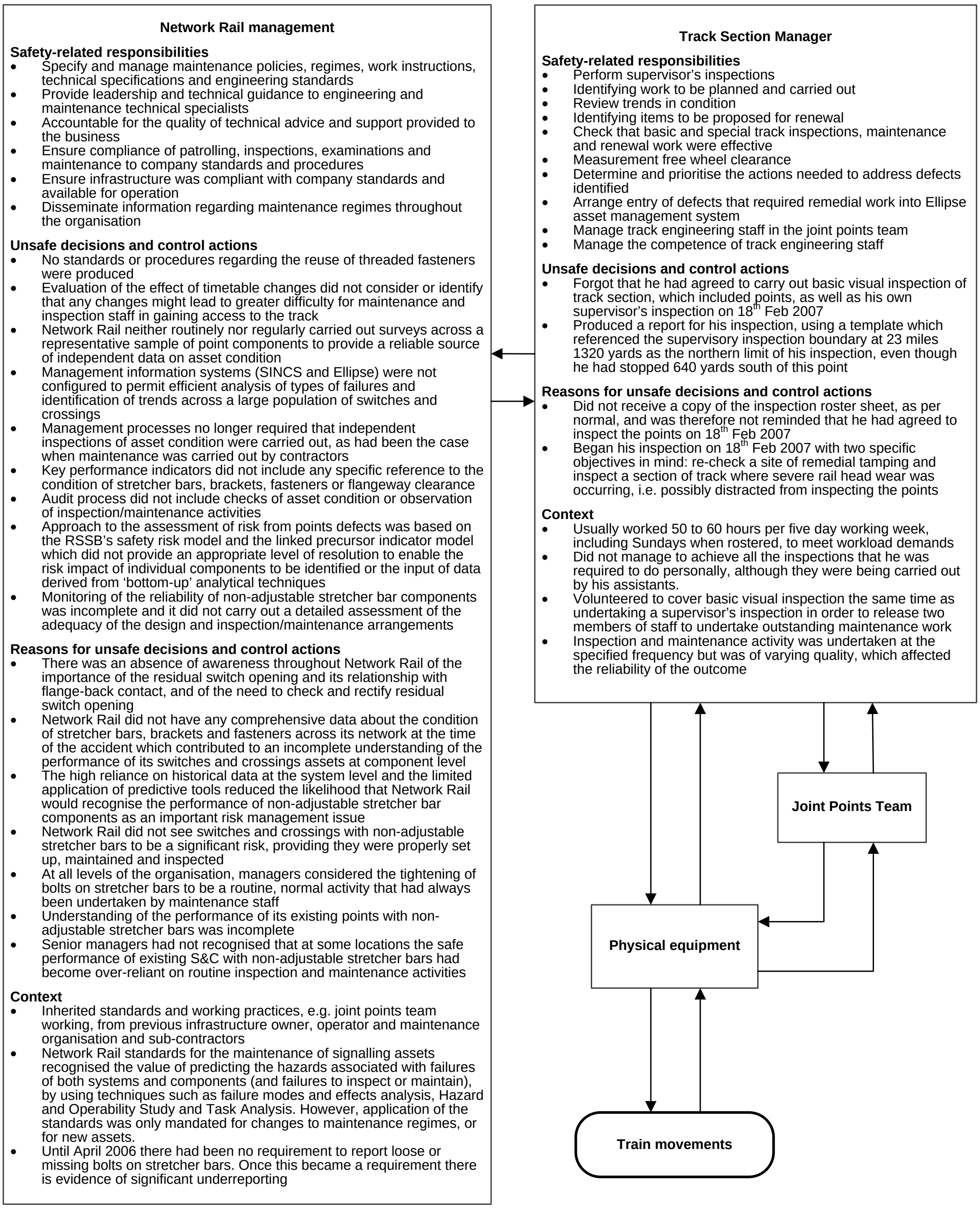

Figure 14 – STAMP analysis of higher-level system components

Many of the actions and decisions taken by the higher levels of the control structure were summarised by the RAIB (2011) as Network Rail's management arrangements. Therefore, these higher level components were amalgamated into a 'Network Rail management' component in order to facilitate the analysis. A number of longstanding and proximal issues were identified whilst assessing the overall coordination and communication throughout the system. Respective examples include: no training was provided to the maintenance teams concerning the required setting for residual switch opening; the points failure was undetectable by the signalling system. Network Rail experienced large changes to its control structure since it took over the running of the rail infrastructure in 2002. However, it was not possible to identify whether these changes resulted in the system migrating to a higher state of risk and increased the chance of an accident.

5.2. Comparing the analysis models

5.2.1. Systems thinking approach

5.2.1.1. System structure

All three techniques require the analysis of the whole system hierarchy which was responsible for preventing the accident, up to and including the regulatory level. However, the ATSB model and AcciMap require the description of events, actions and conditions, rather than system components. Therefore, their analysis charts provide little information about the structure of the system in question, or its boundary. Conversely, the STAMP analysis requires the documentation of the system control structure and provides a clear visual description of the system hierarchy. The boundary of the system (and those of its sub-systems) is defined by the boundary of responsibility for a given hazard and safety constraint. For example, the condition of the points was the responsibility of Network Rail, whereas the condition of the train involved in the accident was the responsibility of a different maintenance organisation (Alstom Transport West Coast Traincare Ltd.).

5.2.1.2. System component relationships

Each model requires the analyst to take a holistic view of the system, i.e. examining the interaction between the various elements of the system, albeit in different ways. The ATSB model and AcciMap analysis charts, rather than describing the system components and their relationships, show the outputs of these relationships and how they reduced system safety. By documenting the control structure, the STAMP analysis process shows the relationships between the various system components. The subsequent stages of the analysis then examine how the dysfunctional interactions between a given component and the rest of the system contributed to its unsafe actions and/or decisions (see Figs. 13 and 14).

5.2.1.3. System behaviour

The ATSB model and AcciMap analysis charts describe (via the caption boxes) key input and output conditions of system components. The transformation processes, which convert the inputs to outputs, are indicated by arrows, although details of the processes are not provided. In keeping with its control theoretic underpinnings, STAMP describes system inputs as the information available to a given component and the control instructions it receives. Component outputs, e.g. unsafe control actions, are described as well as the reasons why they happened, i.e. why the associated transformation processes failed.

Neither the ATSB model nor AcciMap require the analyst to state the safety-related goals of the system. However, they are implicitly addressed, as the principal goal of the system is clearly the avoidance of the main occurrence/critical event. STAMP, however, explicitly defines the system- and component-level safety-related goals during the various stages of the analysis.

The adequacy and impact of the controls and feedback within the system is addressed by the ATSB model via the analysis of the 'risk controls' created by the organisation. The same is true of the AcciMap method, although this information is presented in the decisions and/or consequences caption boxes across the diagram. However, the influence of missing/inadequate feedback on management activities and decisions is not included in either analysis chart. Examining the control and feedback in a system is a core requirement of the STAMP analysis process. As such, this is clearly documented in the system control structure and the detailed analysis of each component.

The ATSB model prompts the investigation of how the system's behaviour changed over time. This is achieved by examining and charting the proximal events and conditions that occurred locally to the accident site, as well as the organisational and regulatory factors that were created further back in the system's history. This approach is also taken by the AcciMap method. The requirement of STAMP to determine the proximal and historic events leading to an accident ensures that the changes in system behaviour are analysed.

The context in which actions and decisions were taken by the various frontline system components are explicitly incorporated into the ATSB model via the description of the local conditions. Although the context in which organisational and regulatory issues were created is not present in the analysis chart, the ATSB suggests that this contextual information can be a useful addition to an analysis (ATSB, 2008, p.44). By describing pre-conditions and the direct/indirect consequences created throughout the system, the AcciMap depicts the context in which decisions and activities took place at the various system levels. The local context in which system component behaviour took place is explicitly addressed by STAMP via the detailed analysis of the control structure (see Figs. 13 and 14).

Given that accident investigation involves determining why a particular set of events and conditions contributed to an accident, the ability of the models to represent equifinality and multifinality is a moot point. A summary of the systems thinking approach comparison is provided in Table 2.

Systems thinking approach comparison			
Model characteristic	**ATSB model**	**Accimap**	**STAMP**
System structure	Requires analysis of the whole system. Describes system as combination of events, actions and conditions. Little information about system structure or boundary provided		Requires analysis of the whole system. System structure and boundary defined by hierarchy of components responsible for controlling safety constraints. System structure graphically described.
System component relationships	Takes a holistic view of the system. Describes the safety-related outputs of relationships throughout the system and their affect on other relationships		Takes a holistic view of the system. Describes component relationships throughout the system and their impact on safety
System behaviour	Incorporates all aspects of system behaviour, although some are only partially described (e.g. feedback availability and context of behaviour at the organisational level). Short- and long-term system history is examined.	Incorporates all aspects of system behaviour, although some are only partially described (e.g. systems goals and feedback availability at the organisational level). Short- and long-term system history is examined.	Incorporates all aspects of system behaviour, which are described in the analysis output. Short- and long-term system history is examined.

Table 2 – Systems thinking approach comparison

5.2.2. Usage characteristics

5.2.2.1. Data requirements

Due to their holistic approach, all of the models require various types of data to be collected from all of the relevant parts of the socio-technical system and its environment. In practice, accident investigators will obtain this evidence in a variety of formats, such as photographic, documentary and witness testimony. A range of preliminary analysis activities is required to convert this data into a format suitable for the subsequent analyses (ATSB, 2008, p.49). This involves the use of techniques to interpret and organise data, e.g. employing photogrammetry to measure the distribution of a wreckage trail from an accident site photograph. The ATSB model, AcciMap and STAMP analyses are, therefore, summaries of the findings produced by these more specific analytical processes. Consequently, the type of information that either model can analyse is not restricted by the original format of that data. More data is, however, explicitly required by STAMP, e.g. details on the system structure and components.

5.2.2.2. Validity

Capturing all of the complexity in a large socio-technical system is seemingly beyond the capability of an individual analysis model and the resource constraints of accident investigation. Therefore, proving the internal validity of the three analysis techniques is not possible. In fact, the ATSB model does not attempt to describe all of the complexities involved in accident causation. Rather it favours providing a general framework that helps guide data collection and analysis during an investigation (ATSB, 2008, p.36). Conversely, AcciMap purposefully sets out to analyse the dynamic behaviour that exists within a system and how it contributes to accidents. Likewise, STAMP deliberately addresses how complexity within a system influences accident events. Regardless of these different approaches, each model was devised specifically for the purposes of accident analysis, is based on a recognised theory of accident causation and has been used across multiple domains, which suggests an acceptable degree of face and external validity exists.

5.2.2.3. Reliability

The qualitative nature of the models negatively impacts on their reliability. None of the techniques provide a detailed taxonomy of contributory factors, which further reduces their reliability and the chance to perform accident trend analysis. However, this also means the analyst has more freedom in how they classify such factors. It is understood that the ATSB use a taxonomy in their accident database, however, details about its content are not publically available (see ATSB, 2008, p.9). The reliability of the ATSB model and STAMP is, however, improved by the detailed descriptions of safety factors and accident causes and the model usage guidance provided by the ATSB (2008) and Leveson (2012, p.92–100). Therefore, both models are considered to have moderate reliability. The AcciMap guidance material (e.g. Svedung and Rasmussen, 2002) provides little support in comparison, albeit that it slightly improves the chance of performing a reliable analysis. Therefore, the method was considered to have low reliability.

5.2.2.4. Usability

Assessing how easy the analysis tools are to understand and apply clearly involves the subjective opinion of the user, an issue which is discussed in Section 6. However, a number of observations regarding the availability and clarity of the guidance material which supports the techniques can be made.

The ATSB (2008) provide a substantial amount of information regarding the theoretical aspects of their model and how it can guide the collection and analysis of data in an investigation. Structured approaches for identifying potential safety factors and testing their validity are also given. The usage guidance provided for STAMP (Leveson, 2012) is also considerable and describes systems theory, how it is applied by STAMP and how to use STAMP to analyse accidents. Therefore, the analyst is provided with a body of information that can facilitate a more effective and efficient analysis. However, the ATSB model and STAMP guidance contains substantial amount of jargon, such as ‘safety factor’ and ‘safety constraint’, and the analyst is required to read a considerable amount of information to gain a full understanding of how to apply the models. The guidance available for AcciMap also provides detailed description about the conceptual aspects and purpose of the method, i.e. analysis of a system’s dynamic behaviour and the variable performance of its components. However, little guidance is provided about how to apply the method and, although there is arguably less jargon associated with the technique, it seems likely that the analyst would have to carefully study the available information to fully understand how to apply AcciMap. Whether the analyst is taught how to use any of these models via self-learning or a training course, conveying such a large amount of information will clearly require more time and funding compared with simpler analysis techniques. The holistic approach taken by the models also means significant resources will be required for data collection.

5.2.2.5. Graphical representation of the accident

The graphical output of the ATSB model, based on the AcciMap method (Rasmussen, 1997), provides a description of the accident scenario on a single diagram (see Fig. 10). The use of colour coding helps to distinguish between the various different types of safety factors presented on the chart.

The influence that a given safety factor has had on others is clearly indicated by arrows linking the caption boxes. Furthermore, by including the sequence of occurrence events leading up to the accident, the reader is provided with a sense of how the accident developed over time. In combination, these features provide a relatively simple means of understanding and communicating the findings of an analysis, albeit that knowledge of the ATSB model and its terminology is required to interpret the diagram. Similarly, AcciMap describes the accident scenario on one diagram (see Fig. 11), provides information about the proximal sequence of events (via information contained in Level 5 of the analysis chart) and the relative influence of the identified actions, decisions and consequences etc. Given that there is comparatively little jargon associated with the method, the AcciMap chart is also relatively simple to understand. However, the lack of colour-coding utilised by Rasmussen (1997) and Svedung and Rasmussen (2002) (see Fig. 5) arguably increases the difficulty in reading an AcciMap analysis chart (additional colour-coding was implemented by the authors to ease the visual communication of the AcciMap findings).STAMP presents the findings of an analysis over several documents, some of which are mainly text based (e.g. Fig. 13), and does not lend itself to a simple graphical representation of an accident (Leveson, 2012, p.91). Therefore, graphical communication of the accident analysis findings is not performed as efficiently as the ATSB approach. A summary of the model usage characteristics comparison is provided in Table 3.

Usage characteristic comparison			
Model characteristic	**ATSB model**	**Accimap**	**STAMP**
Data requirements	Data required from all system levels. Compatible with all forms of data.		
Validity	Provides a general framework devised for accident analysis. Underpinned by a recognised accident causation theory. Used in multiple domains. Face and external validity provided.	Specifically designed to analyse the dynamic behaviour of a system. Underpinned by a recognised accident causation theory. Used in multiple domains. Face and external validity provided.	Specifically designed to analyse the complexity in a system. Underpinned by a recognised accident causation theory. Used in multiple domains. Face and external validity provided.
Reliability	Qualitative technique with no detailed (publically available) taxonomy of contributory factors. Safety factor definitions and analysis process guidance provided. Moderate reliability achieved.	Qualitative technique with no detailed taxonomy of contributory factors. Little analysis process guidance provided. Low reliability achieved.	Qualitative technique with no detailed taxonomy of contributory factors. Structured analysis process guidance and classification of accident causes provided. Moderate reliability achieved.
Usability	Substantial guidance provided about the model, its application and safety factor identification and testing. Resource intensive to learn and use.	Substantial guidance provided about system behaviour and the purpose of Accimap. Little application guidance provided. Resource intensive to learn and use.	Substantial guidance provided about systems theory, its use in STAMP and the application of the model . Resource intensive to learn and use.
Graphical representation of the accident	All (colour coded) safety factors, their relationships and proximal timeline included in one diagram. Effective visual communication of accident.	All actions, decisions and consequences etc., their relationships and proximal timeline included in one diagram. Effective visual communication albeit lack of colour-coding reduces effectiveness.	Findings presented over several documents. Model does not lend itself to simple graphical representation. Ineffective visual communication of accident.

Table 3 – Usage characteristic comparison

6. Discussion

6.1. Comparing the analysis models

6.1.1. Systems thinking approach

The ATSB model, AcciMap and STAMP all provide a systems thinking approach, i.e. they require the analysis of a system's structure, the relationship of its components and its behaviour. However, there is a considerable difference between how the models achieve this.

A number of the systems theory concepts are only implicitly and/or partially contained within the ATSB model. This is particularly true with respect to the description of the system structure and its boundary, the impact of missing/inadequate feedback and contextual factors on the actions and decisions made at the organisational level (see Section 5.2.1). Indeed, the ATSB (2008, p.47) suggest that the model does not fully explain the complex, dynamic nature of accident development. Therefore, strict adherence to the format of the ATSB model may result in an incomplete application of the systems thinking approach. However, although such usage may prevent investigators from exploring all of a system's complexity, the model does not preclude this in anyway either (Ghirxi, 2010). If investigators understand and apply the systems theory concepts during an investigation then the ATSB model can fulfil its intended role as a framework for analysis activities and act as a gateway to SAA (see Section 2.1).

Similarly to the ATSB model, AcciMap implicitly or partially describes the system structure, its boundary and the impact of missing/inadequate feedback. It does, however, provide a clearer representation of the context in which managerial decisions and activities took place. Nevertheless, a prescriptive application of the method may also result in an incomplete systemic accident analysis. Some of the system theory concepts implicitly covered by the ATSB model and AcciMap would naturally be addressed by investigators, such as identifying the components involved in an accident. For example, an 'individual action' cannot be examined until the person who performed that action is known. However, without explicit instructions to do so, some information may remain uncollected and/or undocumented, e.g. missing/inadequate feedback. In the case of AcciMap, this problem can be overcome by using the ActorMap and InfoFlowMap techniques that also form part of the risk management process suggested by Svedung and Rasmussen (2002, p.403). The ActorMap identifies the organisational bodies and individual actors involved in risk management whereas the InfoFlowMap graphically represents the communication between these decision makers. Whilst originally intended for use in risk management, these techniques could easily be utilised to provide information about the system components involved in an accident and any missing/inadequate communication.

However, the use of additional techniques has usage implications, which are discussed in Section 6.1.2.

STAMP more clearly embodies the core components of systems theory (see Table 2). This is unsurprising, given that it was specifically designed to employ a systems thinking approach to accident analysis. Furthermore, the structured process for applying STAMP deliberately guides the analyst to consider these core components. By doing so, STAMP arguably provides a more effective means of applying the systems thinking approach. Therefore, when considering how much of the systems thinking approach could be applied during a live investigation, the difference between the models seems to be a small one. Instead, the more noticeable difference between the ATSB model, AcciMap and STAMP comes from how they guide investigators to apply the components of systems theory. The systems thinking approach comparison of the models is visually represented in Fig. 15.

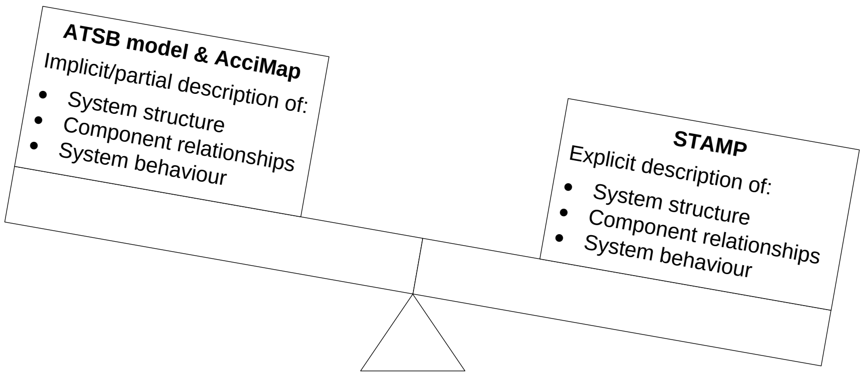

Figure 15 – Systems thinking approach comparison of the ATSB model, AcciMap and STAMP

6.1.2. Usage characteristics

As mentioned in Section 4.2.2, the ability of an individual to employ the systems thinking approach depends on the usage characteristics of their chosen method. When comparing the models in relation to these characteristics, it appears that the data requirements, validity and reliability of the ATSB model and STAMP are not significantly different (see Table 3). Therefore, it is arguable that these aspects of the techniques will not necessarily hinder the application of systems thinking relative to one another. Whilst similar in its data requirements and validity, the arguably lower reliability of AcciMap suggests that its application of the systems thinking approach may be more problematic. However, without formally testing the models, this evaluation is a subjective one.

The usability of an analysis tool is affected not only by its features but also by the characteristics of its users (Thomas and Bevan,1996). Therefore, although aspects relating to the usability of the models seem to be similar, as mentioned in Section 5.2.2.4, any judgement about a technique's usability is a subjective one. This is evidenced by the conflicting opinions regarding the usability of AcciMap and STAMP contained within the research literature (see Underwood and Waterson, 2012). The most significant usability issue encountered by the authors of this paper related to the classification of evidence. In the case of the ATSB model analysis, some of the safety factors did not neatly fit into one of the levels of the model. Similarly with the STAMP analysis, it was sometimes hard to distinguish between the reason why unsafe decisions and control actions were made and the context they were made in. Furthermore, the lack of specificity in the investigation report, regarding which elements of the Network Rail management contributed to the accident, made it hard to determine which AcciMap system level to attribute various decision/actions and consequences to. The application time of STAMP in this study was approximately double that of the ATSB model and AcciMap. This was attributed to the greater number of steps required to complete the STAMP analysis and the associated need for more information about the system structure and its components. It is considered by the authors that, had the ActorMap and InfoFlowMap methods been employed to complement the AcciMap and produce a more thorough analysis, the application time would have been similar to that of STAMP.

The clearest difference between the models, in terms of their usage characteristics, lies in their graphical outputs. The ATSB model and AcciMap analysis charts provide a relatively succinct summary of all of the safety factors which contributed to an accident. This similarity is not surprising, given that the ATSB model charting format is based on the AcciMap. However, the different features of the underlying models do produce notable variations in the graphical outputs of the techniques. For example, the authors believe that the ATSB model chart more clearly delineates the various events, activities and conditions that occurred at a local level. Conversely, incorporation of the Risk Management Framework (Rasmussen, 1997) format enables AcciMap to provide a more detailed description of the accident across the different organisational levels of the system. In the ATSB's experience, the use of their charting format has helped investigators maintain awareness of their progress during an investigation and assists the explanation of complex occurrences to industry personnel (ATSB, 2008,p.45). It seems likely that AcciMap would provide the same benefits, particularly if colour-coding was used to improve the effectiveness of its visual communication (as per Fig. 11). In the authors 'opinion, STAMP would also enable an awareness of an investigation's progress to be maintained. However, given that STAMP does not lend itself to a simple graphical representation of an accident, its usefulness in communicating an investigation's findings to a non-expert audience may be limited (Leveson, 2012, p.91). This problem may also exist if AcciMap were to be complemented by the ActorMap and InfoFlowMap techniques. The differing usage characteristics of the models are described in Fig. 16.

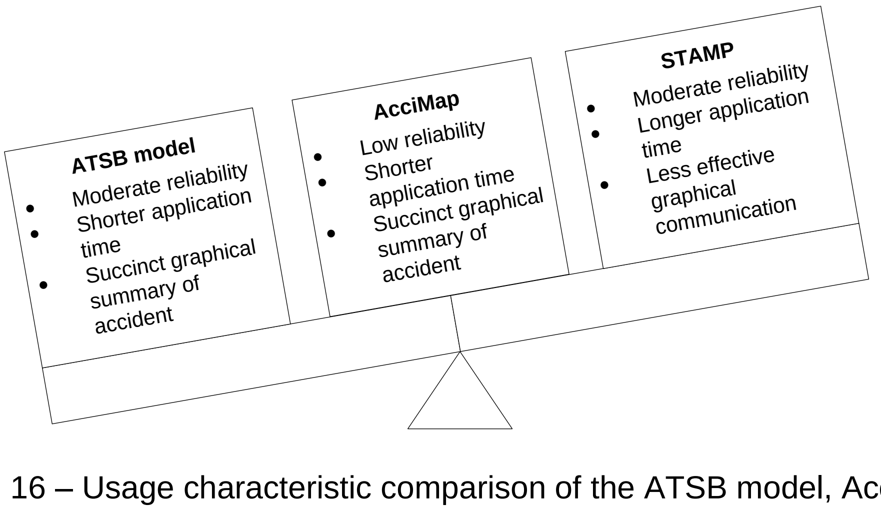

Figure 16 – Usage characteristic comparison of the ATSB model, AcciMap and STAMP

6.2. Systems thinking and accident analysis: a trade-off

Comparing the three techniques shows that there are a number of similarities between them as well as some important differences. Indeed, a comparison of any analysis methods would highlight various strengths and weaknesses.

It is clear that no single method can meet the needs of every analyst, otherwise there would be far fewer available. So, how does an individual select the most appropriate tool for a systemic analysis, if free to do so? A trade-off must be made between multiple factors associated with the requirements of the analysis and those of the user. These trade-offs are considered within the context of research and practice to help explain how the different needs of the two communities can affect the method selection process.

6.2.1. Analysis trade-offs

In any form of analysis, a compromise must be made between the thoroughness of the analysis and the resources available to complete it. Performing a systemic analysis of an accident is, by definition, a thorough process and, therefore, resource intensive. However there are some differences between the how the practitioner and researcher communities make this trade-off. Practitioners can be placed under intense amounts of pressure (e.g. commercial and legal) to provide an explanation for an accident (Hayward and Lowe, 2004, p.378). There is also a need to conclude an analysis quickly so that feedback does not come too late to be of any use and resource expenditure, which can be significant, can be optimised (Hollnagel, 2009, p.70). Therefore, practitioners are likely to require a method which provides a thorough enough analysis to generate useful safety lessons whilst also ensuring efficient resource usage. The ATSB (2008, p.47) claims that their model provides such a balance. Practitioner feedback on SAA methods, such as STAMP, AcciMap and FRAM, has not been widely publicised and, therefore, it is not possible (at present) to determine whether they can also satisfy this efficiency-thoroughness trade-off. However, given the similarities to the ATSB model (see Section 5.2), it is arguable that AcciMap may well meet this requirement.

Whilst researchers are also required to make such a trade-off, the scope of their accident analysis is generally quite different. For example, accident case study analyses tend to focus on whether a given method can provide additional safety insights (e.g. Hickey, 2012; Stanton et al., 2012) or if it is suitable for use in a given domain (e.g. Kazaras et al., 2012). Furthermore, there is significantly less external pressure on researchers to deliver a timely analysis. Therefore, there is a justifiable tendency to perform as thorough an analysis as possible. Furthermore, the cost of performing such research is small in comparison to an accident investigation so the need for efficiency is arguably less. It is possible that, due to the procedural requirement for an extensive analysis which incorporates all of the systems thinking concepts, STAMP may be a more attractive option for researchers conducting SAA. This is not to say that practitioners would find that STAMP does not provide an appropriate balance of thoroughness and resource requirements. However, in everyday practice the efficiency of a method often outweighs the drawback of reduced thoroughness (Hollnagel, 2009, p.132). AcciMap, as a standalone method, may be better suited for use by practitioners. However, if it is combined with the ActorMap and InfoFlowMap, the increased coverage of systems theory concepts may better meet the analysis needs of researchers.

Practitioners and researchers arguably have some dissimilar requirements of their analysis method outputs too. For example, practitioners will often need to classify the various findings of their analyses via a taxonomy, in order to conduct trend analysis. Although accident trend analysis is a well-established part of safety research, there is not such a pressing need for researchers to conduct accident case study analyses with a taxonomic method. Therefore, it is possible that researchers are afforded a wider choice of methods, including the SAA methods, which are yet to have industry-specific taxonomies developed for them.

6.2.2. User trade-offs

The choice of method can be influenced by a number of factors, such as its usability and how it suits the user's way of thinking (Underwood and Waterson, 2013). For example, it may be easier for someone to view safety inadequacies in a system as holes in allayer of Swiss cheese and, therefore, increase the chance of them using an SCM-based method (despite the fact, for example, that the ineffective safety constraint controls described by STAMP represent the same thing). The influence that an individual's understanding of accidents has on their method selection is obviously common to both researchers and practitioners. On this basis, it is not possible to say whether SCM-based methods would be favoured over SAA techniques by one or both communities. However, it should be noted that one of the reasons for the success of the SCM (and its related methods) is that it offers a simple, easily remembered description of accident causation (Reason et al., 2006, p.9). Therefore, it is likely that the SCM will continue to be a popular choice of analysis technique.

The impact that a method's usability (which is partly affected by its compatibility with a user) has on its selection by researchers and practitioners is slightly clearer to distinguish. As described in Section 6.2.1, researchers tend to focus on performing very thorough analyses of accidents and are subjected to less intense pressure to deliver a timely outcome. Therefore, it is possible that they are more able to sacrifice the usability of a method for the level of analysis detail it provides. Consequently, given its higher resource requirements and its less efficient communication, STAMP (or the combined AcciMap, ActorMap and InfoFlowMap techniques) may be better suited for use by researchers.

Selecting a method with an established track record in accident investigation can also influence an individual's choice of technique. Practitioners may be reluctant to try new methods in a live investigation, particularly if they are conducting accident investigation on a consultancy basis and need to establish credibility with their client (Underwood and Waterson, 2013, p.159). Therefore, the ATSB model may be a more suitable option for them. Conversely, the research community, when conducting academic studies, may be incentivised to use relatively untested and/or developmental techniques (such as the SAA methods) in order to advance the understanding of accidents. The different factors that affect the method selection of researchers and practitioners are represented in Fig. 17.

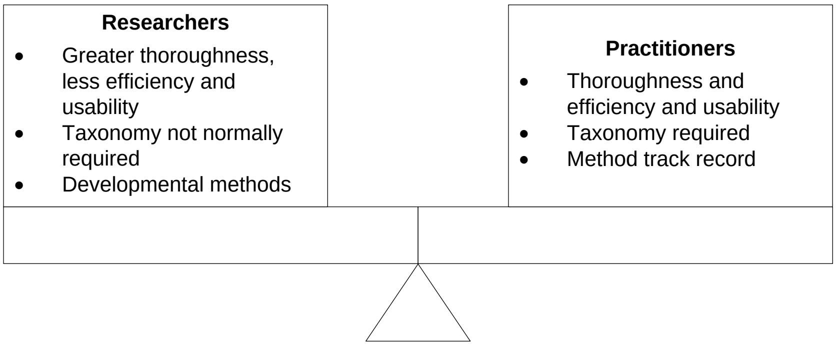

Figure 17 – Method selection trade-off factors

The choice of analysis method is subject to a complex trade-off of various factors and, therefore, it is hard to prescribe any one method to a given individual undertaking an analysis. However, it may be that, in general, the SAA methods may offer a more suitable systems thinking approach to accident analysis researchers until their suitability for use in live accident investigations can bedemonstrated.

6.3. Performing SAA with the SCM

The discussion, so far, has focused on the similarities and differences between the ATSB model, AcciMap and STAMP. What implications do these factors have on the application of the SCM and the systems thinking approach? The modifications made to the SCM by the ATSB when developing their model (see Section 2.1) supplemented the concepts embodied by the SCM, rather than eliminate them. Therefore, as the various components of systems theory can be applied with the ATSB model, this suggests that the underlying SCM can also achieve this and act as a gateway to SAA. Consequently, it seems that the SCM does provide a viable means of applying the systems thinking approach.

This statement, however, comes with an important caveat. As described in Section 1.2, the SCM is not a detailed accident analysis model, nor was it intended to be (Reason et al., 2006, p.21).Therefore, it should be applied via a method to ensure that the systems thinking approach is correctly utilised. However, this places an onus on the developers of SCM-based analysis methods to ensure that their techniques promote, rather than restrict, this application. This requirement is obviously true of any systemic analysis method. However, methods which explicitly incorporate the key concepts of systems theory, such as STAMP, go some way to resolving this problem. Therefore, it could be argued that such SAA techniques represent an evolution, rather than a revolution, in the application of the systems thinking approach.

6.4. Analysis and study limitations

An important question in this type of study is whether any of the analysis techniques highlighted systemic issues that were not addressed in the investigation report. The findings presented in Section 5.1 indicate that insufficient information was provided in the report to complete the AcciMap and STAMP analyses. In the case of AcciMap this manifested as an inability to analyse the influence of the governmental level of the system, whereas it was not possible to examine the long-term changes to the system overtime with STAMP. Although the ATSB model analysis was relatively complete in comparison, the next stage of analysis would naturally be to examine why the organisational and regulatory issues existed.

These limitations raise the important issue of when to stop evidence collection in an investigation. To fulfil the data requirements of AcciMap, STAMP and (to a lesser degree) the ATSB model, the RAIB would have needed to expand the boundary of the system they were investigating and look further back into the system's history. The collection of this extra information may not have occurred fora number of reasons, e.g.: the resource constraints of the investigation; the analysis processes used by the RAIB did not need the information; the required evidence was not available. Even if one of the three models used in the study had been adopted by the RAIB, it is possible that resource constraints and/or evidence availability would have prevented a complete analysis. Therefore, suggesting that a more extensive SAA would have yielded more in-depth results, whilst true, does not necessarily account for the practicalities of accident investigation. Furthermore, the RAIB (2011) report was written for a general audience and therefore, it is unclear what information was left out of the report for the sake of readability, personal or commercial sensitivity, etc.

Due to the resource constraints of this study, only three analysis models were utilised. Therefore, comments about how the SCM and its related methods compare in general to the SAA techniques are not necessarily representative of all of the available methods. However, it is felt that the comparison of the methods and the trade-offs associated with their selection is indicative of the current state of accident analysis in research and practice. The resource limitations of the study also prevented the researchers from independently performing an analysis of the derailment with each model. Whilst this would have been the ideal approach to take, the authors consider that the analysis process employed in the study (see Section 4.1) was sufficiently robust and provides accurate findings.

7. Conclusions

The systems thinking approach is arguably the dominant concept within accident analysis research. Its application, via systemic accident analysis (SAA), supposedly provides an improved description of accident causation, avoids the incorrect apportioning of blame and helps inform more effective safety recommendations. Debate exists within the research literature over whether the popular and widely adopted Swiss Cheese Model (SCM) provides an out-dated view of accident causation or remains a viable means of applying the systems thinking approach to accident analysis. This issue was examined by applying an SCM-based analysis model (the ATSB accident investigation model) and two SAA methods (AcciMap and STAMP) to the Grayrigg train derailment. A comparison of the analysis outputs and usage of the techniques showed that each model did apply the systems thinking approach, albeit in different ways. The ATSB model and AcciMap did not explicitly address all of the key systems theory concepts, but graphically presented their findings in a more succinct manner. Conversely, STAMP more clearly embodied the concepts of systems theory but did not provide a simple graphical representation of the accident. Given the differing nature of accident analysis within the practitioner and research communities, the trade-offs associated with method selection suggest that ATSB model provides a suitable option for practitioners. Conversely, STAMP may be better suited for use within research. With the option to use it as a standalone method or in combination with the ActorMap and InfoFlowMap techniques, the AcciMap method may more easily meet the needs of both parties. Finally, this study suggests that the SCM remains viable model for understanding accidents and that SAA methods offer an evolutionary progression, rather than complete transformation, in accident analysis.

References

Australian Transport Safety Bureau, 2008. Analysis, causality and proof in safety investigations. Aviation Research and Analysis Report AR-2007-053. Australian Transport Safety Bureau, Canberra City.

Belmonte, F., Schoen, W., Heurley, L., Capel, R., 2011. Interdisciplinary safety analysis of complex socio-technological systems based on the functional resonance accident model: an application to railway traffic supervision. Reliability Engineering& System Safety 96 (2), 237–249.

Benner, L., 1985. Rating accident models and investigation methodologies. Journal of Safety Research 16 (3), 105–126.

Branford, K., Naikar, N., Hopkins, A., 2009. Guidelines for AcciMap analysis. In: Hopkins, A. (Ed.), Learning from High Reliability Organisations. CCH Australia, Sydney, Australia, pp. 193–212.

Cooke, D.L., 2003. A system dynamics analysis of the Westray mine disaster. System Dynamics Review 19 (2), 139–166.

Dadashi, N., Wilson, J.R., Golightly, D., Sharples, S., Clarke, T., 2013. Practical use of work analysis to support rail electrical control rooms: a case of alarm handling. Journal of Rail and Rapid Transit 227 (2), 148–160.

de Carvalho, P.V.R., 2011. The use of functional resonance analysis method (FRAM) in a mid-air collision to understand some characteristics of the air traffic management system resilience. Reliability Engineering & System Safety 96 (11),1482–1498.

Dekker, S., 2011. Drift into Failure: From Hunting Broken Components to Under-standing Complex Systems. Ashgate Publishing Company, Farnham.

Dekker, S., 2006. The Field Guide to Understanding Human Error. Ashgate Publishing Limited, Aldershot.

Ferjencik, M., 2011. An integrated approach to the analysis of incident causes. Safety Science 49 (6), 886–905.

Ghirxi, K.T., 2010. The stopping rule is no rule at all: Exploring maritime safety investigation as an emergent process within a selection of IMO member states. World Maritime University (PhD Thesis).

Goh, Y.M., Brown, H., Spickett, J., 2010. Applying systems thinking concepts in the analysis of major incidents and safety culture. Safety Science 48 (3),302–309.

Goh, Y.M., Love, P.E.D., Brown, H., Spickett, J., 2012. Organizational accidents: a systemic model of production versus protection. Journal of Management Studies 49 (1), 52–76.

Hayward, B., Lowe, A., 2004. Safety investigation: systemic occurrence analysis methods. In: Goeters, K. (Ed.), Aviation Psychology: Practice and research. Ashgate, Aldershot, pp. 363–380.

Herrera, I.A., Woltjer, R., 2010. Comparing a multi-linear (STEP) and systemic (FRAM) method for accident analysis. Reliability Engineering & System Safety 95 (12),1269–1275.

Hickey, J., 2012. A System Theoretic Safety Analysis of U.S. Coast Guard Aviation. Massachusetts Institute of Technology (MSc dissertation).

Hollnagel, E., 2012. FRAM—The Functional Resonance Analysis Method. Ashgate, Farnham.

Hollnagel, E., 2004. Barriers and Accident Prevention. Ashgate Publishing Limited, Aldershot.

Hollnagel, E., Speziali, J., 2008. Study on Developments in Accident Investigation Methods: A Survey of the State-of-the-art. SKI Report 2008:50. Sophia Antipolis, France, Ecole des Mines de Paris.

Hollnagel, E., 2009. The ETTO Principle: Efficiency-thoroughness Trade-off: Why Things that go Right Sometimes Go Wrong. Ashgate Publishing Ltd, Farnham, Surrey.

Hudson, P.T.W., Reason, J.T., Wagenaar, W.A., Bentley, P.D., Primrose, M., Visser, J.P.,1994. Tripod delta: proactive approach to enhanced safety. Journal of PetroleumTechnology 46 (1), 58–62.

Jacobsson, A., Sales, J., Mushtaq, F., 2009. A sequential method to identify underlying causes from industrial accidents reported to the MARS database. Journal of Loss Prevention in the Process Industries 22 (2), 197–203.

Johansson, B., Lindgren, M., 2008. A quick and dirty evaluation of resilience enhancing properties in safety critical systems. In: Hollnagel, E., Pieri, F., Rigaud, E.(Eds.), Third Symposium on Resilience Engineering. 28–30 October 2008. Écoledes mines de Paris.

Jönsson, H., 2007. Risk and vulnerability analysis of complex systems: A basis for proactive emergency management. Lund University, Department of Fire Safety Engineering and Systems Safety (Licentiate thesis).

Kazaras, K., Kirytopoulos, K., Rentizelas, A., 2012. Introducing the STAMP method in road tunnel safety assessment. Safety Science 50 (9), 1806–1817.

Le Coze, J.C., 2013. What have we learned about learning from accidents? Post-disasters reflections. Safety Science 51 (1), 441–453.

Leplat, J., 1984. Occupational accident research and systems approach. Journal ofOccupational Accidents 6 (1–3), 77–89.

Leveson, N., 2011. Applying systems thinking to analyze and learn from events. Safety Science 49, 55–64.

Leveson, N., 2012. Engineering a Safer World: Systems Thinking Applied to Safety. The MIT Press, Cambridge, MA.

Leveson, N., 2004. A new accident model for engineering safer systems. Safety Science 42 (4), 237–270.

Office of Rail Regulation, 2013. Periodic Review 2013: Draft Determination of Network Rail's Outputs and Funding 2014–19. Office of Rail Regulation, London.

Ouyang, M., Hong, L., Yu, M., Fei, Q., 2010. STAMP-based analysis on the railway accident and accident spreading: taking the China—Jiaoji railway accident for example. Safety Science 48 (5), 544–555.

Rail Accident Investigation Branch, 2011. Rail accident report: Derailment at Grayrigg 23 February 2007. Report 20/2008 v5 July 2011. Rail Accident Investigation Branch, Department for Transport, Derby.

Rasmussen, J., 1997. Risk management in a dynamic society: a modelling problem. Safety Science 27 (2–3), 183–213.

Read, G.J.M., Salmon, P.M., Lenné, M.G., 2013. Sounding the warning bells: the need for a systems approach to understanding behaviour at rail level crossings. Applied Ergonomics 44 (5), 764–774.

Reason, J., 2008. The Human Contribution: Unsafe Acts, Accidents and Heroic Recov-eries. Ashgate, Farnham.

Reason, J., 1997. Managing the Risks of Organizational Accidents. Ashgate Publishing Ltd, Aldershot.

Reason, J., 1990. Human Error. Cambridge University Press, Cambridge.

Reason, J., Hollnagel, E., Paries, J., 2006. Revisiting the «Swiss cheese» model of accidents. EEC Note No. 13/06. EUROCONTROL Experimental Centre, Brétigny-sur-Orge, France.

Salmon, P.M., Cornelissen, M., Trotter, M.J., 2012. Systems-based accident analysis methods: a comparison of AcciMap, HFACS, and STAMP. Safety Science 50 (4),1158–1170.

Salmon, P.M., Read, G.J.M., Stanton, N.A., Lenné, M.G., 2013. The crash at Kerang: investigating systemic and psychological factors leading to unintentional non-compliance at rail level crossings. Accident Analysis & Prevention 50,1278–1288.

Shorrock, S., Young, M., Faulkner, J., Braithwaite, G., 2004. Who moved my (Swiss)cheese? The (R)evolution of human factors in transport safety investigation. In: Stone, R., Fager, S., Martinez, E. (Eds.), Proceedings of the 35th Annual International Seminar: 'Investigate—Communicate—Educate'. 30 August–2 September 2004. International Society for Air Safety Investigators, pp. 141–144.

Sklet, S., 2004. Comparison of some selected methods for accident investigation. Journal of Hazardous Materials 111, 29–37.

Skyttner, L., 2005. General Systems Theory: Problems, Perspectives, Practice, 2nd edn. World Scientific Publishing Ltd., London.

Song, T., Zhong, D., Zhong, H., 2012. A STAMP analysis on the China-Yongwen railway accident. In: Ortmeier, F., Daniel, P. (Eds.), SAFECOMP 2012. 25 September 2012.Springer, pp. 376–387.

Stanton, N.A., Rafferty, L.A., Blane, A., 2012. Human factors analysis of accidents in systems of systems. Journal of Battlefield Technology 15 (2), 23–30.

Svedung, I., Rasmussen, J., 2002. Graphic representation of accident scenarios: mapping system structure and the causation of accidents. Safety Science 40 (5),397–417.

Szeremeta, M., Janica, J.R., Niemcunowicz-Janica, A., Pepinski, W., 2013. Fatal drowning as a result of an airplane crash—case report. Forensic Science International 226 (1–3), e12–e15.

Thomas, C., Bevan, N., 1996. Usability Context Analysis: A Practical Guide, Version 4.04. National Physical Laboratory, Teddington.

Underwood, P., Waterson, P., 2013. Systemic accident analysis: examining the gap between research and practice. Accident Analysis & Prevention 55,154–164.

Underwood, P., Waterson, P., 2012. A critical review of the STAMP, FRAM and AcciMap systemic accident analysis models. In: Stanton, N.A. (Ed.), Advances in Human Aspects of Road and Rail Transportation. CRC Press, Boca Raton, pp.385–394.

Vicente, K.J., 1999. Cognitive Work Analysis: Toward Safe, Productive, and Healthy Computer-based Work Mahwah. Lawrence Erlbaum Associates, NJ. Wagenaar, W.A., van der Schrier, J., 1997. The goal, and how to get there. Safety Science 26 (1–2), 25–33.

Waterson, P., 2009. A critical review of the systems approach within patient safety research. Ergonomics 52 (10), 1185–1195.

Waterson, P.E., Jenkins, D.P., 2010. Methodological considerations in using AcciMaps and the risk management framework to analyse large-scale systemic failures. In: 5th IET International Conference on System Safety, 18–20 October 2010. IET Conference Publications, pp. 1–6.

Wiegmann, D.A., Shappell, S.A., 2003. A Human Error Approach to Aviation Accident Analysis: The Human Factors Analysis and Classification System. Ashgate Publishing Ltd, Burlington, Vermont, USA.

Wilson, J.R., 2013. Fundamentals of systems ergonomics/human factors. Applied Ergonomics, http://dx.doi.org/10.1016/j.apergo.2013.03.021.

Xue, L., Fan, J., Rausand, M., Zhang, L., 2013. A safety barrier-based accident model for offshore drilling blowouts. Journal of Loss Prevention in the Process Industries26 (1), 164–171.

Appendix 2.1

Science Direct search for research-practice gap articles

Total of 102 articles found for: pub-date > 2010 and title((research w/5 practice) or (theory w/5 practice) w/5 (gap or divide))

26 articles related to research-practice gaps including (Underwood and Waterson, 2013a)

Web of Science search for research-practice gap articles

Total of 414 articles found for: TS=(((research NEAR/5 practice) OR (theory NEAR/5 practice)) NEAR/5 (gap OR divide))

Timespan=2011-2013. Databases=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, CCR-EXPANDED, IC.

108 articles related to research-practice gaps excluding (Underwood and Waterson, 2013a) and duplicates of Science Direct search results

Science direct search for accident analysis and investigation research-practice gap articles

Two articles found for: pub-date > 2000 and title-abstr-key((research w/5 practice) or (theory w/5 practice) w/5 (gap or divide)) and ({accident analysis} or {accident investigation})

Web of Science search for accident analysis and investigation research-practice gap articles

Two articles found for: TS=(((research NEAR/5 practice) OR (theory NEAR/5 practice)) NEAR/5 (gap OR divide)) AND TS=("accident analysis" OR "accident investigation")

Timespan=2000-2013. Databases=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, CCR-EXPANDED, IC.

Appendix 3.1

SAA literature search string

title-abstr-key(((accident* or disaster* or incident*) w/5 (analy* or investigat*)) AND (system* w/5 (theor* or approach)))

SAA model identification search string

title-abs-key(((accident* w/15 analy*) or (accident* w/15 investigat*)) OR ((disaster* w/15 analy*) or (disaster* w/15 investigat*)) AND (model or method or tool or technique or framework) and system*)

Model citation count search strategy

- If the name of the model is a unique noun then search using that name
- If the name of the model is not a unique noun then include the originating researcher's name, e.g. STAMP and Leveson, to stop the search engines generating excessive numbers of unrelated articles
- If the model name has an acronym, e.g. STAMP, then search for both the acronym and the full name
- Include the terms accident*, disaster* and inciden* to filter out documents that are not related to accident analysis
- If the model has no name or acronym then use the originating researcher's name
- Search for citations from the year the model was first published to prevent generating invalid search results from previous years

Search strings for SAA methods other than STAMP, FRAM and AcciMap are not included in appendix, however, all searches followed the format described above.

STAMP

(accident* or disaster* or incident*) and (STAMP or Systems-Theoretic Accident Model and Processes) and Leveson

For Google Scholar search use:

Exact phrase: Systems-Theoretic Accident Model and Processes

At least one word: accident* or disaster* or incident*

Published since: 2002

FRAM

(accident* or disaster* or incident*) and (“FRAM” or “functional resonance accident model”) and (Hollnagel or Goteman)

AcciMap

(accident* or disaster* or incident*) and (accimap* or “acci map”) and (Rasmussen or Svedung)

Appendix 4.1

Study 2 sample demographics

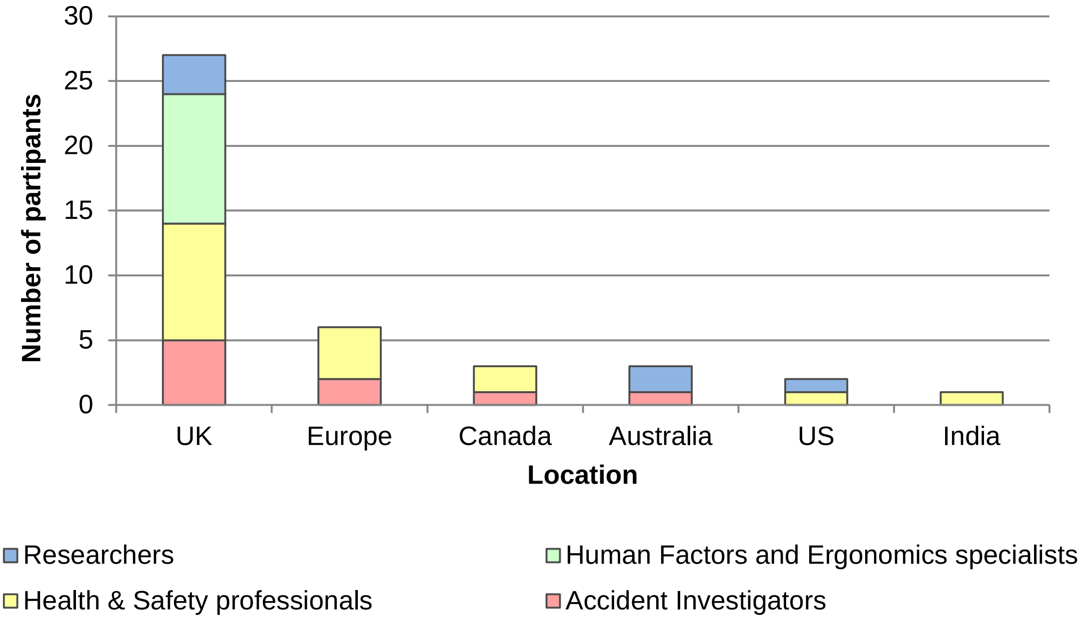

Figure 50 - Participant location

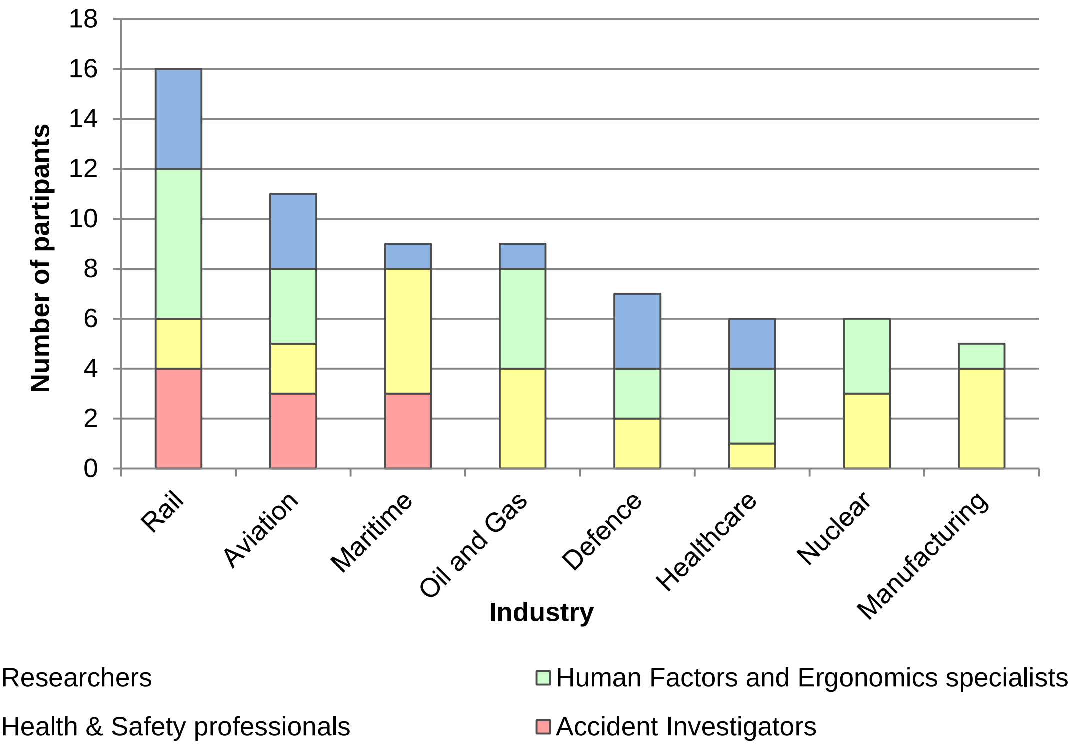

Figure 51 - Industries worked in by participants

Appendix 4.2

Study 2 Interview questions

Background information

1. What is your age?

2. What is your current job title?

3. What are the main duties of your current role?

4. As a percentage, how much of your time is spent analysing accidents?

5. How many years of experience do you have of analysing accidents?

6. How many accidents have you analysed?

7. What types of accidents have you analysed?

8. Which industries did these accidents occur in?

9. When would you be called into perform an analysis/risk assessment?

10. In your opinion, what is the main reason why major accidents within the industry you work in?

    10.1 Why?

The systems approach

11. Have you heard of the systems approach?

12. What is your understanding of the systems approach to accident analysis?

    12.1 How did you gain this understanding?

13. Do you apply a systems approach to accident analysis?

    13.1 How do you apply it?

14. What do you think the benefits of using the systems approach are?

15. What are the drawbacks of using the systems approach?

The current approach

16. When you perform an analysis, what steps do you go through?

17. How much time is spent on analysing the data compared with its collection and report writing?

18. What method(s) do you currently use to analyse accidents?

19. What made you choose that specific method?

20. What are the benefits of the method?

21. What are the drawbacks of the method?

22. What other methods did you consider?

23. Why is your current method better than the alternatives?

24. When selecting a method what consideration do you give to:

    24.1 Validity and reliability?

    24.2 Usability?

    24.3 How it helps you generate recommendations?

25. If I asked you to write a wish list of the features that your ideal analysis technique would possess, what would you write?

Research–practice gap

26. How do you keep up-to-date with new analysis theories and methods?

27. What sort of input would you value from the researcher/practitioner community?

28. What are the barriers which prevent the application of accident analysis research?

29. How do you think those barriers could be removed?

Appendix 4.3

Study 2 analysis model awareness table

Participant Number:

Analysis tool	I have never heard of it	I have heard of it but don't I know how it works	I understand how it works but I have never used it	I have used it before but do not use it currently	I currently use it
STAMP					
FRAM					
Accimap					
Swiss Cheese					
MORT					
Fault Tree Analysis					
Domino model					

STAMP: Systems-Theoretic Accident Model and Processes

FRAM: Functional Resonance Accident Model

MORT: Management Oversight and Risk Tree

Figure 52 - Analysis model awareness table

Appendix 5.1

RAIB (2011) investigation findings

The Cause of the Derailment

This section describes RAIB's conclusions as to the causal, contributory and underlying factors that led to the derailment, and also its observations on infrastructure issues.

The cause of the derailment

Immediate cause

512 The immediate cause of the derailment was the interaction of the train with 2B points, which were in an unsafe state and forced some of the wheelsets from the first vehicle into the reducing gauge between both switch rails. All the other vehicles of train 1S83 derailed as a consequence.

Reference paragraphs 80 and 538.

Causal factors[33]

513 Lambrigg 2B points were in an unsafe condition on 23 February 2007 because all restraint on the left-hand switch rail had been lost. This was caused by successive failures of all three permanent way stretcher bar assemblies and the lock stretcher bar assembly. This combination of failures allowed the left-hand switch rail to move, un-commanded by the signalling system, to a position close to the stock rail without losing signalling detection.

Reference paragraph 174.

Fastener loading and design

514 The first failure in the degradation of the points was the undetected failure of the third permanent way stretcher bar right-hand bracket to switch rail joint, caused by the clamping force in the joint being less than the normal forces of traffic. The failure of the joint was a causal factor of the accident.

Reference paragraphs 139 and 182.

Recommendations 1, 2, 3, 4, 5 and 12.

Excessive residual switch opening

515 The setting of the escapement joint to give a residual switch opening of between 7 and 10 mm (this was greater than the nominally specified value of 1.5 mm), allowed the flange-back contact by most wheelsets[9] on the left-hand switch rail to occur once the third permanent way stretcher bar right-hand bracket to switch rail joint had failed, increasing the forces seen by the remaining stretcher bars and causing the subsequent collapse of the points system. The excessive residual switch opening was a causal factor of the accident.

Reference paragraphs 154, 182 and 284.

Recommendations 1 and 8.

Missed inspection

516 The deterioration in the condition of the third permanent way stretcher bar and its joint, and possibly some aspects of the deterioration of the second permanent way stretcher bar, should have been visible to a basic visual inspection on 18 February 2007, had it passed 2B points. The omission of the basic visual inspection of 2B points on 18 February 2007 was a causal factor.

Reference paragraphs 230 and 247.

Recommendations 10, 11 and 12.

[33] A causal factor is any condition, event or behaviour that was necessary for the occurrence. Avoiding or eliminating any one of these factors would have prevented the occurrence from happening.

Contributory factors[34]

Access for inspection and maintenance and resource availability

517 The constraints from access problems were a contributory factor in the the track section manager's decision to combine his supervisory inspection with a basic visual inspection on 18 February 2007, which ultimately led to 2B points not being inspected on that date.

Reference paragraphs 239 to 246 and Appendix H.

Recommendations 16 17 and 19.

518 The omission of the basic visual inspection at 2B points was not identified at the plan-do-review meeting on 19 February 2007. The depot records were incorrectly updated to record that inspection H was completed and this made it less likely that the omission of part of that inspection would be identified, or that corrective action would be taken. The weak process and inaccurate input was a contributory factor.

Reference paragraphs 231 and 251.

Recommendations 11 and 14.

[34] A contributory factor is any condition, event or behaviour that affected or sustained the occurrence, or exacerbated the outcome. Eliminating one or more of these factors would not have prevented the occurrence but their presence made it more likely, or changed the outcome.

Underlying factors[35]

519 The following points were underlying factors to the derailment:

- Network Rail's incomplete technical knowledge and analysis of the maintenance requirements of S&C with non-adjustable stretcher bars resulted in:
  - an absence of clear, properly briefed, standards for setting up, periodically checking and adjusting the supplementary drive and the residual switch opening;
  - little or no investigation of loose or missing fasteners; and
  - the maintenance instructions not specifying how stretcher bar fasteners found in need of tightening should be tightened.

Reference paragraph 416.

Recommendations 1, 7, 8, 9 and 12.

- The absence of awareness throughout Network Rail of the importance of the residual switch opening, its relationship with flange-back contact, and the need to check and rectify it.

Reference paragraph 290.

Recommendations 1, 2, 3, 4, 5, 6, 8 and 12.

- Network Rail's limited application of a systematic risk-based process for the analysis of design and maintenance requirements resulted in an incomplete understanding of the design, maintenance and inspection of non-adjustable stretcher bar S&C.

Reference paragraph 440.

Recommendation 1.

- Network Rail's perception that the risk associated with the existing design of S&C with non-adjustable stretcher bars in some applications was low adversely affected its regime for inspection, reporting of faults and maintenance of S&C of this design.

Reference paragraph 408.

Recommendation 2.

- Incomplete management information within Network Rail regarding the performance of safety-related components in S&C.

Reference paragraph 400.

Recommendations 2, 14 and 15.

- Within Network Rail's organisation there was an incomplete understanding of the performance of S&C, and no detailed assessment of the adequacy of the design or the inspection and maintenance arrangements.

Reference paragraph 414 and 450.

Recommendation 18.

[35] An underlying factor is any factor associated with the overall management systems, organisational arrangements or the regulatory structure.

- Network Rail's processes for performance measurement of S&C were not based on a thorough understanding of risk and control measures.

Reference paragraph 425.

Recommendations 2 and 14.

- Network Rail's maintenance of S&C assets fell short of industry good practice as laid down in the Yellow Book.

Reference paragraph 421.

Recommendation 20.

Observations[36]

520 The process used for detecting and recording defects found by the basic visual inspections at Carnforth varied considerably between individuals. As there is no physical evidence that the joint was deteriorating until after the inspection of 11 February 2007, it is not possible to definitely link this process to the derailment.

Reference paragraph 213 and 234.

Recommendations 1, 10 and 13.

521 The track section manager worked extended hours in the weeks before the accident. The RAIB has no clear evidence whether this contributed to the omission of the basic visual inspection but is aware of other work which suggests that there may be a link between long hours and performance. The RAIB recommends further study in this area as it is aware that supervisory managers often work extended hours.

Reference paragraph 229.

Recommendation 29.

522 In the course of this investigation, the RAIB found considerable evidence of issues relating to staff competence, indicating that there were deficiencies in the competence management system. However, the only competency issue that can be positively linked to the derailment was the lack of knowledge about residual switch opening issues, which has already been identified as an underlying factor. The other deficiencies in the competence management system, although unsatisfactory, cannot otherwise be directly linked to the causation of the accident. Accordingly, several recommendations include issues regarding competency of staff.

Reference paragraphs 208, 213 and 264.

Recommendation 12.

523 There were deficiencies in the audit system, primarily because it did not include any examination of the asset. The audits that were performed did not detect the inconsistencies in the documented maintenance regime and its practice.

Reference paragraphs 336 and 337.

Recommendation 15.

524 Network Rail's investigations into non-adjustable stretcher bar fastener failures at Grangetown, Wood Green and Shaftholme before the Grayrigg accident reviewed the performance of inspection and maintenance, but did not carry out a detailed investigation into what caused the fasteners to come undone.

Reference paragraph 444.

Recommendation 5.

525 The placing of the area signalling engineer within the infrastructure maintenance manager's team increased the likelihood of being distracted from engineering duties by other activities.

Reference paragraph 447.

Reference actions taken, paragraph 681.

[36] An *observation* is an element discovered as part of the investigation that did not have a direct or indirect effect on the outcome of the accident but, in the opinion of the RAIB, does deserve scrutiny.

526 HMRI identified that S&C was the third highest risk element on Network Rail in preparing risk topic strategies as input to their 2006/7 delivery plan, but decided not to include S&C as part of the track topic. HMRI did not reflect the significance of S&C risk in the briefing of the track assignments chosen for the 2006/2007 delivery plan to ensure that an appropriate focus on S&C risk was made by its regional teams charged with undertaking the assignments.

Reference paragraph 493.

Recommendation 21.

527 The detection of the position of the open switch rail relied upon the integrity of the connection of the detection equipment to the switch rail. Alternative options that might detect open switch movement include the provision of independent open switch rail detection, or trying to link the detection rod and the switch separately from the connection to the lock stretcher bar. On the basis of one accident, where the lack of this detection may not have made any difference to the outcome, the RAIB considers that making these changes is not likely to be reasonably practicable in relation to the risks identified. This is particularly the case if the RAIB's other recommendations are implemented, and the risk of a similar failure occurring is thus reduced.

Reference paragraph 171.

Appendix 6.1

STAMP workshop material

STAMP Application Process

1. Identify the system(s) and hazard(s) involved in the loss
2. Identify the system safety constraints and system requirements associated with the hazard(s)
3. Document the safety control structure (can be done in parallel with later steps)
4. Determine the proximate events leading to the accident, i.e. create an accident timeline – *already done*
5. Analyse the accident at the physical system (hardware and software) level
6. Moving up the control structure levels, determine how and why each successive higher level allowed or contributed to the inadequate control at the current level
7. Examine how the overall coordination and communication throughout the system contributed to the accident
8. Determine the changes in the system and any weakening of the safety control structure that occurred over time

Figure 53 - STAMP application process form

STAMP Analysis

Your name:

1. Identify the system(s) and hazard(s) involved in the loss

- System: Railway
- Systems hazard(s):

2. Identify the system safety constraints and system requirements associated with the hazard(s)

Figure 54 - CAST step 1 and 2 form

Your name:

Analyse the accident at the physical system (hardware and software) level

Physical system description:

Safety requirements and constraints violated:

Physical controls:

Failures and inadequate controls:

Contextual factors:

1

Figure 55 - CAST step 5 form

Your name:

Analyse the higher levels of the control structure

System component description:

Safety-related responsibilities:

Unsafe decisions and control actions:

Dysfunctional interactions (e.g. mental model flaws, communication flaws):

Contextual factors:

1

Figure 56 - CAST step 6 form

Your name:

Examine how the overall coordination and communication throughout the system contributed to the accident:

Figure 57 - CAST step 7 form

Your name:

Determine the changes in the system and any weakening of the safety control structure that occurred over time

Figure 58 - CAST step 8 form

Appendix 6.2

STAMP evaluation questionnaire

STAMP Evaluation Questionnaire

Your name:

Your team number:

During the previous three-day investigation exercise in Weeks 2 and 3

1. What method(s) did you use to analyse your evidence?

Before attending the Fundamentals of Accident Investigation course

2. Were you aware of the STAMP method? Yes [ ] No [ ]

3. Had you used the STAMP method? Yes [ ] No [ ]

Some questions about STAMP

The following is a set of statements about using the STAMP method. For each statement please say whether you:

[6] – Strongly agree
[5] – Agree
[4] – Slightly agree
[3] – Are neutral
[2] – Slightly disagree
[1] – Disagree
[0] – Strongly disagree

Put a tick in the appropriate box.

	Strongly disagree			Neutral			Strongly agree
4. STAMP is a suitable method for analysing accidents	[0]	[1]	[2]	[3]	[4]	[5]	[6]
5. STAMP effectively describes the event timeline of an accident	[0]	[1]	[2]	[3]	[4]	[5]	[6]
6. STAMP effectively analyses the contribution to an accident from:							
a. Technical components, e.g. hardware, software	[0]	[1]	[2]	[3]	[4]	[5]	[6]
b. Human factors issues, e.g. workload, fatigue	[0]	[1]	[2]	[3]	[4]	[5]	[6]
c. Organisational issues, e.g. policies and procedures	[0]	[1]	[2]	[3]	[4]	[5]	[6]
d. Environmental issues, e.g. climate and noise levels	[0]	[1]	[2]	[3]	[4]	[5]	[6]

	Strongly disagree			Neutral			Strongly agree
7. STAMP provides a comprehensive description of an accident	[0]	[1]	[2]	[3]	[4]	[5]	[6]
8. STAMP effectively represents the relationships between system components (i.e. people and equipment)	[0]	[1]	[2]	[3]	[4]	[5]	[6]
9. STAMP correctly identifies the causes of an accident	[0]	[1]	[2]	[3]	[4]	[5]	[6]
10. STAMP could be applied to any type of accident in my industry	[0]	[1]	[2]	[3]	[4]	[5]	[6]

Some questions about the usability of STAMP

The following is a set of statements about the usability of STAMP. For each statement please put a tick in the appropriate box

	Strongly disagree			Neutral			Strongly agree
11. STAMP is an easy method to understand	[0]	[1]	[2]	[3]	[4]	[5]	[6]
12. The terms and concepts used in STAMP are clear and unambiguous	[0]	[1]	[2]	[3]	[4]	[5]	[6]
13. It is easy to identify the system safety requirements	[0]	[1]	[2]	[3]	[4]	[5]	[6]
14. It is easy to define the system control structure	[0]	[1]	[2]	[3]	[4]	[5]	[6]
15. It is easy to identify unsafe decisions and inadequate control actions	[0]	[1]	[2]	[3]	[4]	[5]	[6]
16. It is easy to describe:							
a. Dysfunctional interactions (e.g. communication flaws)	[0]	[1]	[2]	[3]	[4]	[5]	[6]
b. The context of decisions/actions taken by different system components	[0]	[1]	[2]	[3]	[4]	[5]	[6]
17. STAMP is an easy method to use	[0]	[1]	[2]	[3]	[4]	[5]	[6]
18. STAMP is easy to use in a team-based analysis	[0]	[1]	[2]	[3]	[4]	[5]	[6]
19. STAMP promotes team collaboration during analysis	[0]	[1]	[2]	[3]	[4]	[5]	[6]
20. A STAMP diagram is a useful communication tool	[0]	[1]	[2]	[3]	[4]	[5]	[6]
21. A STAMP analysis can be completed in an acceptable timescale (remember that you had more time to complete your analysis in Week 3)	[0]	[1]	[2]	[3]	[4]	[5]	[6]
22. It would be easy for me to become skilled at using STAMP	[0]	[1]	[2]	[3]	[4]	[5]	[6]
23. I received sufficient training in the use of STAMP to effectively use the method	[0]	[1]	[2]	[3]	[4]	[5]	[6]

Any other comments?

Appendix 6.3

STAMP workshop outputs

Hazard	**Participant number**					
	1	**2**	**3**	**4**	**5**	**6**
Trains operating during maintenance/people or equipment on track	1	1	1	1	1	1
Incorrect use/failure of speed signage	0	0	1	0	1	1
Adverse environmental conditions	0	0	1	0		1
Train derailment	0	0	0	0	1	0
Brake failure	0	0	0	0	1	0
Use of cumbersome equipment during repairs	0	0	1	0		0
Total	1	1	4	1	4	3

Table 22 - Hazard identification[7]

System safety constraint		Participant number					
		1	2	3	4	5	6
Speed restrictions	Slow trains for inspection	1	0	0	0	0	0
	Stop trains for maintenance	1	0	0	0	0	0
Personnel requirements	Duties of signalman	0	0	1	0	0	0
	Flagman warns workers of train	1	0	0	1	1	0
	Signalman stops rail	1	0	0	0	0	0
	Use of flagman	0	1	1	0	1	0
	Use of signalman	0	1	0	0	1	0
Procedures	Daily train driver briefings	0	0	0	1	0	0
	Maintenance forms	0	1	0	2	0	0
	Procedures for control of track	0	0	1	0	0	0
	Request stoppage for maintenance	1	0	0	0	0	0
	Use of radio communication devices	0	0	0	0	1	0
Speed restriction signage and warning systems	AWS to warn drivers	1	0	0	0	0	0
	Speed limit signals and AWS	0	3	2	2	0	1
	Warnings issued to train drivers	1	0	0	0	0	0
Other	Unscheduled train	0	1	0	0	0	0
	Levers to change status of track from green to red	0	0	1	0	0	0
Total		7	7	6	6	4	1

Table 23 - System safety constraint identification[7]

Physical control description		Participant number						Total
		1	2	3	4	5	6	
Physical equipment	AWS	1	2	1	0	0	0	4
	AWS master switch	0	0	0	0	0	1	1
	Driver notifications	1	0	0	0	0	0	1
	Electrical train control system	0	0	0	0	1	0	1
	Flagman flag	0	0	1	1	0	0	2
	Flagman whistle	0	0	0	1	0	0	1
	Speed limit signs	1	2	1	1	1	0	6
	Train whistle	0	0	0	1	0	0	1
	Warning label on signal lever	0	0	1	0	0	0	1
	Work permit form 181	1	0	0	1	1	0	3
Personnel	Flagman	0	1	0	0	1	0	2
Other	Reliable supervisor required	0	0	0	0	0	1	1
	Semaphore signals	0	0	0	1	0	0	1
	Work permit form held by COSS and signalman	0	1	0	0	0	0	1
Total		4	6	4	6	4	2	

Table 24 - Physical control description[7]

Physical system failures and inadequate controls		Participant number						Total
		1	2	3	4	5	6	
Physical equipment failures	AWS malfunction	0	0	0	0	0	1	1
	AWS not installed	1	2	0	0	0	0	3
	Failure of electrical control system	0	0	0	0	1	0	1
	No back-up electrical control system	0	0	0	0	1	0	1
	Speed limit signals not correctly installed	1	1	1	1	1	0	5
	Work permit form 181 open to interpretation	0	1	0	1	0	0	2
	Work permit was for inspection only	1	0	0	0	0	0	1
Personnel failures	COSS did not check speed limit sign installation	0	1	0	0	0	0	1
	Failure of engineers to follow procedures	0	0	0	0	1	0	1
	Failure of engineers to impose line blockage	0	0	1	0	0	0	1
	Failure of flagman to remain in position	0	0	0	0	1	0	1
	Failure of train drivers to adhere to speed limit	0	0	0	0	1	0	1
	Failure of train drivers to see speed limit signs	1	0	0	0	0	0	1
	Failure to change signal lever to stop position	0	0	1	0	0	0	1
	Flagman did not put up speed limit sign	0	1	0	0	0	0	1
	Flagman not in position	0	1	0	1	0	0	2
	Inadequate communication between train stations	0	0	0	0	1	0	1
	Local working arrangements voided use of train whistle	0	0	0	1	0	0	1
	Semaphore signal not activated in time	0	0	0	1	0	0	1
	Work permit form not communicated correctly	0	1	0	0	0	0	1
Other	Fatigue of workers	0	0	0	0	0	1	1
	Unscheduled train	0	1	0	0	0	0	1
Total		4	9	3	5	7	2	

Table 25 - Physical system failures and inadequate controls[7]

Appendix 6.4

STAMP evaluation questionnaire individual responses

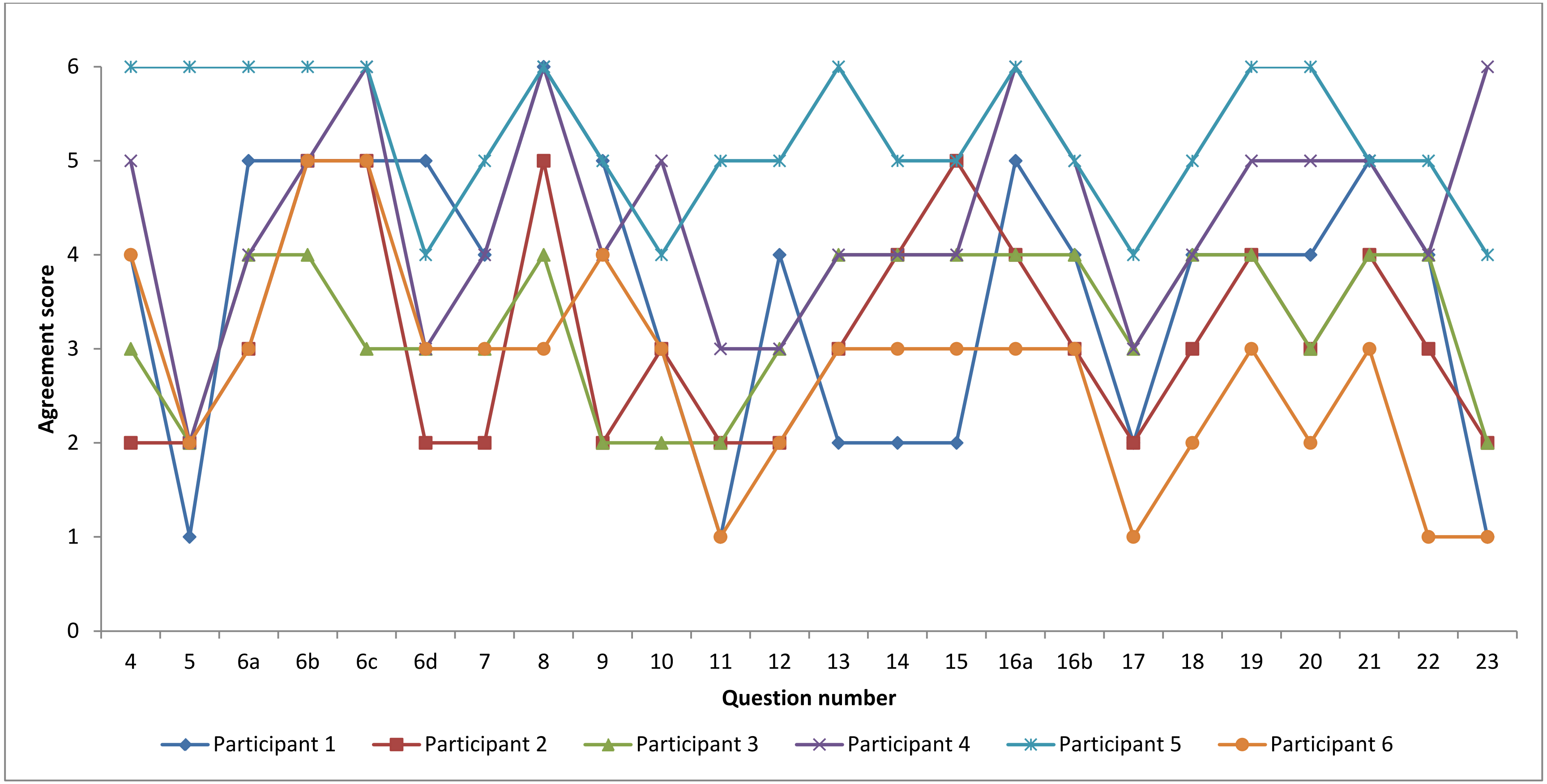

Figure 59 - STAMP evaluation questionnaire individual responses

Appendix 7.1

Examples of research-practice knowledge transfer events

Astronomy: http://www.globalsciencecollaboration.org/Events/1st-implementation-workshop-for-the-aerap-framework-programme-for-cooperation

Healthcare: http://www.acmedsci.ac.uk/index.php?pid=101&puid=243

Human factors: http://www.ehf2013.org.uk/debates-discussions/

Multi-domain: http://www.university-industry.com/pdf/Conference_Program_Final.pdf

Rail: http://rruka.org.uk/events-activities/

Robotics: http://www.europeanrobotics12.eu/news/best-practice-for-knowledge-transfer-and-industry-academia-collaboration-in-european-robotics.aspx

Appendix 7.2

System of systems definition

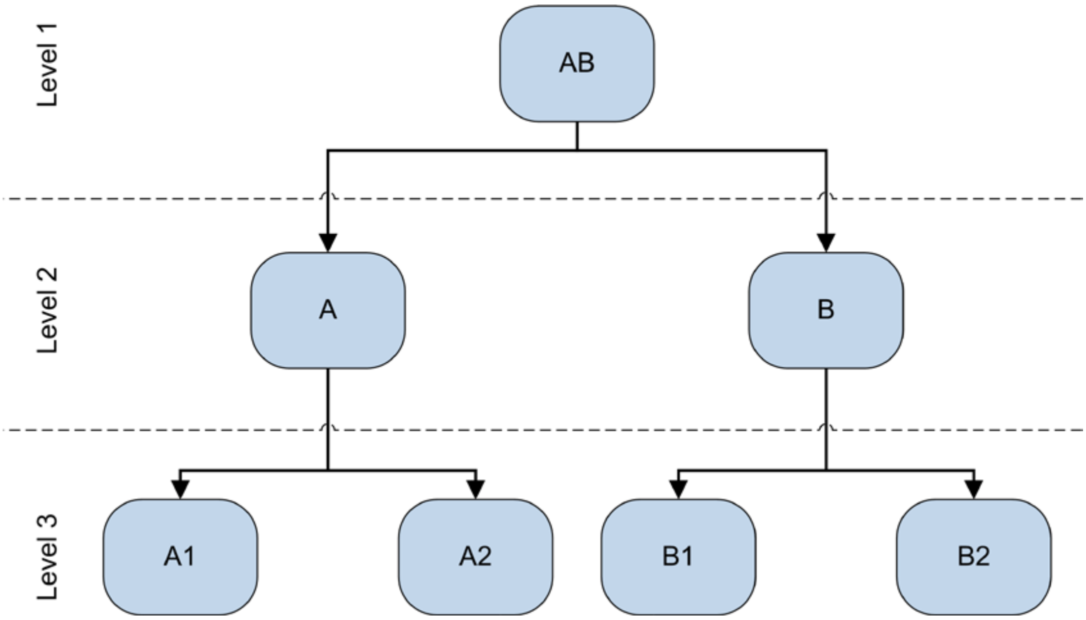

Figure 60 - System of systems vs. large system definition. Adapted from Leveson (Leveson, 2013b)

System A and System B can be considered to be in a ‘system of systems’ or part of the larger AB system.