'Remixing Rasmussen': The Evolution of Accimaps within Systemic Accident Analysis

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Abstract

Throughout Jens Rasmussen’s career there has been a continued emphasis on the development of methods, techniques and tools for accident analysis and investigation. In this paper we focus on the evolution and development of one specific example, namely Accimaps and their use for accident analysis. We describe the origins of Accimaps followed by a review of 26 studies which have applied and adapted Accimaps over the period 200-2015 to a range of domains and types of accident. Aside from demonstrating the versatility and popularity of the method, part of the motivation for the review of the use of Accimaps is to address the question of what constitutes a sound, usable, valid and reliable approach to systemic accident analysis. The findings from the review demonstrate continuity with the work carried out by Rasmussen, as well as significant variation (e.g., changes to the Accimap, used of additional theoretical and practice-oriented perspectives on safety). We conclude the paper with some speculations regarding future extension and adaptation of the Accimap approach including the possibility of using hybrid models for accident analysis.

Keywords: Accident analysis and investigation, sociotechnical systems, Accimaps, organisational design, Jens Rasmussen.

1. Introduction

During the 1980's and 1990's a series of high-profile accidents including Chernobyl (1986), Zeebrugge (1987), Challenger (1986) and Ladbroke Grove (1999) prompted researchers within the fields of human factors and safety science to move away from accounts of human error based solely around individual factors and to place more emphasis on the role played by human and organisational influences on safety. Hale and Hovden (1998) characterize the goals of what they termed the 'third age' of safety, as the achievement of a better understanding of the management issues, particularly in terms of safety 'culture' and 'climate' (Zohar, 1980; Antonsen, 2009). This shift of emphasis from 'micro' to 'macro' accounts of error (Le Coze, submitted) is reflected in the types of methods for accident analysis and investigation which developed from the 1980's up until the present day. These methods in themselves derive from a number of traditions including systems and macroergonomics (Hendrick and Kleiner, 2002; Wilson, 2014), safety engineering (Hollnagel, 2004) and cognitive systems engineering (Rasmussen, Pejtersen and Goodstein, 1994).

Figure 1 about here

More recent developments such as the growth of the internet, social media and globalisation, have introduced new forms of systemic risk into complex sociotechnical systems (e.g., security, financial and environmental risks - Goldin and Mariathasan, 2014) and are reflected in a later generation of accident analysis tools and methods (e.g., Systems-Theoretic Accident Model (STAMP) – Leveson, 2012; Functional Resonance Analysis Method (FRAM) – Hollnagel, 2012) which draw on sociotechnical systems theory, as well as the work which was conducted at the Risø Nuclear Plant by Jens Rasmussen and others from the late 1960's up until 2000 (figure 1).

1.1 Rasmussen and Systemic Accident Analysis (SAA)

The work of Jens Rasmussen and his colleagues was very much at the forefront of the new view of error which emphasised the role played by organisational and wider environmental and political factors in accident causation. In a paper summarising a workshop held at the World Bank in October, 1988 to discuss risk management in the wake of the late 1980's financial crisis (Rasmussen and Batstone, 1989), he emphasised the fact that technological and societal developments along with increasing competitive and commercial pressures on companies, had raised the potential for major accidents to occur. He also emphasised that part of the challenge involved in combating these pressures was the need for an expanded account of human behaviour which was sensitive to organisational and cultural context:

"… the human factors specialists are challenged to expand their vision beyond the confines of human error and reliability analysis and to explore ways in which they could link with the cognitive, decision, systems and organizational specialists in developing risk profiles of organizational and management systems in different regulatory and cultural environments (page iii) … *The rapid trend in the technological development now calls for a fresh view on risk management and safety control in large-scale hazardous systems* (p. 39)… (Rasmussen and Batstone, 1989).

This emphasis was repeated a number of times in subsequent publications in the 1990's, for example, in the much cited paper which introduced the risk management framework (Rasmussen, 1997). The paper also included Rasmussen's dynamic model of safety, the purpose of which was to demonstrate how economic considerations and workload pressures can move the system away from safe performance and closer to the margin of error (figure 2):

"We need more studies of the vertical interaction among levels of socio-technical systems with reference to the nature of the technological hazard they are assumed to control." (Rasmussen 1997, p. 187).

Figure 2 about here

These ideas were incorporated into the Accimap method which was subsequently developed by Rasmussen and Inge Svedung in the late 1990's and early 2000's (Rasmussen, 1997; Rasmussen and Svedung, 2000; Svedung and Rasmussen, 2000). Accimaps attempt to model the dynamic interaction between multiple sociotechnical levels (regulatory, organisational, workplace) and account for the role these play in shaping the course of an accident as it happens over time. The use of Accimaps to provide insight into accidents and human error has grown in the last few years and a number of papers have applied the method to a wide variety of safety domains (e.g., public health – Vicente and Christoffersen, 2006; oil and gas industries – Hopkins, 2000; aerospace – Johnson and de Almeida, 2008). Figure 3 (a) shows a graph of the number of citations of Rasmussen (1997) starting form the first year in which it received a citation (2000). Figure 3 (b) shows a similar graph of citations for Rasmussen and Svedung (2000). Recent interest in Accimaps and other aspects of Rasmussen's approach to safety and risk management is demonstrated by the fact that in 2014 the 1997 paper received its highest number of citations relative to other years (n=84). Aside from the academic community, Accimaps are also used for accident analysis and human factors training within a number of organisational contexts (e.g., the UK's Rail Safety and Standards Board, Royal Australian Air Force – Branford, 2010).

Figures 3 (a) and (b) about here

1.2 Aims and objectives of the paper

In this paper we consider the how Accimaps and their use have evolved over the last decade and a half and how they have been used by other researchers. The paper partly came about as the result of the authors using Accimaps in order to analyse safety across a variety of different application areas (e.g., Healthcare, Policing and

Transport). Another aim was to provide details of part of the later period of Rasmussen's career (following on from other accounts which focus on his early work – e.g., Green, 1988; Sanderson and Harwood, 1988; Vicente, 2001). The specific objectives of the paper are:

- To carry out a review of studies which have used Accimaps for systemic accident analysis over the period 2000-2015 and is based on a framework which considers aspects of the theoretical and practical of using Accimaps (e.g., theoretical background to the study, aspects of the procedure used to build the Accimap; changes to the original format of the Accimap);
- To consider the outcomes from the review in terms of what it illustrates about the theory and practice of Systemic Accident Analysis (SAA) and the legacy of Jens Rasmussen.

2. The origins of the Accimap

In this section we first describe the format and content of the original version of the Accimap as outlined in Rasmussen (1997) and Svedung and Rasmussen (2000). We trace back the origins to two components or 'building blocks' from earlier work namely the 'abstraction hierarchy' and 'decision ladder'and the influence of ideas from control theory and engineering.

2.1 Accimap format and content

Accimaps typically focus on failures across six levels of analysis: government policy and budgeting; regulatory bodies and associations; local area government planning & budgeting (including company management, technical and operational management); physical processes and actor activities; and equipment and surroundings. According to Rasmussen (1997) each systemic level is involved in safety management via the control of hazardous processes through laws, rules, and instructions. For systems to function safely decisions made at high levels should promulgate down and be reflected in the decisions and actions occurring at lower levels of the system. Conversely, information at the lower levels (e.g. staff, work, equipment) regarding the system's status needs to transfer up the hierarchy to inform the decisions and actions occurring at the higher levels. Without this so called ‘vertical integration’, systems can lose control of the processes that they are designed to control (Cassano-Piche et al., 2009). Rasmussen (1997) argues that accidents are typically ‘waiting for release’ (p. 190); the stage being set by the routine work practices of various actors working within the system. Normal variation in behaviour then serves to release accidents. The risk management framework and Accimap method are shown in Figures 4 and 5.

Figures 4 and 5 about here

It is worthwhile noting that Rasmussen (1997; Svedung and Rasmussen, 2000) describe a set of sub-components within the overall Accimap – the Actormap, Infomap and Conflict Map). Actormaps provide ‘a layout of the decision-makers, planners, and actors who have been involved in the preparation of accidental conditions’ (Svedung and Rasmussen, 2000, p. 18). The intention behind Infomaps is to show lines of strong and weak communication within an organization. Finally, Conflict Maps illustrate potential conflicts and tensions between actors that might have contributed to the preconditions for the incident (de Almeida and Johnson, 2008).

2.2 Accimaps, the ‘abstraction hierarchy’ and ‘decision ladder’

Looking through the publications and reports produced by Rasmussen dating back to 1968 provides a number of insights into the origins and subsequent development of Accimaps. As Cook (2014) points out, Rasmussen was a very visual thinker whose work was shaped by his training in electronics and engineering (see also Vicente, 2001 for an explanation of Rasmussen’s background on his subsequent work on human error). The various papers and Risø reports produced by Rasmussen and colleagues are frequently illustrated by a variety of engineering diagrams, drawings and other graphical material. Some of this material shows signs of some of earliest stages in the development of the risk management framework and Accimaps. Figure 6 for example is an early attempt (1974) to describe the ‘abstraction hierarchy’ (Rasmussen and Vicente, 1989) or ‘decision ladder’ (Rasmussen, 1986). Each successive rung in the ladder represents the mental operations of the operator as they move from assessing the current system state (e.g., a control room interface) towards the target state to be achieved. A similar hierarchy (figure 7) is described in another paper (Rasmussen, 1987) where the focus is on the interaction between physiological and psychological factors and their combined role in contributing toward human error. In comparing figures 6 and 7 it seems not unreasonable to speculate that Rasmussen was gradually shifting the emphasis in his work on human error further ‘upwards’ in the hierarchy and moving toward an account of the influence of managerial and wider organisational factors in accident causation. A movement that was taken further and integrated into his work on the risk management framework and Accimaps through the inclusion of political, economic and regulatory factors (figure 4).

Figures 6 and 7 about here

2.3 The influence of control theory

Rasmussen’s work involved consulting a wide range of sources and evidence of reading across a large range of disciplines within the physical, engineering and social sciences. Le Coze (submitted) similarly argues that much of his work demonstrated the influence of thinking based on cybernetics and the work of Norbert Wiener and William Ross Ashby amongst others (e.g., mechanisms for system feedforward and feedback). Leveson (submitted) also points to the influence of control theory on his research from the 1960’s onwards. The Accimap 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:

"The propagation of an accidental course of events is shaped by the activity of people that either can trigger an accidental flow of events or divert a normal flow. Safety, then, depends on the control of work processes so as to avoid accidental side effects causing harm to people, environment, or investment"(Rasmussen and Svedung, 2000, p.9)

Figure 8 (Rasmussen, 1968) shows an example of the use of a box and arrow diagram to describe the interaction between the operator and the instrumentation within a process plant. Similarly, figure 9 (Rasmussen, 1980) illustrates a model of the human operator in a control system which incorporates more sophisticated aspects of the information processing. It is interesting to draw parallels between these box-model control flow diagrams and the arrangement of causal factors, preconditions and consequences which contribute towards an accident and make up part of the Accimap diagram (figure 4). Rasmussen's earlier work within control theory and the abstraction hierarchy/decision ladder appear to be integrated in subsequent research and accident analysis in the late 1990's and early 2000's.

Figures 8 and 9 about here

3. Recent research using Accimaps

3.1 Search strategy

In order to identify recent studies which have used Accimaps to analyse large-scale, complex accidents, we adopted a strategy of working backwards from the scientific published literature (e.g., within bibliometric databases), as well as looking at articles citing the original publications and reports by Rasmussen which relate to Accimaps (i.e., Rasmussen, 1997; Rasmussen and Svedung, 2000; Svedung and Rasmussen, 2002). The search covered the period 2000-2015 and was conducted in June 2015. A final method of locating studies was to compare our own personal lists of studies and to discuss our literature amongst ourselves (all four authors have been active Accimap users over the last few years). We also contacted and gathered information from other researchers who had used and published papers in the last decade or so. Four databases were searched using the term ‘Accimap*’ and variations of the form of the word (e.g., AcciMap, ACCIMAP), these were: the ISI Web of Science; Google Scholar, Ergonomics Abstracts and PsycINFO.

3.2 A framework for analysing and comparing the use of Accimaps

In order to cover both the theoretical implications of using Accimaps and details of practical concerns (e.g., how they were constructed), we used 10 separate categories in order to compare studies, these covered: the context in which the Accimap was used (e.g., healthcare, transport, aviation); the goals and objectives of the study (e.g., providing a systemic account of the factors contributing to the accident); the theoretical background of the study (e.g., sociotechnical systems theory); the procedure described in building the Accimap (e.g., use of two or more analysts; use of thematic coding or other qualitative data analysis methods); the outcomes from the analysis (e.g., type of Accimap); comparisons with other models (e.g., with HFACS, STAMP); levels of analysis (i.e., number and type of levels used); casual factors (i.e., number); changes to the standard Accimap (i.e., major/minor deviations from the format of the Accimaps described in Rasmussen and Svedung, 2000); and, other details (i.e., any other noteworthy or idiosyncratic features of the analysis).

4. Findings

4.1 Recent research using Accimaps

Table 1 shows the results of searching though the four databases. We removed duplicates and studies which did not report in details using Accimaps to carry out an analysis of an accident (e.g., Branford et al., 2009 where guidelines for the use of Accimaps are described; Salmon et al., 2012 where a high-level illustration of the application of Accimaps to road transport is presented) and studies which reported using the Accimap in two or more publications (e.g., in a journal article and conference presentation). The final sample comprised 26 studies. Table 2 lists the authors and titles of these studies. Appendix 1 contains a list of the studies and their publication details.

Tables 1 and 2 about here

4.2 Applying the framework

Table 3 is a summary of the results of applying the framework described in section 3.2 to the 26 studies. In subsequent sections (4.2.1 to 4.2.5) of the paper, we refer to individual studies with reference to their numbering in table 2 (e.g., study 2 is Woo and Vicente, 2005).

Table 3 about here

4.2.1 Context of use

A total of 10 separate domains are covered by the studies: Manufacturing (12); Nuclear (13); Aviation and Aerospace (5, 14, 16, 21 and 23) ; Emergency Response (22); Civil Engineering (25); Oil and Gas (1, 24); Public Health (2, 6, and 7); Transport (Rail – 3, 17, 18, 26 and Road – 21 and 26); Outdoor Recreation (8, 9); and Policing and Security (10, 11). The most frequent use of Accimaps occurs in Aviation and Aerospace (5 studies), Transport (Rail – 4 studies), and Public Health (3 studies).

4.2.2 Study goals and objectives and theoretical background

Most of the papers stated that their overall goal was to analyse a complex sociotechnical system and understand the role played by a range of contributory factors in causing an accident to occur. Within this broad category, Accimaps were sometimes used to underline specific aspects and advantages of adopting and applying a systems approach towards accident analysis. For example, studies mentioned the value of Accimaps in terms of their ability to apply a ‘holistic’ (13), ‘big picture’ (14), ‘system of systems’ (24) viewpoint or approach towards accidents. The use of a set of predictions set out by Rasmussen (1997) concerning the risk management framework (e.g., ‘Safety as an emergent property of a complex socio-technical system’) was employed in order to test the explanatory adequacy of the framework for specific domains (e.g., Public Health – 4, 6; Policing and Security – 10; emergency response – 22; Accidents involving young drivers – 26). Other papers placed emphasis on the value of using Accimaps to probe deeper into the 'causal networks' (1), 'interdependencies' (10) and general system-wide failures (24) within complex sociotechnical systems. Accimaps were also used in order to highlight the role played by specific systemic features of accidents which are sometimes underplayed or neglected by other accident analysis techniques (e.g., organisational factors – 7, 16; the dynamic interplay between individual cognition, decision-making and motivation in accident scenarios – 10, 11, 16, and 26). Finally, a few studies compared the outcomes from an Accimap analysis with other accident analysis methods (e.g., Root Cause Analysis – 8; STAMP - 9, 18; Australian Transportation Safety Board (ATSB) Model – 18; HFACS – 9).

The theoretical stance adopted by most studies corresponded to Rasmussen's (1997; figure 2) model of the boundaries of acceptable and unacceptable performance within sociotechnical systems. It is also clear that the studies drawn on a diverse range of disciplines and theoretical traditions in their use of Accimaps, these include: theory oriented around high reliability organisations (Weick and Sutcliffe, 2007) – 1; Normal Accident Theory (Perrow, 1984 – 23); schema theory (Neisser, 1976) - 10, 11 and 16; and, organisational sociology – 1 (Turner, 1978); as well as disciplines such as computer science and logic – 3, safety science and safety engineering – 5, 12, 24 and 25, and human factors, cognitive ergonomics and general engineering – 10, 11, 17, 13 and 20).

4.2.3 Procedure and outcomes

The relative unconstrained manner in which Accimaps are constructed has led a number of authors to raise questions concerning the reliability and validity of Accimaps (e.g., Johnson and de Almeida, 2008; Branford, 2007; Branford et al., 2009; Waterson and Jenkins, 2010, 2011). For this reason we examined the procedure which was used to construct Accimaps across the 26 studies (e.g., the use of coding to identify causal contributory factors; procedures for reviewing the Accimap). Just over half of the studies in the sample (15) did not provide details of the procedure that was used to construct the Accimap. The most common procedure followed was for one or more of the study authors to carry out an initial analysis of the accident and then to present the Accimap for review by other co-authors or analysts (8, 9. 10, 11, 16, 17, 20, 22, 25). In other cases, subject matter or domain experts (e.g., outdoor activity instructors; experts in rail safety) reviewed the Accimaps and suggested some modifications and revisions (9, 16 and 22). In two studies, the method used for qualitative analysis was described in detail (e.g., thematic analysis – Braun and Clarke, 2006 – 24, 25). In other cases explicit detail was provided of the stages in which the Accimap was constructed (e.g., 7, 12).

A range of different outcomes came about from using Accimaps. Some studies for example, use a combination of Accimap, Actormap and Conflict Map in order to describe the accident (2, 5 and 6). In other cases, the Accimap and Actormaps were used to capture causal factors, as well as possible countermeasures which could be put in place to prevent the accident happening again (18). Study 25 involved the use of an aggregate Accimap in order to summarise contributory factors leading to accidents involving young drivers, as well as possible countermeasures. A more common approach was to use the Accimap in combination with another method or accident model (e.g., Why-Because Analysis – Ladkin and Loer, 2008 – 3; Root Cause Analysis – 8; HFACS and STAMP – 9; the Swiss Cheese Model – 15). Many studies provided additional annotation or detail to the basic format of the Accimap (e.g., annotating causal and cross-level relationships – 7, 10; integrating a timeline with the Accimap – 10, 11, representing subsystems in a system-of-systems - 22), as well as using other techniques to provide additional analytical power to the accident analysis (e.g., the use of CWA – 11; Neisser's perceptual cycle – 11, 16). In two studies, the Accimap was used as a basis with which to construct a new model or method (e.g., the AcciTree method which combines Accimaps with a taxonomy based on HFACS – 19; 'Impromaps' which focus on accidents caused by operator improvisation – 20).

4.2.4 Levels of analysis, causal factors, changes and other details

Most studies did not deviate from the standard six levels of analysis as described by Rasmussen (1997). Where there were variations, these tended to be in cases where there was a need to re-label the levels to fit a specific context or application domain (e.g., Hospital management – 7; pedestrian level – 29). The average number of Accimap casual factors described in the study sample, excluding Actormaps and

Conflict maps, was 38. The number of Accimap causal factors ranged from 7-71 and reflects that some studies presented a simplified overview of the accident (e.g., 1), whereas other went into more details and attempted to describe the complex interdependencies which existed between causal factors (e.g., 10, 11). The number of causal factors and level of detail in the Accimap is related to the goals and objectives of the study (section 4.2.2) – some studies (e.g., 1) presenting an overview of the accident, whilst others (10, 11) providing a very detailed, minute-by-minute account of how the accident unfolded across a range of stakeholders. Two studies added 'fault trees' or 'logic gates' to the Accimap (2 and 5), whilst other minor changes were made to the original format in order to accommodate testing of Rasmussen's predictions (6, 8) and formulating a set of cross-level hypotheses (e.g., the interaction between organisational and group levels of analysis – Karsh et al., 2014, study 7).

5. Discussion

5.1 'Remixing Rasmussen'

The 26 studies in tables 2 and 3 share a great deal in common with the original formulation of the Accimap as set out by Rasmussen in the late 1990's and early 2000's. Many of them draw on the dynamic model of safety and system performance (figure 2), as well as other theoretical aspects of the risk management framework (e.g., testing the predictions set out by the framework). Most of the studies also preserve the core Accimap 'building blocks' (section 2; e.g., levels of analysis; layout of causal factors). However, there is also large variation across the studies and these provide some insights into the ways in which the various researchers have been inspired by Rasmussen's work. Some of these variations might be said to reflect the way in which Rasmussen's work on the Accimap has been 'remixed', reinterpreted and evolved over the last few decades. In this section we focus on two aspects of this evolution or 'remixing' process which relate to the theoretical and practical aspects of systemic accident analysis.

5.1.1 Systemic accident analysis: 'rhetorical' aspects of Accimap usage and theory elaboration

All of the studies in the sample aimed to provide a systemic account of factors which contribute towards accidents. Part of this involves emphasising that accidents do not come about as a result of single failures, but are attributable to a range of causal factors distributed across various part of the larger system. Despite the popularity of this view amongst the research community, single-factor explanations often prevail (Dekker et al., 2011). Part of the motivation in using Accimaps might therefore be said to be *rhetorical*: the Accimap provides a means with which to counter this view and to act as a demonstration of the value of adopting a systems perspective on human error, particularly in domains where the ‘bad apply’ theory of accidents (Dekker, 2014; Jun et al., submitted) continues to persist (e.g., aviation – Holden, 2009; study 15). This is especially important in new areas of application where application of the system approach has little precedence (e.g., studies 2, 4, 6, 7, 8, 10, 11, 21). In recent and as yet unpublished work, for example, we have used Accimaps as a means to demonstrate the complexity of accident causation in public safety (food safety) and maritime accidents (shipping collisions - Nayak and Waterson, in preparation; Murray et al., submitted). One of the reasons for doing this was to counter overly–reductionist, person-centred accounts of accident causation in these domains (see for example Pennington, 2003 for an account of how this applies within food safety).

A second goal of systemic accident analysis is to probe deeper into inter-relationships and causality across system levels. The use of Accimaps in study 11 for example, alongside other elements of Rasmussen’s work (e.g., the decision ladder) attempted to integrate cognitive factors at the group level of analysis with a second set of factors related to individual decision-making. A similar desire to understand the causal inter-relationships between different levels of analysis was part of the motivation for using Accimaps in Waterson (2009, study 7). In this case, the analysis began as an attempt to underline the importance of the role of organisational factors in hospital infection control – one use of Accimaps which is common to a number of studies (e.g., 12 and 15). However, subsequent analysis using Accimaps *facilitated* the incorporation of theory drawn from organisational behaviour (in this case the co-called ‘meso-paradigm’ – House et al., 1995), alongside a set of multi-level hypotheses. The use of Accimaps in these and other studies, helped to clarify theoretical aspects of systemic accident analysis, as well as identify gaps in our understanding of the relationship between micro and macro systems components. How far we can go with multi-causal explanations is the subject of some debate (e.g., Reason, 1999; Shorrock et al., 2004), however, it is clear that one ‘spin-off’ from the use of Accimaps is that they help the analyst to develop new insights into the complex causal inter-relationships involved in accidents.

In general, an important characteristic of the evolution of Accimaps since their original formulation has been their use to elaborate and articulate new directions for theory within accident analysis. Part of this has come about because Accimaps focus on providing a systemic overview, as well as an examination of causal inter-relationships. The process of constructing the Accimap might be said to be akin to accident ‘sensemaking’ (Weick, 1995) in that understanding and mapping causal factors within the Accimap often involves unravelling, or at least hypothesising, relationships across and between a wide range of levels of analysis within the overall system in question. Working through the Accimap helps to resolve ambiguities, as well as identifying new hypotheses and areas for further investigation (e.g., links with individual cognition, motivation, group attitudes – studies, 10, 11, 16 and 26). Vaughan (1992, p.175-6) in her account of the process of understanding the causes of the Space Shuttle Challenger Accident describes a similar process in her description of what she calls ‘case analysis’:

“Because of the different sorts of data available from micro- and macro-level analysis, choosing cases that vary both the unit of analysis and the level of analysis, when possible, can lead to the elaboration of theory that more fully merges micro- and macro- understandings. Third, this method can be particularly advantageous for elaborating theories, models, and concepts focusing on large, complex systems that are difficult to study”

It might well be argued that this process of theory elaboration is common to all methods and model of accident analysis (figure 1). The key difference between these methods and models, however, is that in terms of procedure Accimaps are relatively unconstrained and are not intended to be used in a prescriptive, ‘top-down’ manner. The freedom afforded by Accimaps allows the analyst to explore a range of options for analysis and encourages experimentation and exploration of explanations which draw on the systems approach and systems theory. Rasmussen (1999, p. xi) made the following comment about Cognitive Work Analysis (CWA) and much the same philosophy might be said to apply to Accimaps:

"the CWA framework is not a prescriptive method … it is a point of view, a state of mind, and a demonstration of the various dimensions of the problem of analysing work performance in a dynamic society"

5.1.2 Practical trade-offs: validity, reliability and utility

The extent to which models, methods and tools for systemic accident analysis produce outcomes which are valid (e.g., the degree to which the Accimap analysis successfully identifies the causes of an accident) and reliable (e.g., the degree to which accident analysts produce similar Accimaps) are often viewed as an important criteria for judging their appropriateness for accident analysis. For example, in discussing general human factors and ergonomics methods, Baber and Stanton (2002, p. 218) suggest that *"there seems little point in employing a method that does not pass even the basic requirements of validity and reliability"*. Likewise, Kanis (2014) argues that many methods in human factors and ergonomics fail to achieve acceptable levels of reliability and validity when used by both researchers and practitioners. More recently, Ryan (2015) included issues of reliability and validity in a list of eight requirements for methods for accident investigation and analysis.

Table 4 about here

Accimaps appear to meet the first seven requirements in table 4; however, across the 26 studies in the sample there are good reasons for questioning the degree to which they produce reliable and valid outcomes. The majority of studies for example, report very few details of how the Accimap was constructed. In other cases, the use of multiple coders/analysts and validation with domain experts might provide some degree of confidence that a degree of reliability and validity can be achieved by following the right procedure. Branford (2007) has carried out a very the detailed set of studies of the reliability and validity of Accimaps. She concluded that Accimap analyses do not always correctly identify the causes of accidents or the most appropriate corrective actions to prevent their recurrence. In order partly to improve on the validity and reliability, Branford et al., (2009) produced a set of nine guidelines covering construction of the Accimap. These guidelines provide a set of steps and prompts for analysts and are a considerable improvement on the limited information available in Rasmussen (1997; Rasmussen and Svedung, 2000).

Questions concerning the reliability and validity of human factors and accident analysis methods are often raised in conjunction with similar concerns about usability (i.e., how easy if the model, method etc. to use) and utility (how useful are the outcomes regardless of, for example, issues of validity and reliability). In some ways, the chief virtue of the Accimap is that it is relatively easy to use. As one participant at the Rasmussen Legacy symposium held in 2014 at Risø commented: *"it's easy for practitioners to quickly get going with an Accimap, furthermore they understand it straight away"*. The experience of the authors of this paper is that the graphical representations produced by Accimaps also make them very suitable for communicating with audiences from backgrounds and specialisms outside of human factors. This is reinforced by other research comparing various system accident analysis methods and models and assessing the degree to which safety specialists and other practitioners are met by current systemic accident methods and models (Underwood and Waterson, 2013, 2014, submitted). We note however, that there may also be drawbacks with regard to the use of graphical representations. Hollnagel (2004, 2004, pp. 123-124) for example, that accident analysis models such as Accimap are limited to the extent to which they can map multi-causal relationships since they rapidly become overly-complicated when too many casual factors are included (one possible reason, for example, why the average number of contributory causes in our sample is around 35-40 – section 4.2.4).

In some respects questions centred on the reliability and validity of Accimaps may be missing the point. Accimaps are primarily used for the purpose of accident *analysis* (e.g., understanding factors which caused the accident, suggesting countermeasures) and not *investigation* (e.g., finding a root cause or set of root causes). An analogy might be drawn with some observations made by Karl Weick on the trade-offs involved in developing theory within the social sciences (Weick, 1979) and models and methods for accident analysis. Weick (drawing on earlier work by Thorngate, 1976) uses the metaphor of a clock face to argue that it is impossible for a theory of social behaviour to be simultaneously general, accurate and simple - two of these three characteristics may be possible, but not all three. Thus the more general and simple a theory, for example, the less accurate it will be in predicting specifics. Attempts to secure any two of the 'virtues' of a theory will mean that the third will be sacrificed. 'Two o'clock theories' for example, are general and accurate, but they will not be simple. This clock face analogy might well be usefully applied to tools, models and methods for accident analysis. Accimaps might be said to fit the category of a 'two o'clock method (general and simple), but not necessarily accurate.

5.1.3 Accimaps and SAA as 'bricolage'

A final aspect of the 'remixing' process which has taken place in the last decade or so is the construction of new forms of Accimap, alongside combining components (e.g., error taxonomies – study 15, Swiss Cheese, study 19 - HFACS) from other methods and models in order to embellish or improve the outputs from Accimap analysis. The process of constructing these 'hybrid' versions of the original Accimap might be viewed as similar to what the anthropologist Claude Levi-Strauss (1962) called 'bricolage', that is 'the construction [*e.g., an artefact, narrative, tool*] or creation from a diverse range of available things' (Concise Oxford English Dictionary, 12th Edition, 2011). The process of bricolage is very much in keeping with the pragmatic approach taken by many of the 26 studies, and indeed might well have been Rasmussen's original intention. Rasmussen and Svedung (2000) present a variety of Accimaps in their report, many of them with different components and with little guidance covering how to construct these. From this point of view articulating and exploring accidents, as well as demonstrating the value and merit of a systemic approach (section 5.1.3 above), may be more important than applying or being bound by strict criteria such as reliability and validity (section 5.1.2).

6. Summary and new directions

Our review of the studies which have followed on from Jens Rasmussen's in the late 1990's is testament to the influence his work has had on other researchers. Accimaps continue to evolve and Rasmussen's work continues to be 'remixed'. Rasmussen was a pioneer in the field of systemic accident analysis and can be considered as one of the most important founders of the approach. It is a fitting tribute to his work that the tradition of seeing to explain human error beyond individual boundaries has spawned so many followers in the last few decades. Moreover, his legacy has generated both theoretical and practice-oriented debates which are very much grounded within a tradition of research which Lintern (2012) described as work-focused analysis and design. Much of this contrasts with more recent attempts to develop what Dekker (2011) characterises as 'Systems version 2', where the emphasis is perhaps more on conceptual and theoretical description, rather than data-driven analysis and evaluation.

A number of possible future directions for Accimaps are possible, many of which are already underway. Firstly, there is much scope for the further development of 'hybrid' accident models based on the basic Accimap format. Rather than develop new models, there is plenty of scope to 'mix and match' and 'remix' many of the model which already exist (Hovden et al., 2010; Le Coze, 2013). The combination of the HFACS method and Accimaps for example, has already been undertaken by some studies (e.g., study 19), but this could be expanded, or at least experimented with (i.e., in keeping with the spirit of 'bricolage described earlier). Accimaps might benefit from the support of the types of error taxonomic available in HFACS. Likewise, there is scope to develop additional categories of error to suit specific domains (e.g., rail transport) where the HFACS taxonomy may need to be tailored to specific needs and requirements and expanded. Secondly, the guidelines put forward by Branford et al., (2009) could be taken a step further. These might encompass recommendations covering the evaluation and validation of Accimap outputs (e.g., in the manner of some studies which have included these details in their procedure – studies 9, 16 and 22). This sort of future work might help to improve reliability and validity and many, well-respected examples are discernible within the literature on qualitative data analysis (e.g., Corbin and Strauss, 2008), as well as accident analysis (e.g., Snook, 2000). Finally, understanding causality across system levels represents a critical challenge for understanding risks to safety (Hettinger et al., 2015).

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Word Count = 6, 214 (excluding figures and tables)

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Appendix 1: Research using Accimaps (2000-2015)

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Figure 1: The development of methods for sociotechnical systems and safety (adapted from Waterson et al., 2015)

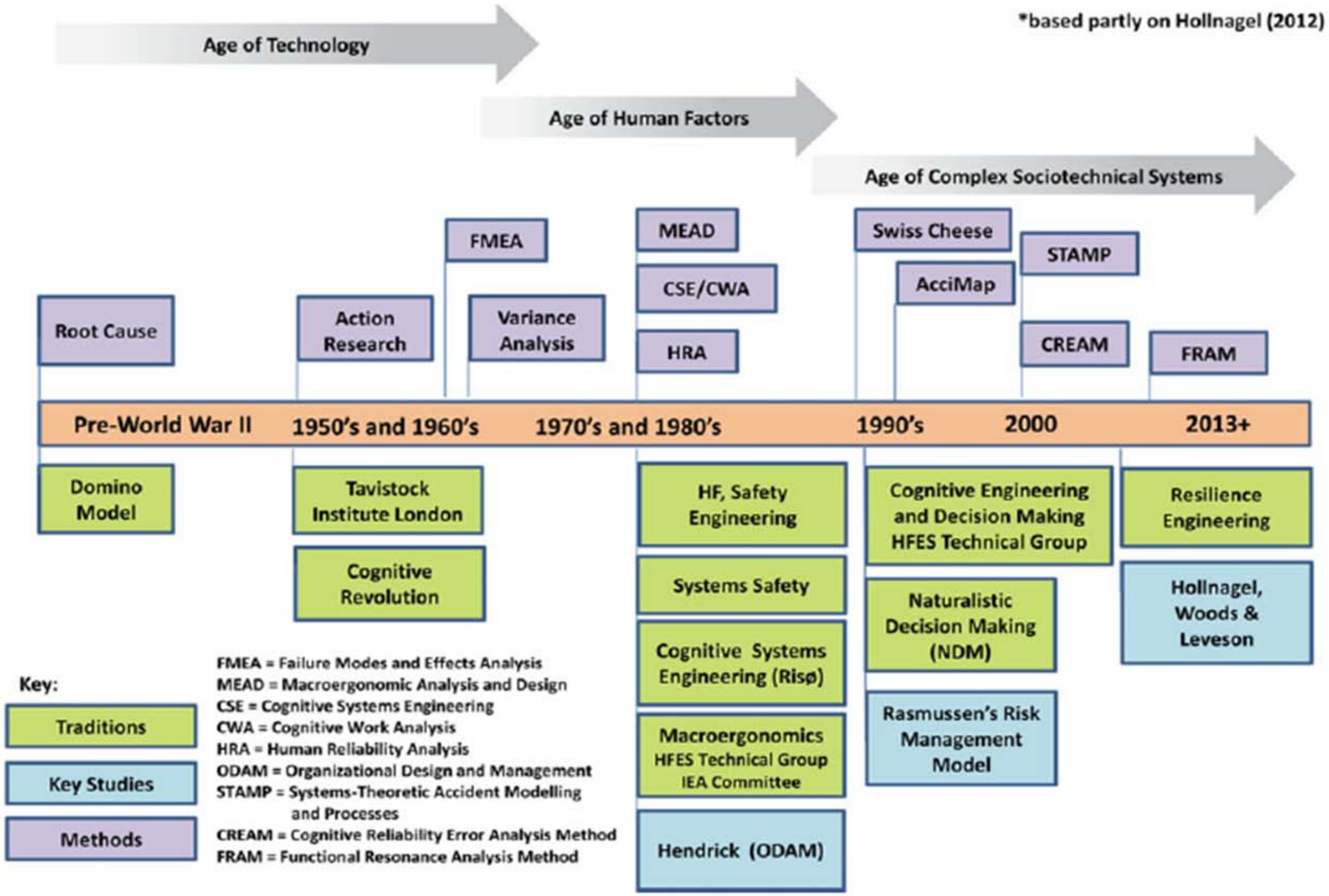


Figure 2: Dynamic model of safety and system performance (Rasmussen, 1997)

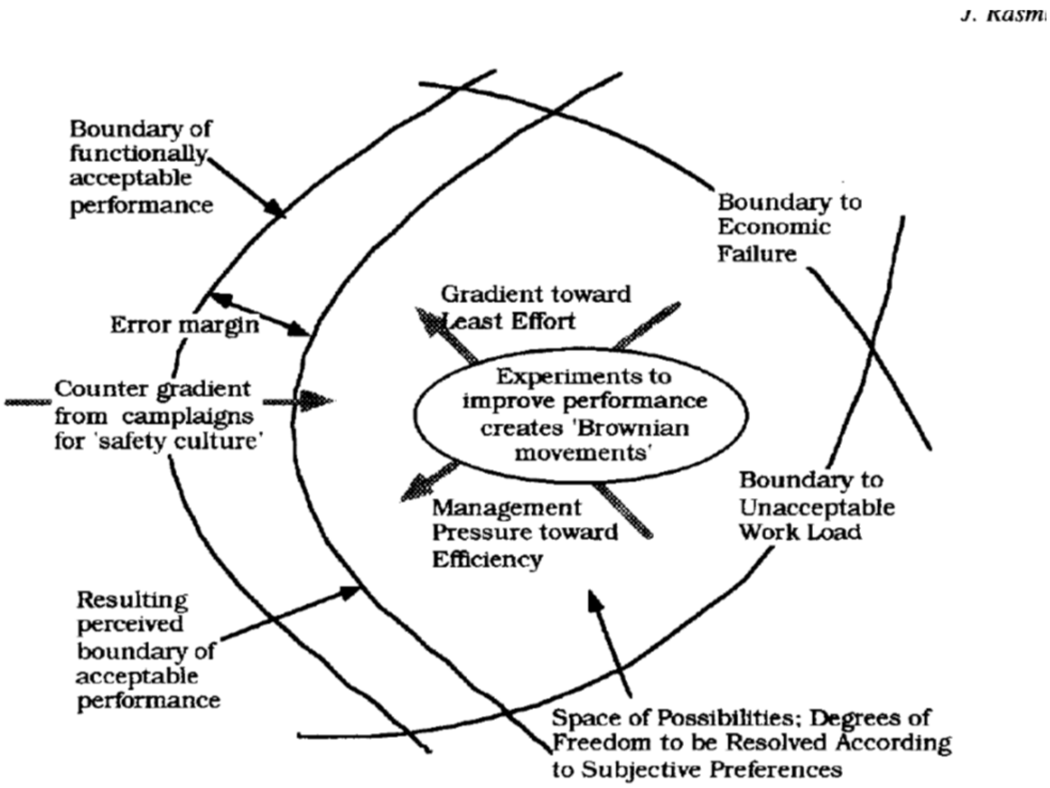
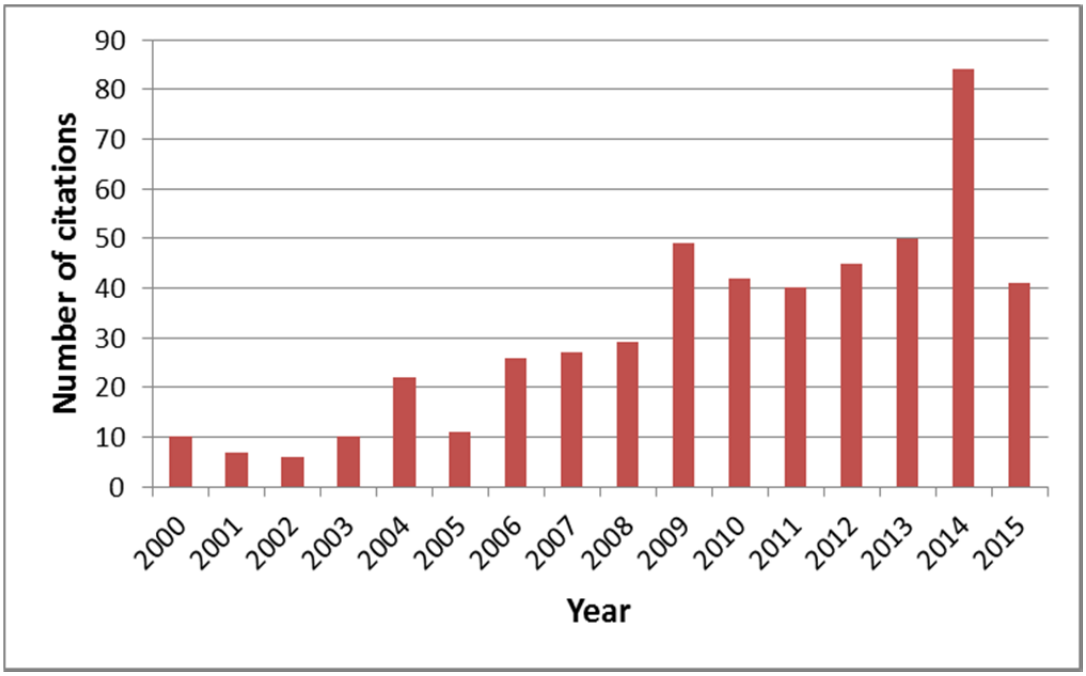


Figure 3: (a) Citations of Rasmussen (1997) over the period 2000- June 2015; (b) Citations of Rasmussen and Svedung (2000) over the period 2000- June 2015

(a)



(b)

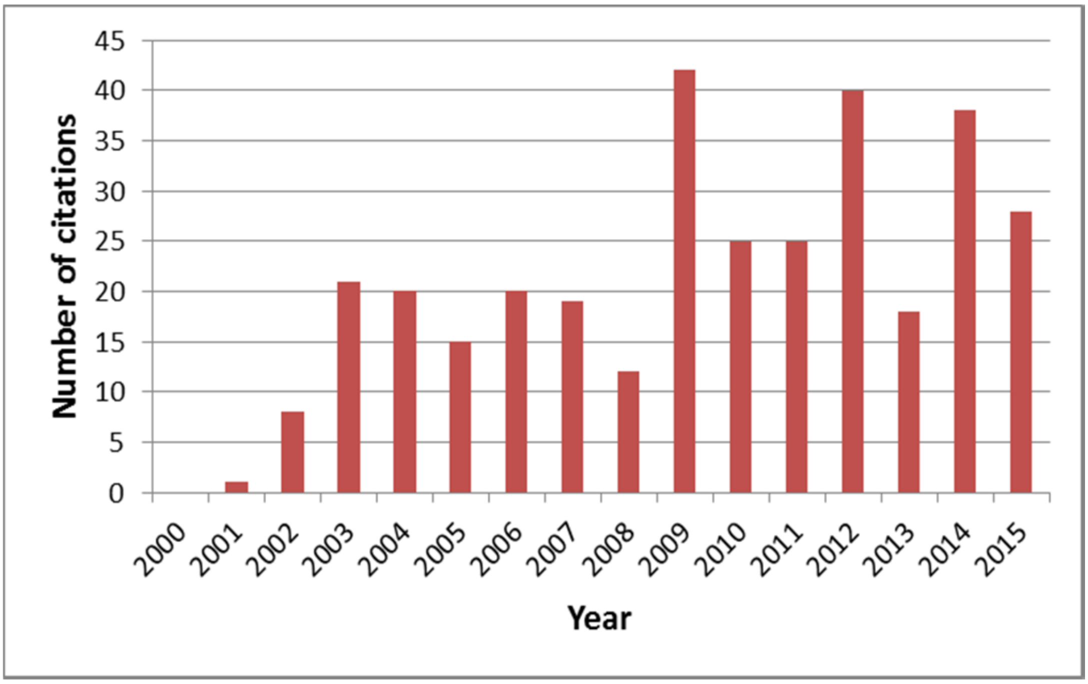


Figure 4: The risk management framework (Rasmussen, 1997)

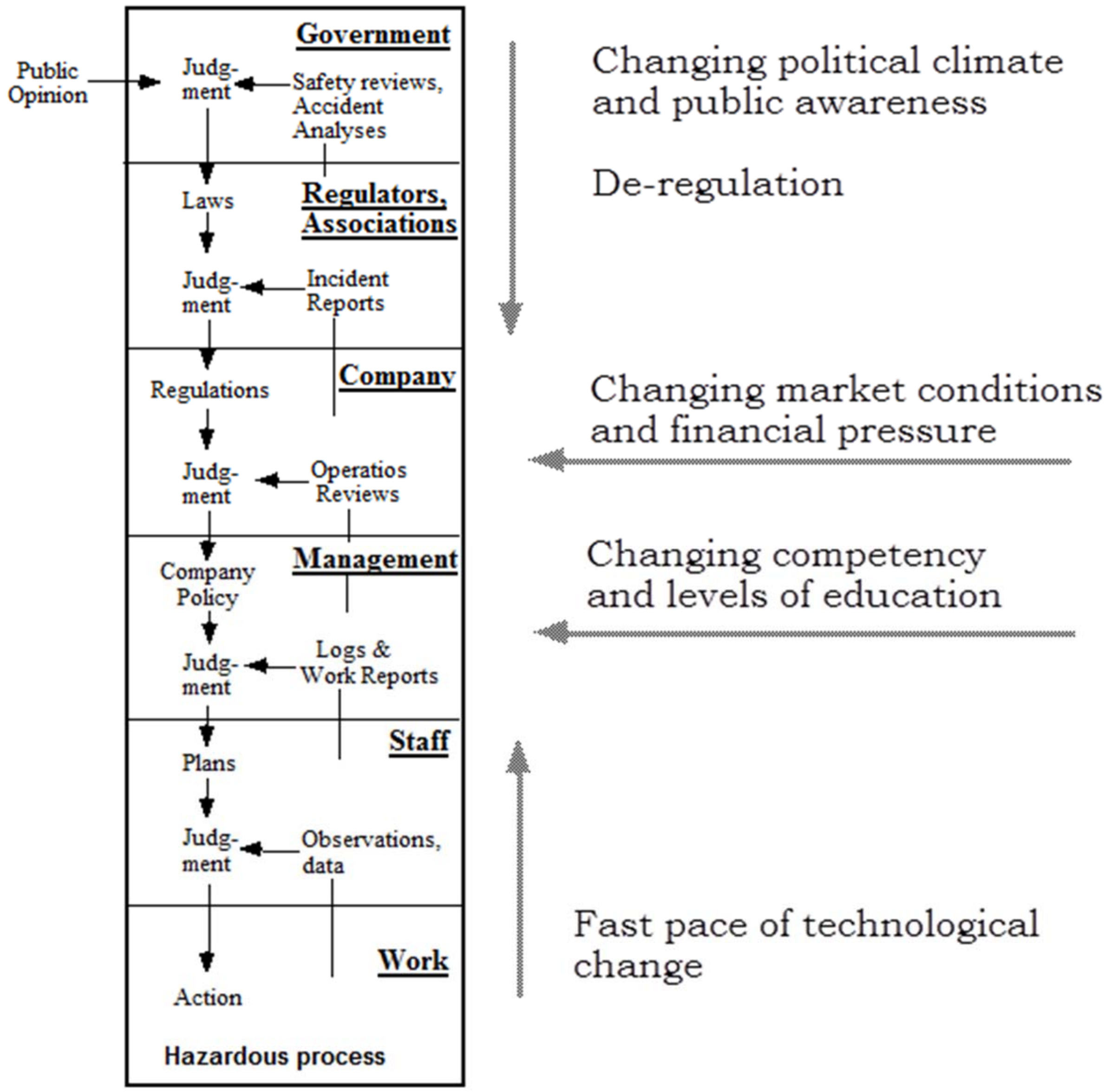


Figure 5: Accimap diagram format (adapted from Rasmussen and Svedung, 2000, p. 21)

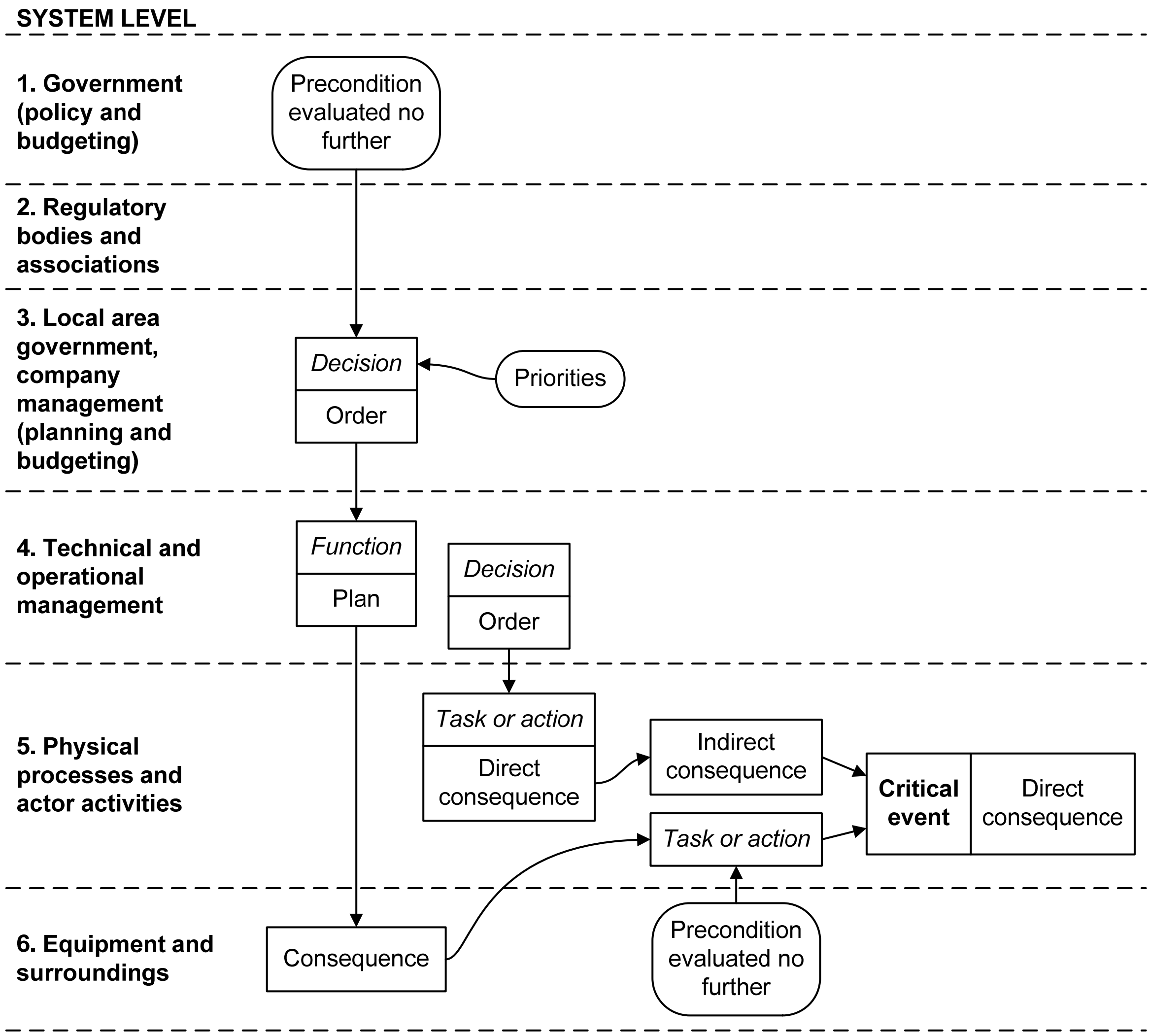


Figure 6: The operator's 'ladder of abstraction' Rasmussen (1974)

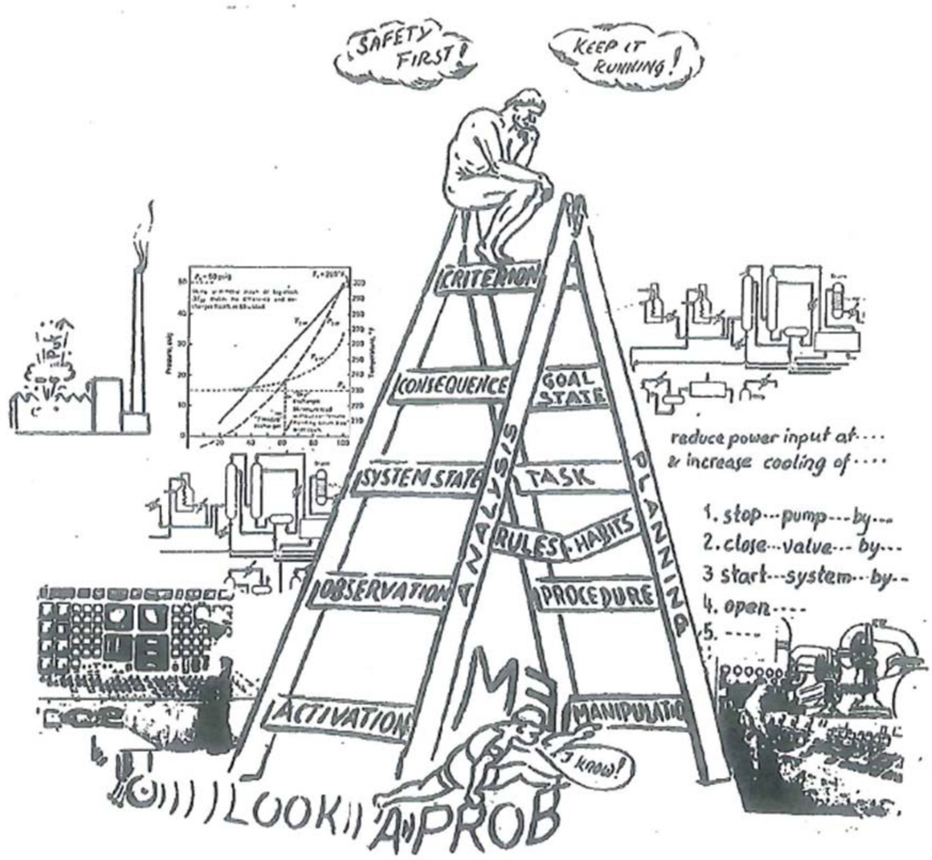


Figure 7: Complex interaction in a man-machine system (Rasmussen, 1982)

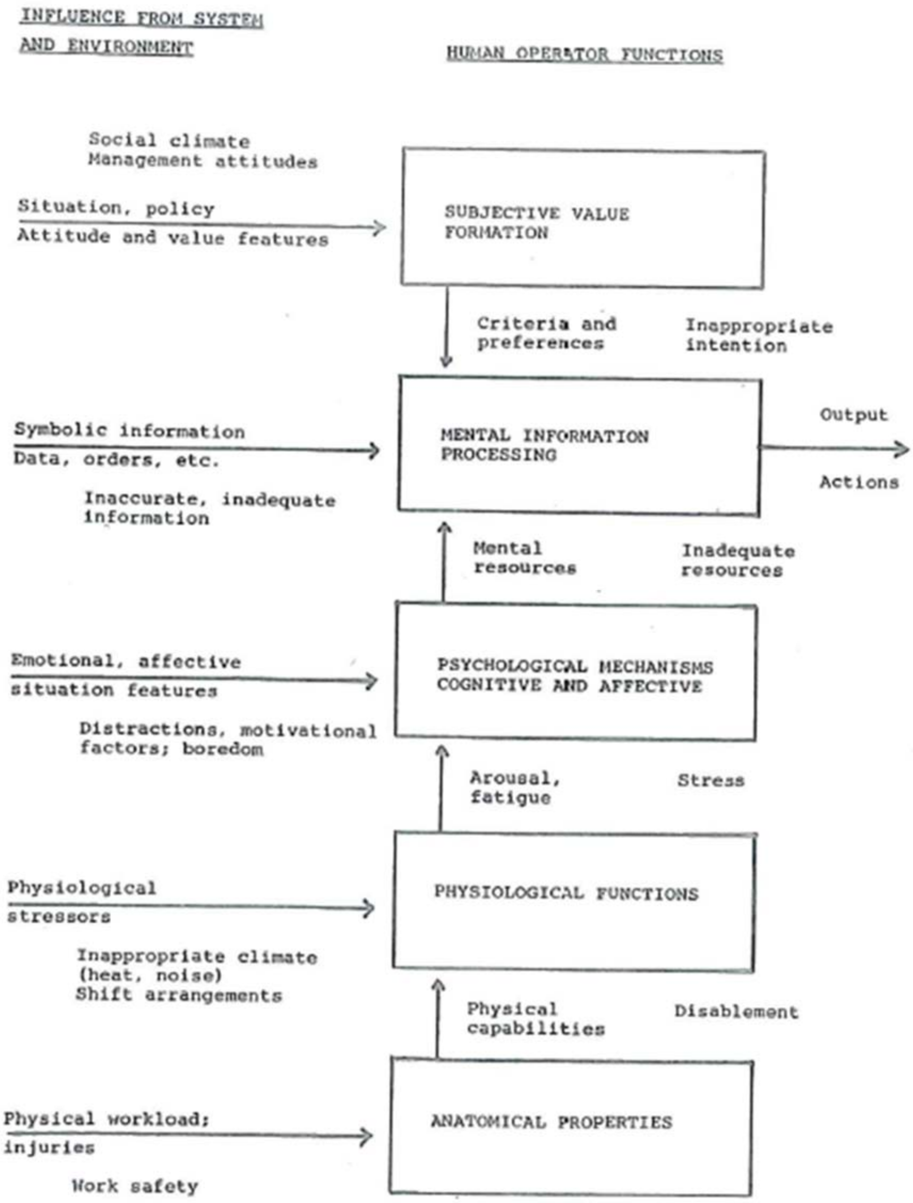


Figure 8: Diagram of control system (Rasmussen, 1968)

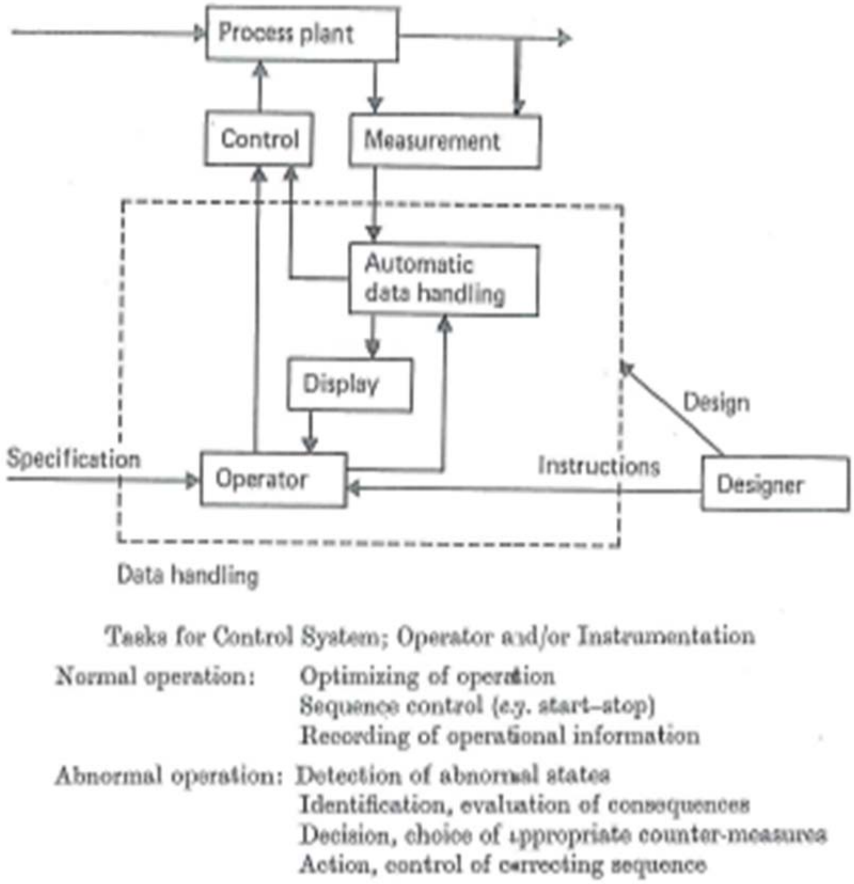


Figure 9: Model of the human operator in a control system (Rasmussen, 1980)

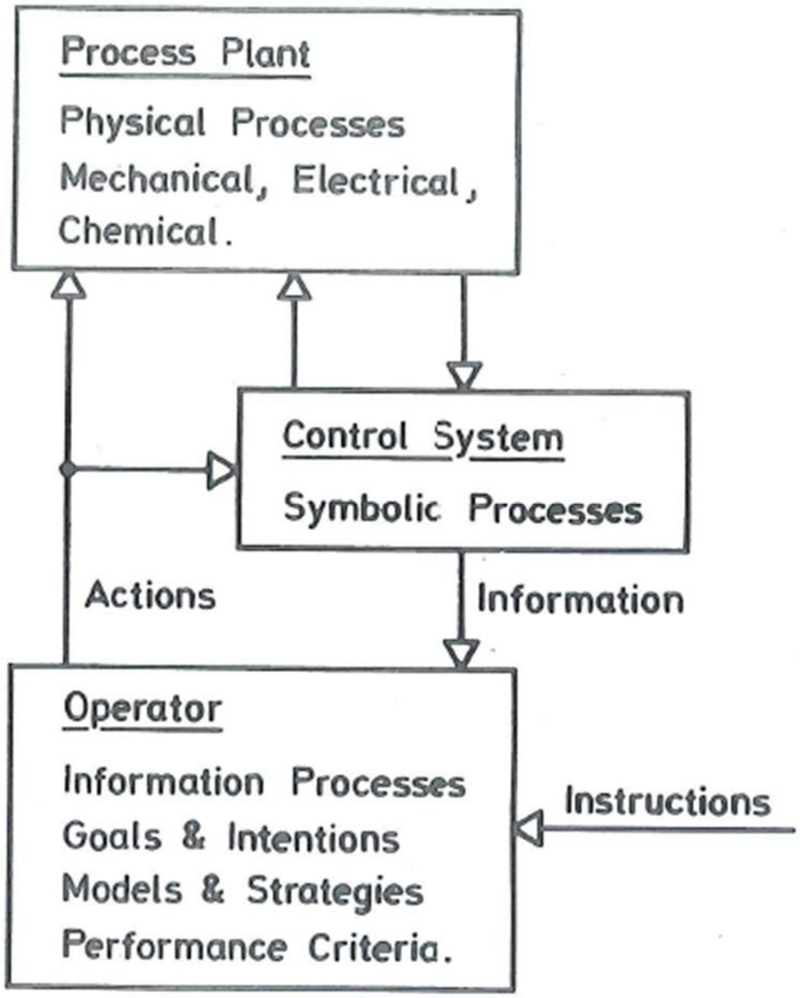


Table 1: Database search results

Database	Number of hits	Articles describing use of Accimaps
Web of Science	15	13
Google Scholar	251	21
Ergonomics Abstracts	11	11
PsycINFO	9	9

Table 2: Study sample

	Study Authors	Study Title
1	Hopkins (2000)	Lessons From Longford: The Esso Gas Plant Explosion
2	Woo and Vicente (2003)	Sociotechnical systems, risk management, and public health: comparing the North Battleford and Walkerton outbreaks
3	Ladkin (2005)	Why-Because analysis of the Glenbrook, NSW rail accident and comparison with Hopkin's AcciMap
4	Vicente and Christophsen (2006)	The Walkerton *E. coli* outbreak: a test of Rasmussen's framework for risk management in a dynamic society
5	Johnson and de Almeida (2008)	An investigation into the loss of the Brazilian space programme's launch vehicle VLS-1 V03
6	Cassano-Piche et al. (2009)	A test of Rasmussen's risk management framework in the food safety domain: BSE in the UK
7	Waterson (2009)	A systems ergonomics analysis of the Maidstone and Tunbridge Wells infection outbreaks
8	Salmon et al. (2010)	Systems-based accident analysis in the led outdoor activity domain: application and evaluation of a risk management framework
9	Salmon et al. (2012)	Systems-based analysis methods: a comparison of Accimap, HFACS and STAMP.
10	Jenkins et al. (2010)	A systemic approach to accident analysis: A case study of the Stockwell shooting.
11	Jenkins et al. (2011)	What could they have been thinking? How sociotechnical system design influences cognition: a case study of the Stockwell shooting
12	Le Coze (2010)	Accident in a French dynamite factory: An example of an organisational investigation
13	Andersson (2010)	Using Accimaps to describe the emergence of critical work situations – a systemic approach to analyse evaluation
14	Branford (2011)	Seeing the big picture of mishaps – applying the AcciMap approach to analyze system accidents
15	Debrincat et al. (2013)	Assessing organisational factors in aircraft accidents using a hybrid Reason and AcciMap model
16	Salmon et al. (2013)	The crash at Kerang: Investigating systemic and psychological factors leading to unintentional non-compliance at rail level crossings
17	Underwood and Waterson (2014)	Systems thinking, the Swiss Cheese model and accident analysis: a comparative systems analysis of the Grayrigg train derailment using the ATSB,

Table 2: Study sample

	Study Authors	Study Title
		Accimap and STAMP models
18	Scott-Parker et al. (2014)	The driver, the road, the rules … and the rest? A systems-based approach to young driver road safety
19	Lei et al. (2014)	An integrated graphic–taxonomic–associative approach to analyze human factors in aviation accidents
20	Trotter et al. (2014)	Impromaps: Applying Rasmussen’s Risk Management Framework to improvisation incidents
21	Salmon et al. (2014)	A systems approach to examining disaster response: Using Accimap to describe the factors influencing bushfire response
22	Harvey and Stanton (2014)	Safety in System-of-Systems: Ten key challenges
23	Tabinzadeh and Meshkati (2015)	Applying the AcciMap methodology to investigate a major accident in offshore drilling: a systematic risk management framework for oil and gas industry
24	Fan et al. (2015)	Analysis for Yangmingtan bridge collapse.
25	Newman and Goode (2015)	Do not blame the driver: a systems analysis of the causes of road freight crashes
26	Stefanova et al. (2015)	Systems-based approach to investigate unsafe pedestrian behaviour at level crossings

Table 3: Applying the framework to the 26 studies

	1	2	3	4	5	6	7	8	9
	Hopkins (2000)	**Woo and Vicente (2003)**	**Ladkin (2005)**	**Vicente and Christopherson (2006)**	**Johnson and de Almeida (2008)**	**Cassano-Piche et al. (2009)**	**Waterson (2009)**	**Salmon et al (2010)**	**Salmon et al. (2012)**
Context of use	Oil and Gas - Explosion at Esso Gas Plant in Longford, Australia resulting in 2 fatalities and widespread disruption	Public Heath - Comparison of two public health *E. coli* outbreaks in Canada (North Battleford and Walkerton)	Rail – Glenbrook train collision (1999)	Public Health – Walkerton *E. coli* outbreak	Aerospace- Explosion of Brazilian Space Vehicle	Public Health – UK 1996 BSE ('Mad Cow' Disease) outbreak	Public Health (Hospital) – Outbreaks of *Clostridium difficile* at Maidstone and Tunbridge Wells NHS Trust (2005-2007)	Outdoor Recreation – Lyme Bay Canoeing Incident (1993)	Outdoor Recreation – Mangatepopo Gorge Incident (2008)
Goals and objectives	Attempt to lay out 'causal networks' leading up to the explosion (Hopkins, 2000, p. 120)	Analysis of complex socio-technical factors contributing to outbreaks (emphasis on public policy and public health)	Comparison with Accimap developed by Hopkins (2005)	Analysis of complex socio-technical factors contributing to outbreaks (emphasis on public policy and public health)	Analysis of complex socio-technical factors contributing to the explosion and how this developed over time. Comparison with STAMP analysis (Leveson, 2003)	Analysis of complex socio-technical factors contributing to outbreaks (emphasis on role played by food production supply chain)	Analysis of complex socio-technical factors contributing to outbreaks (emphasis on role played by organisational/ regulatory factors which contributed to the outbreaks – e.g., Trust management)	Testing the usefulness of the Accimap approach for explaining how and why accidents occur in the outdoor domain (Salmon et al., 2010, p. 927)	Case study based on Mangatepopo Gorge Incident comparison of three methods - Accimap, HFACS and STAMP

Table 3: Applying the framework to the 26 studies

	1	2	3	4	5	6	7	8	9
	Hopkins (2000)	**Woo and Vicente (2003)**	**Ladkin (2005)**	**Vicente and Christopherson (2006)**	**Johnson and de Almeida (2008)**	**Cassano-Piche et al. (2009)**	**Waterson (2009)**	**Salmon et al (2010)**	**Salmon et al. (2012)**
Theoretical background	Organisational Sociology; Findings partly interpreted through High Reliability Organisation (HRO) theory	Rasmussen's model of boundaries of acceptable and unacceptable performance (Rasmussen, 1997)	Logic, computer science approach towards complex systems analysis	Rasmussen's model of boundaries of acceptable and unacceptable performance (Rasmussen, 1997)	Safety-critical systems and Rasmussen's model of risk management and socio-technical failure (Rasmussen, 1997)	Rasmussen's model of boundaries of acceptable and unacceptable performance (Rasmussen, 1997)	Sociotechnical systems theory; Rasmussen's risk management framework (1997)	Sociotechnical systems theory; Rasmussen's risk management framework (1997)	Sociotechnical systems theory; Rasmussen's risk management framework (1997)
Procedure	No explicit mention of procedure (Hopkins, 2000, p. 122)	No explicit mention of procedure	No explicit mention of procedure	No explicit mention of procedure	No explicit mention of procedure but authors discuss issues related to reliability and validity of their analyses	No explicit mention of procedure, but coverage of how predictions were linked to aspects of the Accimap and Conflict Maps	Two stages: (1) System description – mainly involving document analysis and coding; (2) System modelling based on Risk Management Framework (Rasmussen, 1997)	Two analysts using one of two methods (Accimap and Root Cause Analysis - RCA). Three additional researchers reviewed the outputs from the analysts. A validation review was conducted by a group of domain experts and subsequent Accimap and RCA models were modified.	Three human factors experts used the three methods to analyse the incident and collectively reviewed their outputs. An experienced outdoor activity instructor reviewed the outcomes from the analysis.

Table 3: Applying the framework to the 26 studies

	1	2	3	4	5	6	7	8	9
	Hopkins (2000)	Woo and Vicente (2003)	Ladkin (2005)	Vicente and Christopherson (2006)	Johnson and de Almeida (2008)	Cassano-Piche et al. (2009)	Waterson (2009)	Salmon et al (2010)	Salmon et al. (2012)
Outcomes	Causal diagram of Esso Gas Plant Accident (Hopkins, 2000, p.122)	Accimaps for each outbreak; timelines; Actormap of counterproductive interactions (Woo and Vicente, 2003, p. 266)	Comparison and critique of Hopkin's Accimap ; Combination of Accimap with Why-Because-Analysis (WBA)	Accimaps for the outbreak; timeline	Generic Actormap, Conflict Map and Accimap	Accimaps for the outbreak; timeline; annotated 'conflict map' showing poor vertical integration during the outbreak	Adaptations of the risk management framework covering contributory factors; cross-level and whole system relationships.	Accimap for the incident; RCA model (Davidson, 2007)	Accimap, HFACS (Wiegmann and Shappell, 2003) and STAMP (Leveson, 2004) models.
Comparison with other models	None	None	Comparison with Accimap	None	Comparison with STAMP (Leveson, 2003)	None	None	Comparison with RCA (Davidson, 2007)	Comparison with HFACS and STAMP
Levels of analysis	5 levels: Societal; Government/ Regulatory System/ Company/ Organisational/ Physical Accident Sequence	6 levels: Government/ Regulatory Bodies/Local Government/ Technical and Operational Management/ Physical Processes and Actor Activities/ Equipment and Surroundings	Not applicable	6 levels: Government/ Regulatory Bodies/Local Government/ Technical and Operational Management/ Physical Processes and Actor Activities/ Equipment and Surroundings	6 levels: Government/ Regulatory Bodies/Local Government/ Technical and Operational Management/ Physical Processes and Actor Activities/ Equipment and Surroundings	6 levels: Government/ Regulatory Bodies/Local Government/ Technical and Operational Management/ Physical Processes and Actor Activities/ Equipment and Surroundings	6 levels: Government/ Regulatory / Trust Governance/ Hospital Management/ Clinical Management/ Equipment and Surroundings	6 levels: Government/ Regulatory / Trust Governance/ Hospital Management/ Clinical Management/ Equipment and Surroundings	6 levels: Government/ Regulatory / Trust Governance/ Hospital Management/ Clinical Management/ Equipment and Surroundings

Table 3: Applying the framework to the 26 studies

	1	2	3	4	5	6	7	8	9
	Hopkins (2000)	**Woo and Vicente (2003)**	**Ladkin (2005)**	**Vicente and Christopherson (2006)**	**Johnson and de Almeida (2008)**	**Cassano-Piche et al. (2009)**	**Waterson (2009)**	**Salmon et al (2010)**	**Salmon et al. (2012)**
Causal factors	27 factors, most organised at the 'organisational' level of analysis	Walkerton – 33 factors; North Battleton – 53 factors. Mostly evenly distributed for both outbreaks	Not applicable	33 factors	33 factors	43 factors	7 contributory factors; 3 hypothesised cross-level relationships and 3 whole system relationships	42 factors	61 factors
Changes to standard Accimap	Small deviation from original formulation	No major changes	Not applicable	No major changes	Small deviation from original formulation (no distinction drawn between indirect and direct causes)	No major changes; addition of 'critical event' factor	Use of the Risk Management Framework and not standard Accimap format	Small deviation from original formulation (no distinction drawn between indirect and direct causes)	Small deviation from original formulation (no distinction drawn between indirect and direct causes)
Other details	Relatively simple Accimap; use of arrows to indicate cross-level causality	Integration of 'logic gates' in the Accimap	Graphical representation of WBA and Accimap	Integration of fault trees in the Accimap. Attempt to test some of the 'predictions' made by Rasmussen's (1997) Risk Management Framework	Actormap is used as the basis for the Accimap. Conflictmap is used to illustrate inter-relationships between actors, decisions and other influences leading up to the explosion	Attempt to test some of the 'predictions' made by Rasmussen's (1997) Risk Management Framework	Attempt to hypothesise difference causal relationships within the hospital. No identification of specific causal factors.	Attempt to test some of the 'predictions' made by Rasmussen's (1997) Risk Management Framework; Comparison with RCA outputs	Comparison between three methods; recommendation that Accimaps include a domain specific taxonomy of failure modes

Table 3: Applying the framework to the 26 studies

	10	11	12	13	14	15	16
	Jenkins et al. (2010)	**Jenkins et al. (2011)**	**Le Coze (2010)**	**Andersson (2010)**	**Branford (2011)**	**Debrincat et al. (2013)**	**Salmon et al. (2013)**
Context of use	Policing - Stockwell (2005) shooting	Policing - Stockwell (2005) shooting	Manufacturing – Accident in a dynamite factory at Billy Berclau, France (2003)	Nuclear – 'Out-of-The Loop'(OOTL) performance problem in automation	Aviation – Analysis of the Überlingen mid-air collision	Aviation – Crash of Royal Australian Navy King Helicopter (2005)	Rail – Accident at level crossing involving a vehicle at Kerang, Australia (2007)
Goals and objectives	Exploration of the interdependencies and between actions, omissions and decisions which led up to the shooting incident	Builds on Jenkins et al. (2010), but focuses on individual factors (flow of alerts, information, goals, task and procedures (Jenkins et al. 2010, p. 103).	Aim is to illustrate trends in safety auditing and accident investigation with an emphasis on targeting organisational factors (Le Coze, 2010, p. 80)	Exploration of how Accimaps can be used to provide a holistic overview of automation related problems	Demonstration of the ('big picture') benefits of the Accimap approach towards systemic accident analysis	Aim is to determine which tools can assist with achieving organisational improvement within the aviation industry, particularly in terms of identifying and visualising organisational factors.	Aim is to examine the level crossing system in which the accident took place and understand the actions of the individual truck driver in crossing the track in the presence of an oncoming train
Theoretical background	Sociotechnical systems theory; Rasmussen's risk management framework (1997)	Sociotechnical systems theory; Rasmussen's risk management framework (1997). Use of a number of theoretical approaches to analyse the incident (e.g., situational awareness, Endsley,	Safety engineering and management; human and social sciences	Human factors, safety science	Rasmussen's model of boundaries of acceptable and unacceptable performance (Rasmussen, 1997)	Systemic accident analysis; Human factors approach (James Reason)	Sociotechnical systems theory; Rasmussen's risk management framework (1997). Use of a number of theoretical approaches to analyse the incident (e.g., schema theory, Neisser, 1976)

Table 3: Applying the framework to the 26 studies

	10	11	12	13	14	15	16
	Jenkins et al. (2010)	**Jenkins et al. (2011)**	**Le Coze (2010)**	**Andersson (2010)**	**Branford (2011)**	**Debrincat et al. (2013)**	**Salmon et al. (2013)**
		1995; schema theory, Neisser, 1976, decision-ladder, Rasmussen, 1974)					
Procedure	One human factors practitioner (lead author) carried out the analysis, co-authors (3) checked and validated the analysis	Lead author generated the models, these were then validated by the 4 co-authors	No explicit procedure described for the Accimap, but steps in the analysis of the accident described (e.g., building up detailed chronology, identifying barriers, investigating business environment)	No explicit mention of procedure	No explicit procedure described for the Accimap	No explicit procedure described for the Accimap	Three human factors experts initially discussed the findings from the investigation report; one expert build the Accimap and two others reviewed the results; the Accimap was refined through discussion and reviewed by two rail safety practitioners and the lead investigator from the official investigation team
Outcomes	Accimap for the incident, 'time stamped' and coded according to time phase, causal relationships and 'weak' causal links	As Jenkins et al. (2011), but with additional analysis based on schema theory, decision ladders	Accimap of the accident	Accimap describing the factors influencing OOTL performance during use of an automatic turbine system in a nuclear plant	Accimap of the accident	Accimap of the accident and development of hybrid model based on Reason's (1990) Swiss Cheese model	Accimap for the accident with additional analyses applying Schema theory (Neisser perceptual cycle – Neisser, 1976) in

Table 3: Applying the framework to the 26 studies

	10	11	12	13	14	15	16
	Jenkins et al. (2010)	Jenkins et al. (2011)	Le Coze (2010)	Andersson (2010)	Branford (2011)	Debrincat et al. (2013)	Salmon et al. (2013)
							order to account for the truck driver's behaviour
Comparison with other models	None	None	None	None	None	Comparison with Swiss Cheese Model	None
Levels of analysis	6 levels: Government Policy and Budgeting/Regulatory Bodies and associations/Local Area Government, Planning and Budgeting, Company Management (strategic command)/Technical and Operational management (Tactical Command)/ Physical Processes and Actor Activities/ Equipment and	As Jenkins et al. (2011)	6 levels: Society, market/Government regulatory system/ Company/ Site management/ Operational management/Shop floor and installations	4 levels: Company management/Technical and operational management/ Physical Processes and operator activities/ Equipment and Surroundings	4 levels: External/Organisational/ Physical and Actor Events, Processes and Conditions	No explicit mention of levels of analysis	6 levels: Government/ Regulatory / Trust Governance/ Hospital Management/ Clinical Management/ Equipment and Surroundings

Table 3: Applying the framework to the 26 studies

	10	11	12	13	14	15	16
	Jenkins et al. (2010)	**Jenkins et al. (2011)**	**Le Coze (2010)**	**Andersson (2010)**	**Branford (2011)**	**Debrincat et al. (2013)**	**Salmon et al. (2013)**
	Surroundings						
	43 factors	As Jenkins et al. (2011)	36 factors	21 factors	29 factors	26 factors	36 factors
Changes to standard Accimap	Addition of 'time stamp' and coding according to time phase, causal relationships and 'weak' causal links	As Jenkins et al. (2011)	Labels covering the levels of analysis within the overall system changed	Annotation of Accimap with 'paths' which describe factors likely to contribute to OOTL problems	Simplification of system levels (4 as compared to standard 6), shading used to highlight the role played by the air traffic controller in the accident and the influences within the overall system upon their actions and decisions	No explicit labelling of system levels of analysis; Accimap simplified with causal connection numbered ; levels (e.g., safety culture, working environment) distributed across the Accimap	No major changes to the standard format
Other details	Attempt to test some of the 'predictions' made by Rasmussen's (1997) Risk Management Framework; Use of	Accimap used as a basis for further application of theory in order to understand the decision-making process of individuals	Study places emphasis on the role played by changes within the history of the company and how this ultimately shaped the course of the accident	Accimap is partly used to identify function allocation problems and assess likelihood of occurrence of cognitive error (e.g.,	Accimap is partly used to illustrate the influence of the broad sociotechnical context in aviation safety	Accimap records casual factors across the whole of the system; deviates from standard format and had a 'freeform' structure	Additional analysis using schema theory in order to embellish the systems analysis with an individual, psychological account

Table 3: Applying the framework to the 26 studies

	10	11	12	13	14	15	16
	Jenkins et al. (2010)	Jenkins et al. (2011)	Le Coze (2010)	Andersson (2010)	Branford (2011)	Debrincat et al. (2013)	Salmon et al. (2013)
	decision-ladders (Rasmussen, 1974) to depict allocation of function between personnel resources during the shooting	during the incident		divided attention)			of the accident

Table 3: Applying the framework to the 26 studies

	17	18	19	20	21	22	23	24
	Underwood and Waterson (2014)	**Scott-Parker et al. (2014)**	**Lei et al. (2014)**	**Trotter et al. (2014)**	**Harvey and Stanton (2014)**	**Salmon et al. (2014)**	**Tabinzadeh and Meshkati (2015)**	**Fan et al. (2015)**
Context of use	Transport (Rail) – Grayrigg (UK) accident involving train derailment (2007)	Transport (Road) – accidents involving young drivers	Aviation – crash of flight demonstrator (China - February 2009) and unmanned aircraft (US 0 April 2006)	Outdoor Recreation and Space Flight – Mangatepopo Gorge Incident (2008) – Apollo 13LM Consumables Incident (April, 1970)	Aviation (Military) – Hawk Jet Missile Simulation	Emergency Response (Fire) - Murrindindi Bushfire (February, 2009)	Oil and Gas – BP Deepwater Horizon blowout (2010)	Civil Engineering – Yangmingtan Bridge Collapse (August, 2012)
Goals and objectives	Comparison between three difference accident analysis models (Accimap, STAMP, and Australian Transport Safety Bureau model – ATSB)	Use of Accimaps to demonstrate the value of applying as systems approach to the causes of accidents involving young drivers	Development of 'AcciTree' – the main being to combine the graphical representation available within an Accimap with the error taxonomy available in HFACS	Examination of systems related factors in the form of 'Prompmaps' which were involved in improvisation incidents leading to positive and negative accident outcomes	Use of case study to demonstrate and illustrate a set of core challenges for real-world systems-of-systems	Testing the usefulness of the Accimap approach for examining the systemic characteristics of disaster response	Analysis of main contributing causes of system failure and interactions of key decision-makers and stakeholders	Analysis of system wide failures leading up to bridge collapse
Theoretical background	Safety Science; Human Factors and Ergonomics	Sociotechnical systems theory; Rasmussen's risk management framework (1997)	Safety Science; Human Factors and Ergonomics	Sociotechnical systems theory; Rasmussen's risk management framework (1997)	Safety science; human factors and ergonomics	Sociotechnical systems theory; Rasmussen's risk management framework (1997)	Safety Science; Sociotechnical systems theory; Rasmussen's risk management framework (1997)	Engineering; Rasmussen's risk management framework (1997)

Table 3: Applying the framework to the 26 studies

	17	18	19	20	21	22	23	24
	Underwood and Waterson (2014)	**Scott-Parker et al. (2014)**	**Lei et al. (2014)**	**Trotter et al. (2014)**	**Harvey and Stanton (2014)**	**Salmon et al. (2014)**	**Tabinzadeh and Meshkati (2015)**	**Fan et al. (2015)**
Procedure	Procedure followed the outline guidance provided by Svedung and Rasmussen, (2002). Coding using qualitative data software of accident investigation report: (1) Topography of the accident scene; (2) decision./actions taken by actors; (3) direct/indirect causal consequence; and, (4) preconditions requiring no further evaluation	No explicit details	No explicit details	One human factors expert competed the analysis, a second expert checked it and reviewed the 'Impromaps'	No explicit details	2 human factors experts generated the Accimap; Accimap was then validated by three subject matter experts	No explicit details	Coding using qualitative software based on multimedia sources (newspaper reports, we-based materials, videos – no official report available)
Outcomes	Accimap of the accident	Actormap; Accimap (causal factors); Accimap (countermeasures)	AcciTree models of both accidents	Impromaps for both incidents	Accimap of the subsystems involved with the Hawk Jet Missile System-of-Systems (SoS)	Accimap of bushfire	Accimap of the Deepwater Horizon blowout	Accimap of the Yangmingtan Bridge Collapse

Table 3: Applying the framework to the 26 studies

	17	18	19	20	21	22	23	24
	Underwood and Waterson (2014)	**Scott-Parker et al. (2014)**	**Lei et al. (2014)**	**Trotter et al. (2014)**	**Harvey and Stanton (2014)**	**Salmon et al. (2014)**	**Tabinzadeh and Meshkati (2015)**	**Fan et al. (2015)**
Comparison with other models	Australian Transport Safety Bureau (ATSB) model, and STAMP (Leveson, 2003)	None	HFACS, SHEL (Edwards, 1988)	None	None	None	None	None
Levels of analysis	6 levels: Government/ Regulatory Bodies/Local Government/ Technical and Operational Management/ Physical Processes and Actor Activities/ Equipment and Surroundings	6 levels: Government/ Regulatory Bodies/Local Government/ Technical and Operational Management/ Physical Processes and Actor Activities/ Equipment and Surroundings	No applicable	6 levels: Government/ Regulatory Bodies/Local Government/ Technical and Operational Management/ Physical Processes and Actor Activities/ Equipment and Surroundings	6 levels: Government/ Regulatory Bodies/Local Government/ Technical and Operational Management/ Physical Processes and Actor Activities/ Equipment and Surroundings	6 levels: Government/ Regulatory Bodies/Local Government/ Technical and Operational Management/ Physical Processes and Actor Activities/ Equipment and Surroundings	6 levels: Government/ Regulatory Bodies/Local Government/ Technical and Operational Management/ Physical Processes and Actor Activities/ Equipment and Surroundings	6 levels: Government/ Regulatory Agencies and Associations/Company/ Management/Staff/ Physical Accident Sequence
Causal factors	63 factors	Actormap – 38 actor Accimap (causal factors) – 36 factors Accimap (countermeasures) – 6 factors	Not applicable	Mangatepopo Gorge Incident – 35 factors Apollo 13LM Incident – 64 factors	16 factors	71 factors	66 factors	21 factors

Table 3: Applying the framework to the 26 studies

	17	18	19	20	21	22	23	24
	Underwood and Waterson (2014)	**Scott-Parker et al. (2014)**	**Lei et al. (2014)**	**Trotter et al. (2014)**	**Harvey and Stanton (2014)**	**Salmon et al. (2014)**	**Tabinzadeh and Meshkati (2015)**	**Fan et al. (2015)**
Changes to standard Accimap	Addition of colour coding for factors	None	New 'hybrid' model – AcciTree (Accimap + HFACS)	Addition of categories covering causal factors within one pf the Impromaps (e.g., factors such as experience, organisational culture)	Annotation of SoS aspects of the Hawk Missile System	None	None	Focus on company failures
Other details	-	Use of Accimap to organise previous research findings from the literature on young drivers and accidents, alongside details of possible countermeasures which could be used to reduce accidents in this target group	Argument that the reliability of the original Accimap format is improved with AcciTrees (due to inclusion of HFACS taxonomy)	Modification of Accimap to cover improvisation incidents	-	Test of the applicability of the Accimap approach within emergency response	-	-

Table 3: Applying the framework to the 26 studies

	25	26
	Newman and Goode (2015)	**Stefanova et al (2015)**
Context of use	Transport (Road) – Crashes involving road freight vehicles	Transport (Rail) – Pedestrian safety at level crossings
Goals and objectives	Analyse the complex system of contributory factors involved in road freight transportation	Use of Accimap to illustrate the workings of a systems-based framework for understanding the cognitive, motivational and wider systemic factors contributing to unsafe behaviour at level crossings
Theoretical background	Sociotechnical systems theory; Rasmussen's risk management framework (1997)	Sociotechnical systems theory; Rasmussen's risk management framework (1997)

Table 3: Applying the framework to the 26 studies

	25	26
	Newman and Goode (2015)	**Stefanova et al (2015)**
Procedure	Five stages involving qualitative coding – three analysts: (1) identifying contributory factors and relationships between them; (2) factors were then aggregated using thematic analysis – Braun and Clarke , 2006); (3) two researchers reviewed the coding template; and, (5) two research independently classified the themes according to the Accimap framework and resolved disagreements	No explicit details
Outcomes	Aggregate Accimap of contributory factors leading to road freight transportation crashes and inter-relationships between the factors	Two Accimaps: (1) illustration of crossing context where a pedestrian commits a violation on their way home after shopping; (2) illustration of crossing context where a pedestrian receives a fine for a violation on their way to work.

Table 3: Applying the framework to the 26 studies

	25	26
	Newman and Goode (2015)	**Stefanova et al (2015)**
Comparison with other models	None	None
Levels of analysis	6 levels: Government bodies/ Regulatory Bodies/Other organisations and clients/ Heavy vehicle companies/ Drivers and other actors at the scene of the incident/ Equipment, surroundings and meteorological conditions	6 levels: Government/ Regulatory Bodies/Local Government/ Technical and Operational Management/ Pedestrian level/ Equipment and Surroundings
Causal factors	60 factors	Accimap 1 (19 factors), Accimap 2 (20 factors)

Table 3: Applying the framework to the 26 studies

	25	26
	Newman and Goode (2015)	**Stefanova et al (2015)**
Changes to standard Accimap	Addition of different levels of analysis	Replacement of 'Physical Processes and Actor Activities' with Pedestrian level'
Other details	Attempt to test some of the 'predictions' made by Rasmussen's (1997) Risk Management Framework	Accimaps used to provide support for a new framework

Table 4: Requirements for methods for accident investigation and analysis (Ryan, 2015, p. 827, based on Katsakiori et al., 2009; Sklet, 2004; and, Wagenaar and van der Schrier, 1997)

An accident analysis method should
1. Have a clear scope for analysis (e.g., whether it should focus at the level of the work and the technological system, or more broadly at influences from government and regulators) 2. Be influenced by a model or group of models 3. Provided a detailed description of the accident, including a visual representation of the accident sequence if appropriate 4. Search for and reveal underlying causes 5. Contribute to understanding of prevention (e.g., safety barriers) 6. Help in generating recommendations 7. Give consideration to practical aspects, such as level of education and training that is needed to use the method 8. Be valid and reliable