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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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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).
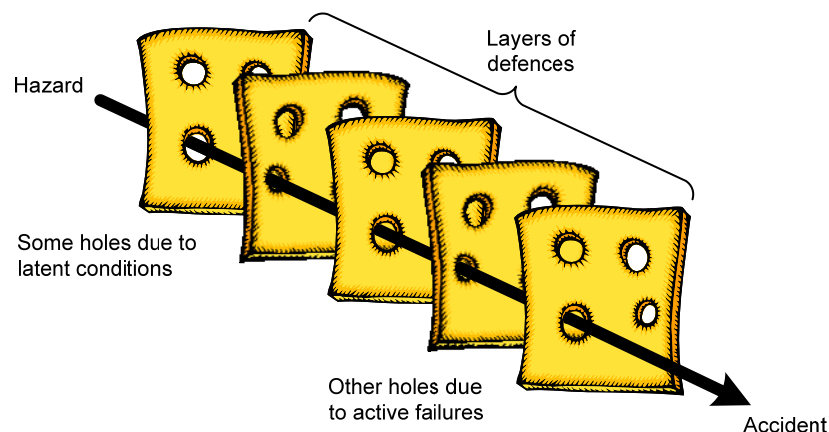
Figure 1 – Swiss Cheese Model (adapted from Reason (2008))

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).
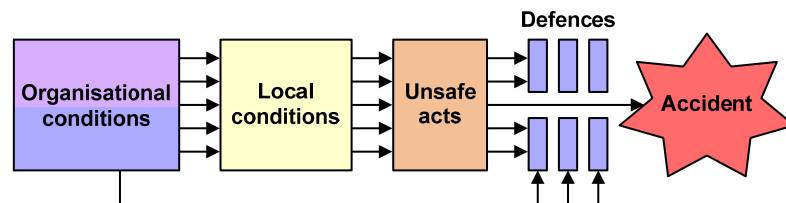
Figure 2 – Latter version of the SCM (adapted from ATSB (2008))
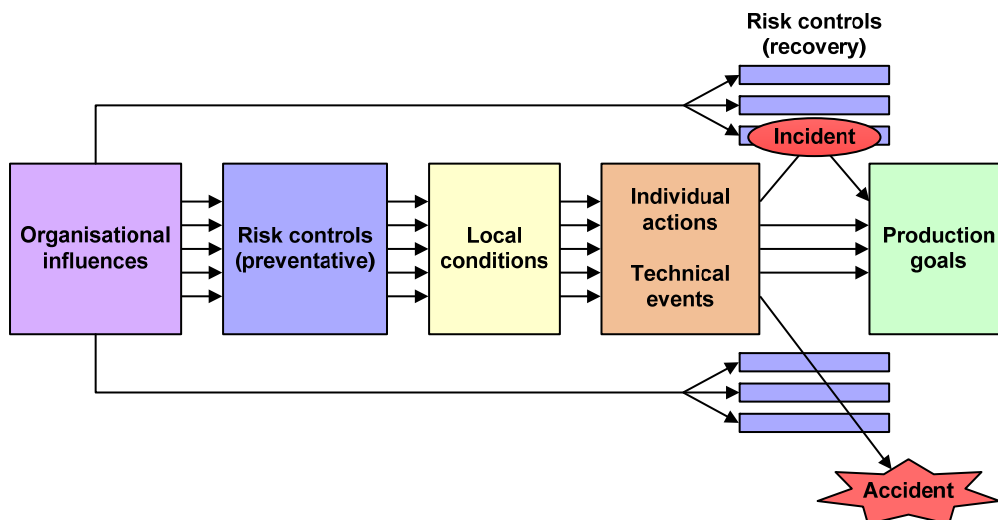
Figure 3 – ATSB adaptation of the SCM (adapted from ATSB (2008))

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.
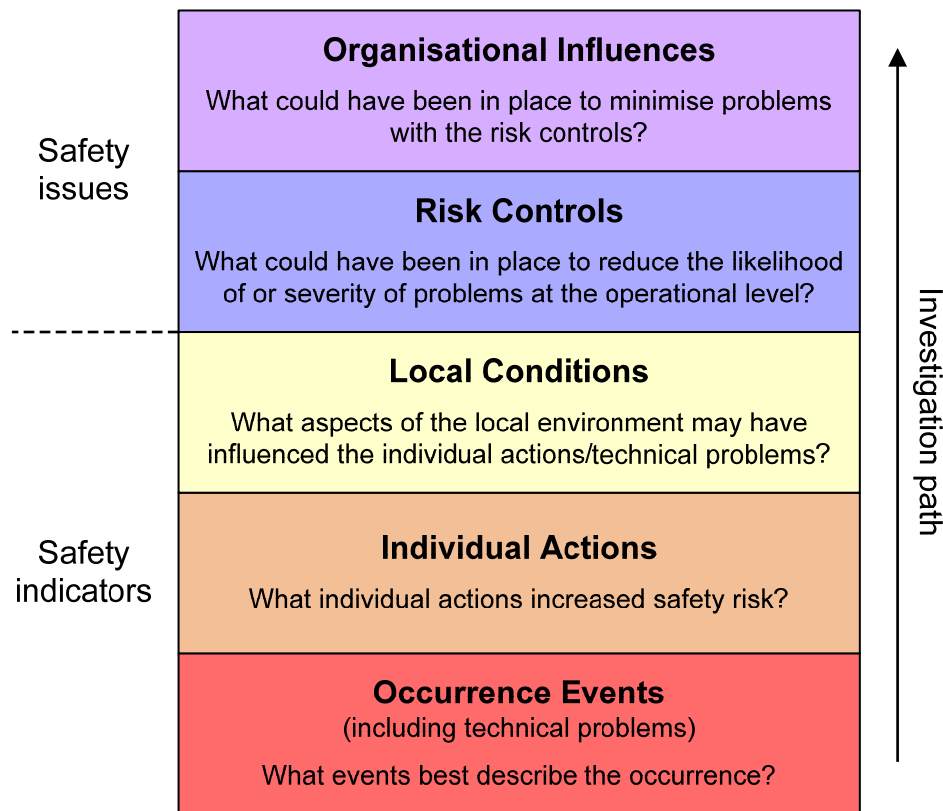
Figure 4 – The ATSB Investigation Analysis Model (adapted from ATSB (2008))

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).

SYSTEM LEVEL

1. Government (policy and budgeting) — Precondition evaluated no further

2. Regulatory bodies and associations

3. Local area government, company management (planning and budgeting) — Decision / Order ← Priorities

4. Technical and operational management — Function / Plan — Decision / Order

5. Physical processes and actor activities — Task or action / Direct consequence → Indirect consequence → Critical event | Direct consequence — Task or action

6. Equipment and surroundings — Consequence — Precondition evaluated no further

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).
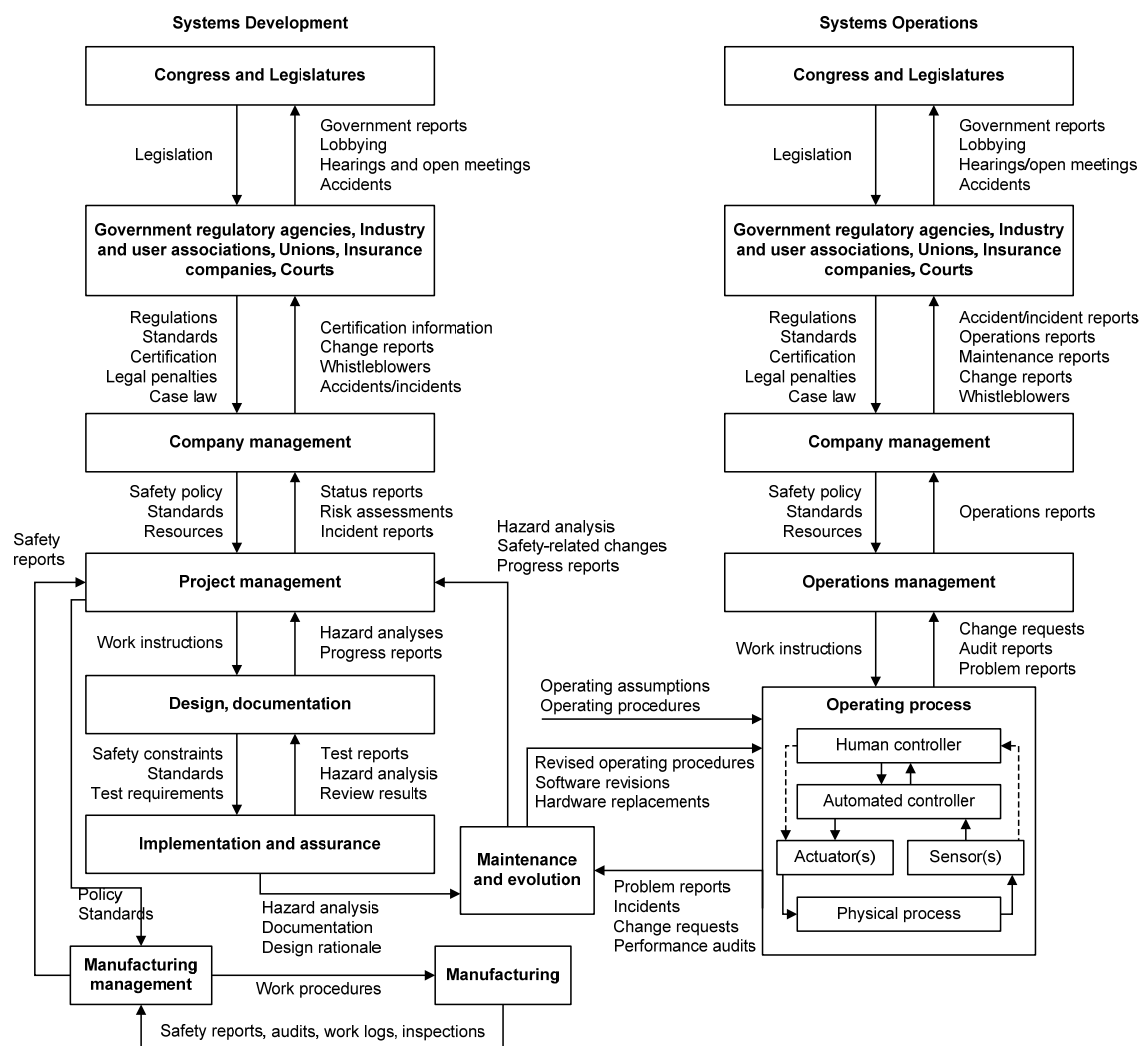
Figure 6 – General socio-technical system hierarchical safety control structure (adapted from Leveson (2011))

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).
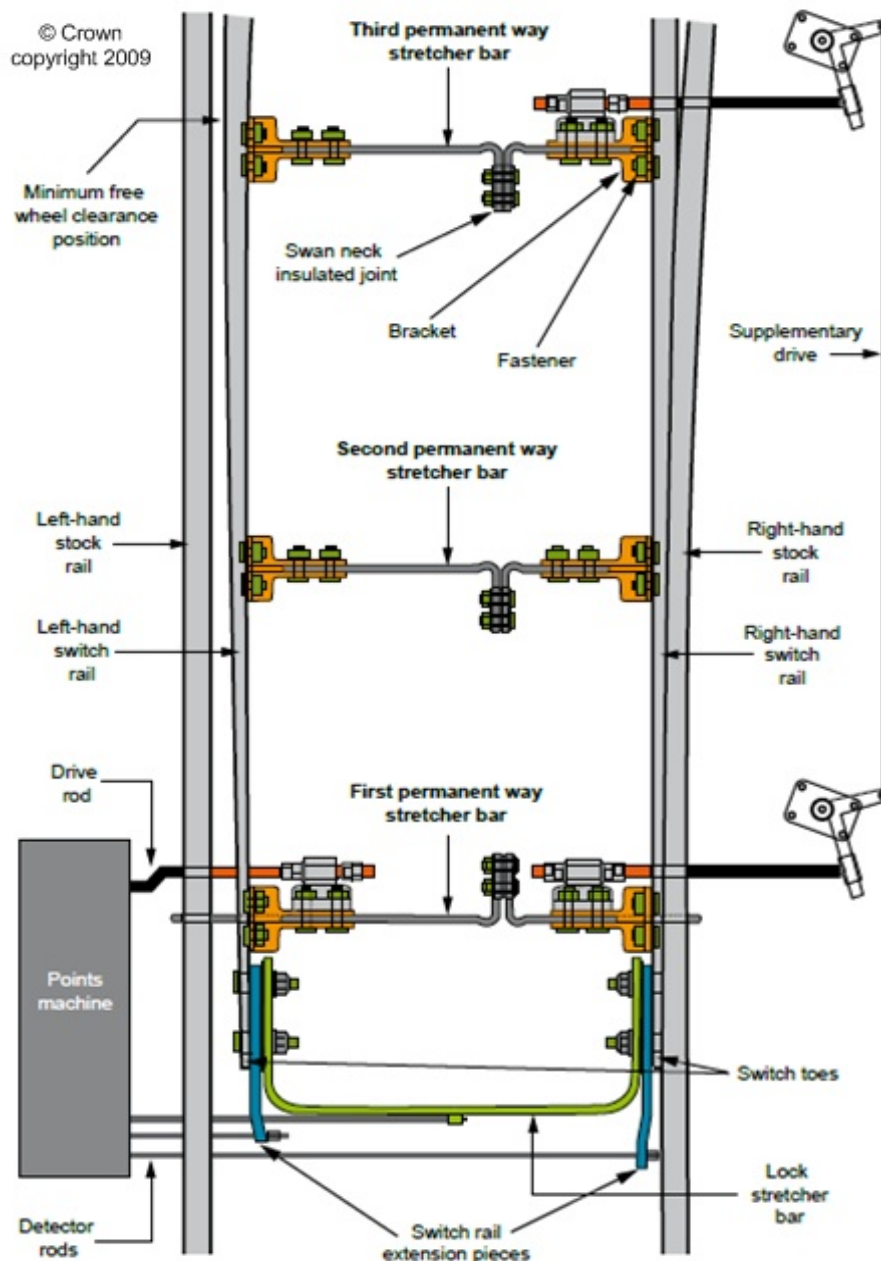
Figure 7 – Layout of points showing switch and stock rails and stretcher bars (from RAIB (2011))

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).

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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.
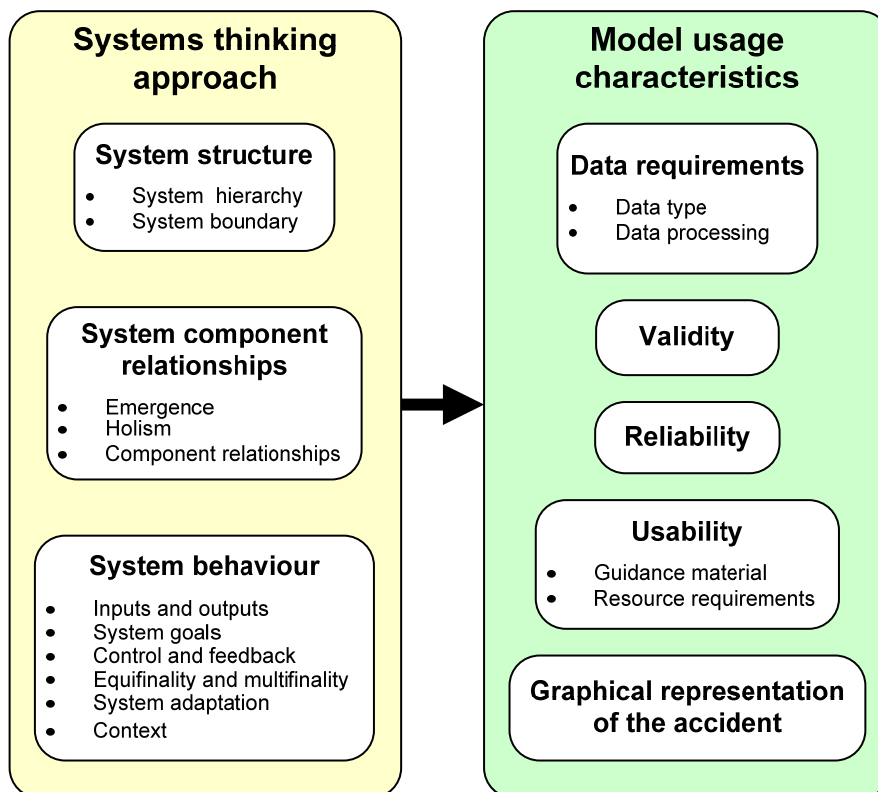
Figure 9 – Evaluation framework

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

Diagram contents (AcciMap of the Grayrigg accident):

SYSTEM LEVEL

2. Regulatory bodies and associations
- Prioritisation of Switches and Crosses in delivery plan
- Communication of maintenance responsibilities

3. Local area government, company management (planning and budgeting)
- Compliance and assurance — Inadequate audits of asset condition and maintenance activities
- Network Rail Special Instruction Notices
- Management of information systems not configured for efficient asset fault analysis
- No independent inspections of assets
- Approach to maintenance management
- Lack of asset surveys
- Under-reporting of faults
- Lack of asset condition knowledge
- Key performance indicators
- Incorrect perception of PWSB risk
- Inadequate maintenance standards
- Use of inappropriate tools for risk assessment
- Approach to risk assessment
- No standards or procedures on reuse of threaded fasteners

4. Technical and operational management
- Patrol procedures not followed — Track maintenance engineer not informed of missed inspection
- Substituted inspection report procedures
- Plan-do review meeting processes
- Missed inspection not identified — Inspection not reinstated
- Track modernisation project
- Routine basic inspections — Loose PSWB nuts not detected
- Difficult to identify loosening of PWSB nuts
- Roster sheet not provided
- Staff recruitment — Staffing level demands
- Increased workload
- Track access policies — Restricted track access
- Limited time for inspections
- Track section manager forgot to perform agreed inspection of 2B points — Points failure not detected
- Staff training — Cancelled joint points team training
- Staff competence
- Incorrect residual switch opening setting
- Equipment design — Inadequate design of PWSB switch rail joint
- Loading from trains exceeded design specification
- Reuse of threaded fasteners — Reduced clamping force
- Effectiveness of nut unwinding mechanism reduced

5. Physical processes and actor activities
- Train passes over 2B points → Derailment
- Left-hand switch rail moves towards its stock rail
- Failure of left-hand switch rail bracket of the first PWSB
- Effects of gravity on canted track
- Vibration from train wheelsets
- Failure of the left-hand lock stretcher bar and first PWSB
- No detection of signal possible
- Increased level of flange-back contact
- Increased loads on 2B points
- Failure of left-hand joints of the lock stretcher bar and first PWSB
- Clamping force exceeded on both rail bracket joints on the second permanent way stretcher bar
- Left-hand switch rail closes further towards the stock rail
- Fracture of the third permanent way stretcher bar
- Flange-back contact
- Extended working hours
- Failure and separation of third stretcher bar/right-hand switch rail joint
- Unwinding of nuts from bolts
- Clamping force of third stretcher bar exceeded by load imposed on joint

6. Equipment and surroundings
- Natural flexure of switch rail
- Reduced daylight in winter

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).
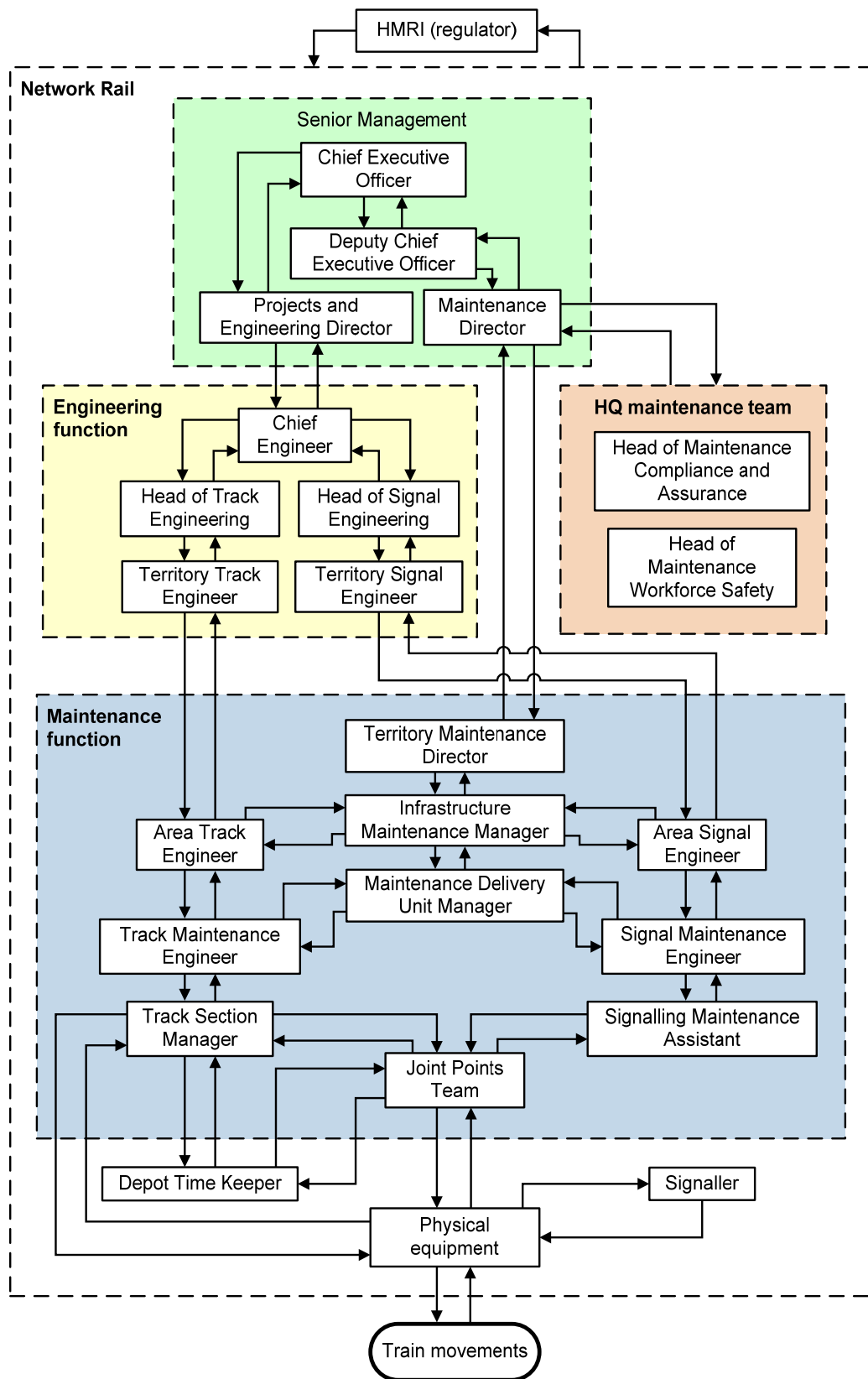
Figure 12 – The control structure in place at the time of the Grayrigg accident

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.

Network Rail management

Track Section Manager

Physical equipment

Safety requirements and constraints violated
- Enable trains to transfer between two sets of rails
- Residual switch opening of 1.5 mm
- No flange-back contact on the open switch rail

Controls
- Switch rails
- Lock stretcher bar
- Fasteners, brackets, bolts and torque nuts
- Switch rail extension piece
- Three permanent way stretcher bars (PWSB)
- PWSB-switch rail fasteners
- Detector rod
- Supplementary drive

Failures and inadequate controls
- Clamping force of third PWSB exceeded by the load imposed on the joint
- Unwinding of nuts from bolts
- Failure and separation of third PWSB bar/right-hand switch rail joint
- Left-hand switch rail closes towards its stock rail
- Residual switch opening between 7-10 mm
- Increasing levels of flange-back contact
- Fracture of third PWSB
- Retention by the supplementary drive was lost
- Failure of rail brackets of first and second PSWB and their brackets
- Failure of fasteners common to lock stretcher bar and switch rail extension piece meant left-hand switch rail closure was undetected by signalling system
- Switch rail closed sufficiently to allow more than one of the train's wheelsets to run into the narrowing track gauge between the two switch rails

Context
- PWSB on correctly set points have a long, albeit finite, life when subjected to normal service forces (in the order of tens of years)
- Points with non-adjustable PWSB bars can withstand forces from flange-back contact for a limited period of time only, which may be a matter of days depending on the degree of flange-back contact
- No evidence to suggest that any significant change in traffic took place at 2B points in the six months before the accident

Train movements

Joint Points Team

Safety-related responsibilities
- Perform inspections and maintenance of the points
- Rectify variety of minor points defects (but not stretcher bar bolts)
- Identify and report other defects and when no defects were found
- Walk through each section of track in the four-foot and observe the condition of the points components
- Observe rail condition, the presence of obstructions, the position and security of check rails, track geometry and track support
- Visually assess the free wheel clearance within points, and report for correction within 36 hours if less than 45 mm
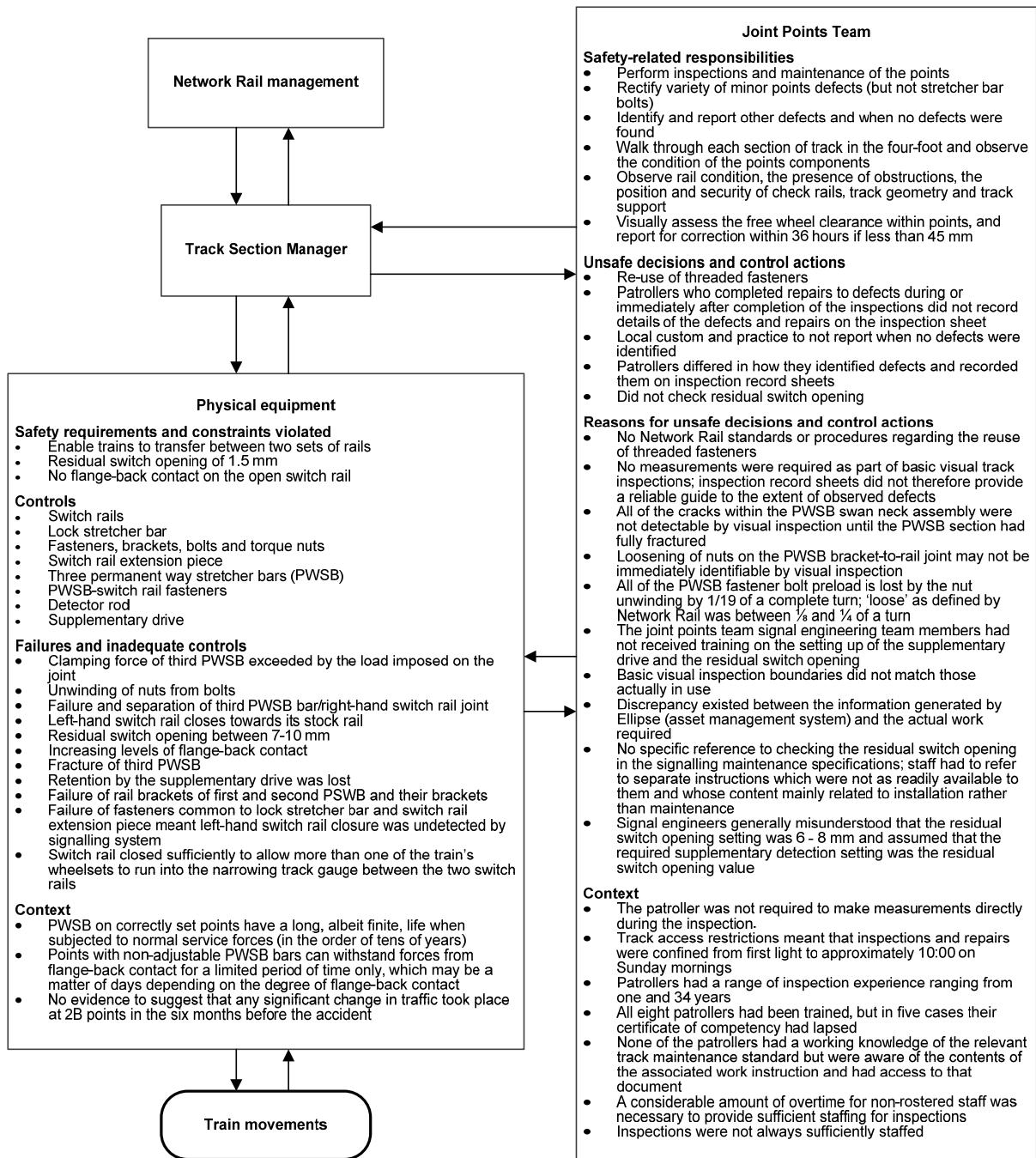
Unsafe decisions and control actions
- Re-use of threaded fasteners
- Patrollers who completed repairs to defects during or immediately after completion of the inspections did not record details of the defects and repairs on the inspection sheet
- Local custom and practice to not report when no defects were identified
- Patrollers differed in how they identified defects and recorded them on inspection record sheets
- Did not check residual switch opening

Reasons for unsafe decisions and control actions
- No Network Rail standards or procedures regarding the reuse of threaded fasteners
- No measurements were required as part of basic visual track inspections; inspection record sheets did not therefore provide a reliable guide to the extent of observed defects
- All of the cracks within the PWSB swan neck assembly were not detectable by visual inspection until the PWSB section had fully fractured
- Loosening of nuts on the PWSB bracket-to-rail joint may not be immediately identifiable by visual inspection
- All of the PWSB fastener bolt preload is lost by the nut unwinding by 1/19 of a complete turn; 'loose' as defined by Network Rail was between ⅛ and ¼ of a turn
- The joint points team signal engineering team members had not received training on the setting up of the supplementary drive and the residual switch opening
- Basic visual inspection boundaries did not match those actually in use
- Discrepancy existed between the information generated by Ellipse (asset management system) and the actual work required
- No specific reference to checking the residual switch opening in the signalling maintenance specifications; staff had to refer to separate instructions which were not as readily available to them and whose content mainly related to installation rather than maintenance
- Signal engineers generally misunderstood that the residual switch opening setting was 6 - 8 mm and assumed that the required supplementary detection setting was the residual switch opening value

Context
- The patroller was not required to make measurements directly during the inspection.
- Track access restrictions meant that inspections and repairs were confined from first light to approximately 10:00 on Sunday mornings
- Patrollers had a range of inspection experience ranging from one and 34 years
- All eight patrollers had been trained, but in five cases their certificate of competency had lapsed
- None of the patrollers had a working knowledge of the relevant track maintenance standard but were aware of the contents of the associated work instruction and had access to that document
- A considerable amount of overtime for non-rostered staff was necessary to provide sufficient staffing for inspections
- Inspections were not always sufficiently staffed

Figure 13 – 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 18th 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 18th Feb 2007
- Began his inspection on 18th 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

Joint Points Team

Physical equipment

Train movements

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.
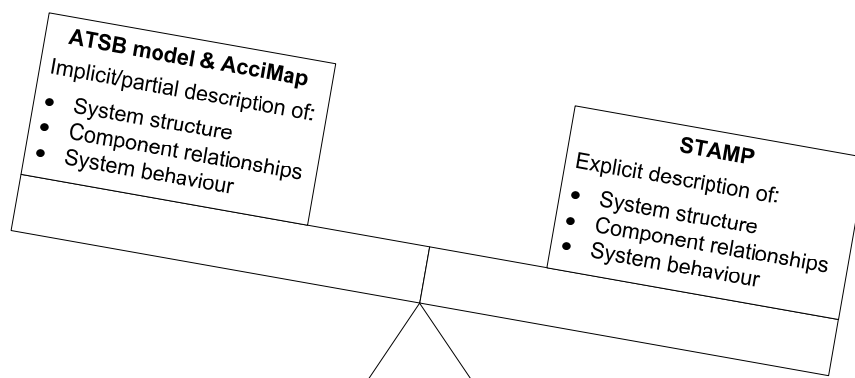
Figure 15 – Systems thinking approach comparison of the ATSB model, AcciMap and STAMP

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.
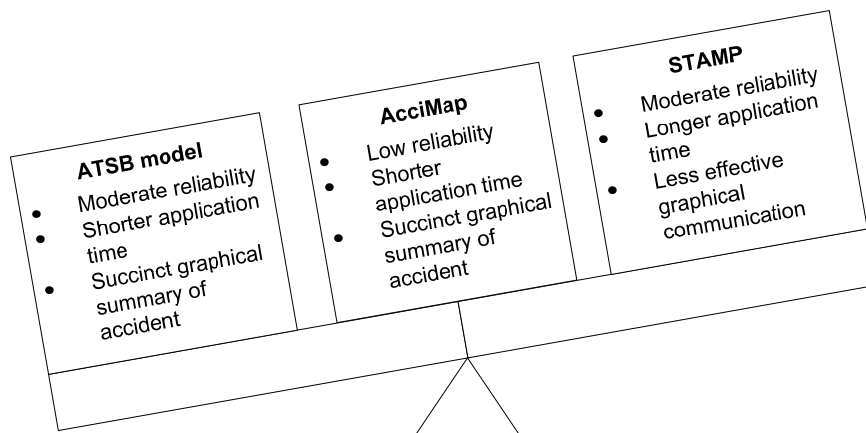
Figure 16 – Usage characteristic comparison of the ATSB model, AcciMap and STAMP

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.
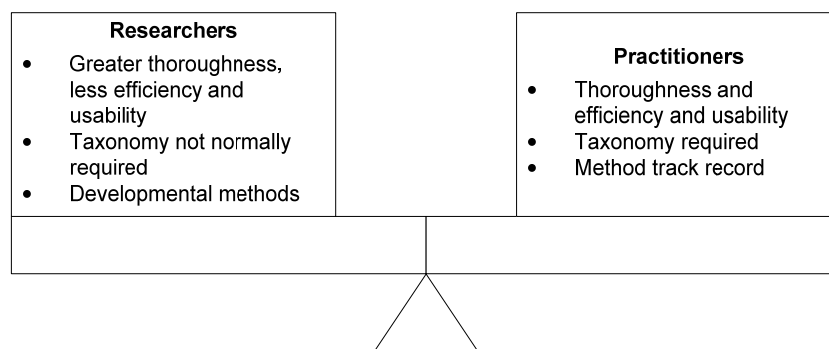
Figure 17 – Method selection trade-off factors

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 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 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.

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