Systems-based accident analysis methods: A comparison of Accimap, HFACS, and STAMP

Paul M. Salmon*, Miranda Cornelissen & Margaret Trotter

Human Factors Group, Monash Injury Research Institute,

Clayton Campus, Monash University, Victoria 3800, Australia

*Corresponding author, email: paul.salmon@monash.edu

Abstract

Three accident causation models, each with their own associated approach to accident analysis, currently dominate the human factors literature. Although the models are in general agreement that accidents represent a complex, systems phenomenon, the subsequent analysis methods prescribed are very different. This paper presents a case study-based comparison of the three methods: Accimap, HFACS and STAMP. Each was used independently by separate analysts to analyse the recent Mangatepopo gorge tragedy in which six students and their teacher drowned while participating in a led gorge walking activity. The outputs were then compared and contrasted, revealing significant differences across the three methods. These differences are discussed in detail, and the implications for accident analysis are articulated. In conclusion, a modified version of the Accimap method, incorporating domain specific taxonomies of failure modes, is recommended for future accident analysis efforts.

Keywords: Accidents, accident analysis, led outdoor activities, Accimap, HFACS, STAMP.

Introduction

Accidents and accident causation remain key themes within Human Factors research efforts worldwide. It is now generally accepted that accidents represent a complex systems-phenomenon in that causal factors reside at all levels of complex sociotechnical systems, and interact across them (e.g. Leveson, 2004; Rasmussen, 1997; Reason, 1990). It is also acknowledged that our understanding of accidents remains incomplete and that accidents will continue to occur within complex sociotechnical systems (Hollnagel, 2004). This arises not as a function of poor research; rather, it reflects the evolving, probabilistic complexity inherent in how accidents unfold. The methods that researchers, practitioners, and accident investigators use to analyse or investigate accidents are, therefore, critical to aid our understanding of the underlying causes as well as indicating where system safety may be improved.

Three accident causation models currently dominate the Human Factors literature: Rasmussen's (1997) risk management framework (e.g. Cassano-Piche et al, 2009; Jenkins et al, 2010; Johnson & De Almeida, 2008; Salmon et al, 2010; Svedung and Rasmussen, 2002); Reason's (1990) omnipresent Swiss Cheese model (e.g. Lawton and Ward, 2005); and Leveson's (2004) Systems Theoretic Accident Modelling and Processes model (STAMP e.g. Ferjencik, 2011; Ouyang et al, 2010). Each engenders its own distinct approach for analysing accidents. Accimap, a generic approach used to identify and link contributory failures across six sociotechnical system levels, accompanies Rasmussen's risk management framework. The Human Factors Analysis and Classification System (HFACS; Wiegmann and Shappell, 2003), a taxonomy-based aviation accident analysis approach, was inspired by Reason's Swiss Cheese model. Finally, the STAMP model uses control theory and systems dynamics methods to describe the systemic control failures involved in accidents. Although all three are underpinned generally by a systems approach, there are significant differences in terms of theoretical underpinning, the methodological approach adopted, and the outputs produced. Despite this, there is little in the way of guidelines to support the selection of one over the other for accident analysis purposes, and methodology selection is more likely to be based on theoretical preference than anything else. The aim of this paper is to compare and contrast the three methods when used for accident analysis purposes. In doing so an analysis of a recent high profile incident in the led outdoor activity domain, the Mangatepopo gorge incident, is presented.

Accident causation and analysis in the led outdoor activity domain

There is an acknowledged risk of both severe and frequent injury associated with active pursuits, especially those participated in for sport, active recreation or leisure (e.g. Finch et al., 2007). One popular form of active pursuit is led outdoor activity (defined as facilitated or instructed activities within outdoor education and recreation settings that have a learning goal associated with them, including activities such as school and scout camping, hiking, harness sports, marine aquatic sports and wheel sports; Salmon et al., 2010). Within Australia, injury-causing accidents are currently recognised by the led outdoor activity industry as a significant problem (Salmon et al., 2010). Whilst exact injury rates remain unknown (largely due to the paucity of exposure data), recent high profile fatal incidents, such as the drowning of a 12 year old student during a college camp (Levy, 2010), highlight the industry's need to understand the causal factors involved and develop appropriate prevention strategies. Recent research, however, indicates that the industry's understanding of accidents is limited, and that the surveillance systems required to enhance it do not exist (e.g. Salmon et al., 2010).

Systems-based accident analysis methods have been applied across the other safety critical domains to identify causal factors and inform appropriate system reform and accident countermeasure development. The application of these methods in the led outdoor activity domain has to date been sparse; however, recent evidence suggests that they are likely to be useful as part of an overall accident and injury surveillance and prevention system (Salmon et al., 2010). The present analysis, therefore, involved not only comparing the three methods generally, but also investigating which of the three accident analysis method is most suited for future accident analysis efforts in this domain.

Systems-based accident models and methods

In this section an overview of the three accident analysis methods, and their theoretical underpinning, is given.

Rasmussen's risk management framework and Accimap

Rasmussen's risk management framework (Rasmussen, 1997) describes the various system levels (e.g. government, regulators, company, company management, staff, and work) involved in production and safety management and considers safety an emergent property arising from the interactions between actors at each of these levels. According to Rasmussen each systemic level is involved in safety management via the control of hazardous processes through laws, rules, and instructions. For systems to function safely decisions made at high levels should promulgate down and be reflected in the decisions and actions occurring at lower levels of the system. Conversely, information at the lower levels (e.g. staff, work, equipment) regarding the system's status needs to transfer up the hierarchy to inform the decisions and actions occurring at the higher levels (Cassano-Piche et al., 2009). Without this so called ‘vertical integration’, systems can lose control of the processes that they are designed to control (Cassano-Piche et al., 2009). According to Rasmussen (1997), accidents are typically ‘waiting for release’; the stage being set by the routine work practices of various actors working within the system. Normal variation in behaviour then serves to release accidents.

Rasmussen (1997) outlined the Accimap method, which is used to graphically represent the system wide failures, decisions and actions involved in accidents. Accimap analyses typically focus on failures across the following six organisational levels: government policy and budgeting; regulatory bodies and associations; local area government planning & budgeting (including company management, technical and operational management; physical processes and actor activities; and equipment and surroundings. Notably, Accimap is a generic approach and does not use taxonomies of failures across the different levels considered. Rasmussen’s risk management framework and Accimap method are presented in Figure 1.

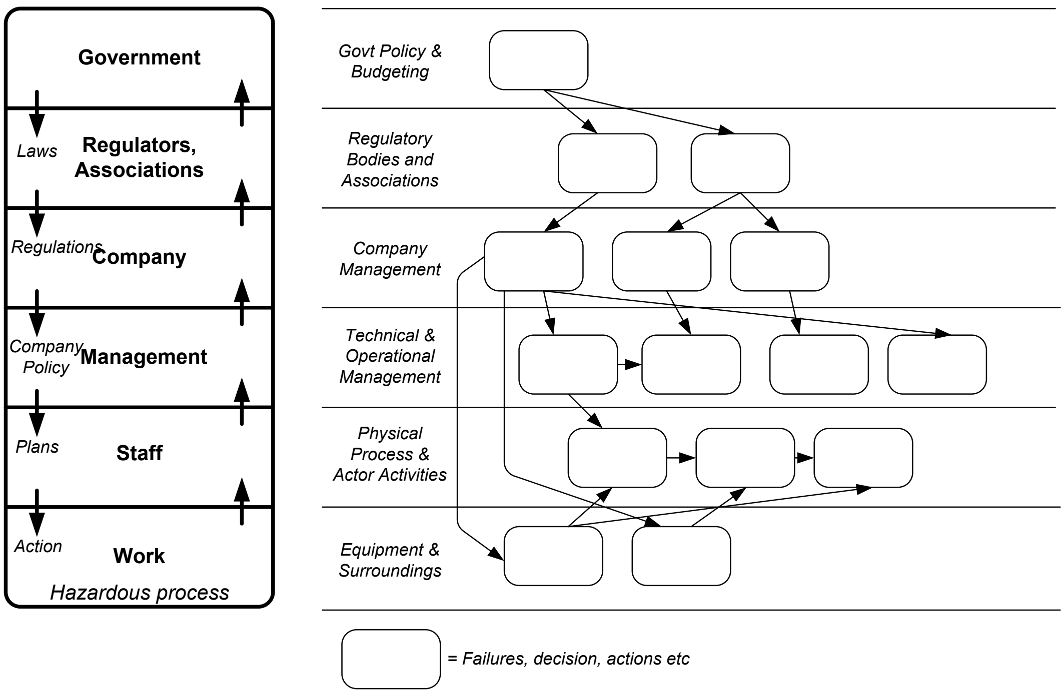

Figure 1. Rasmussen’s risk management framework and Accimap method.

Reason's Swiss Cheese and HFACS

The Swiss cheese model requires little introduction. Undoubtedly the most popular of all accident causation models, Reason's model describes the interaction between system wide 'latent conditions' (e.g. inadequate designs and equipment, supervisory and maintenance failures, inadequate training and procedures) and unsafe acts made by human operators and their role in accidents. The model also describes the role of defences, such as protective equipment, rules and regulations, training, and engineered safety features, which are designed to prevent the accidents. Weaknesses in these defences, created by latent conditions and unsafe acts, allow defences to be breached and accidents to occur.

The impetus for HFACS came from the absence of taxonomies of latent failures and unsafe acts within Reason's Swiss cheese model, which according to Wiegmann & Shappell (2003) limited its utility as an aviation accident analysis method. HFACS was subsequently developed based on an analysis of aviation accident reports (Wiegmann & Shappell, 2003) and provides analysts with taxonomies of failure modes across the following four levels: unsafe acts; preconditions for unsafe acts; unsafe supervision; and organisational influences. The structure of the HFACS method is presented in Figure 2, which shows the different categories mapped onto Reason's model. Working backward from the immediate causal factors, analysts classify the errors and associated causal factors involved using the taxonomies presented.

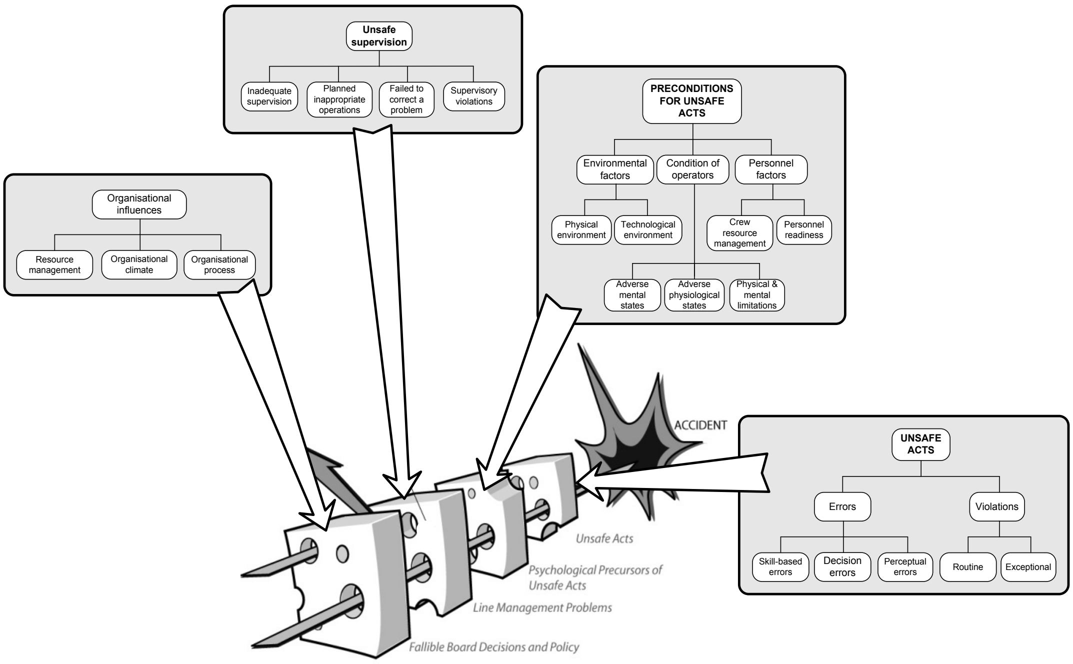

Figure 2. HFACS taxonomies overlaid on Reason's Swiss cheese model.

Leveson's STAMP

STAMP (Leveson, 2004) is a constraints-based model which focuses on the interactions between system components and the control mechanisms used throughout the work system. STAMP views systems as hierarchical levels of controls and constraints, with each level in the hierarchy imposing constraints on the level below. Conversely, information at the lower levels about the appropriateness and condition of the controls and constraints is communicated upwards in the hierarchy to inform the upper levels controls and constraints. . Similar to Rasmussen's framework, STAMP emphasises how complex systems are dynamic and migrate towards accidents due to physical, social and economic pressures, rather than sudden loss of control capacity.

STAMP views accidents as resulting from the inadequate control of safety-related constraints (Leveson, 2004). Accidents occur when component failures, external disturbances, and/or inappropriate interactions between systems components are not controlled, (Leveson, 2009). Leveson (2009) describes various forms of control, including managerial, organisational, physical, operational and manufacturing-based controls.

When used for accident analysis purposes, STAMP produces a description of the system's control structure and then identifies failures in this control structure that contributed to the accident. To support identification of control failures, Leveson (2004) proposes a taxonomy of control failures, including: inadequate control of actions; inadequate execution of control actions; and inadequate or missing feedback. Subsequent STAMP analysis have also included 'mental model flaws' in order to cater better for human control structures in the system since the method origins are in engineering. (Leveson, 2002; Ouyang et al., 2010). The analysis depicts failures across the entire control structure of the system, as well as the interaction between those structures and their control failures that led to the accident. The STAMP taxonomy, along with a generic sociotechnical system control structure, is presented in Figure 3 (adapted from Leveson, 2004).

Inadequate enforcement of constraints
- Unidentified hazards - Inappropriate, ineffective or missing control actions - Failure of control process to enforce constraints - Inconsistent/incomplete/incorrect process models - Inadequate coordination between controllers and decision makers
Inadequate execution of control actions
- Communications failures - Inadequate actuator operations - Time lag
Feedback failures
- Not provided through system design - Communications failures - Time lag - Inadequate sensor operation

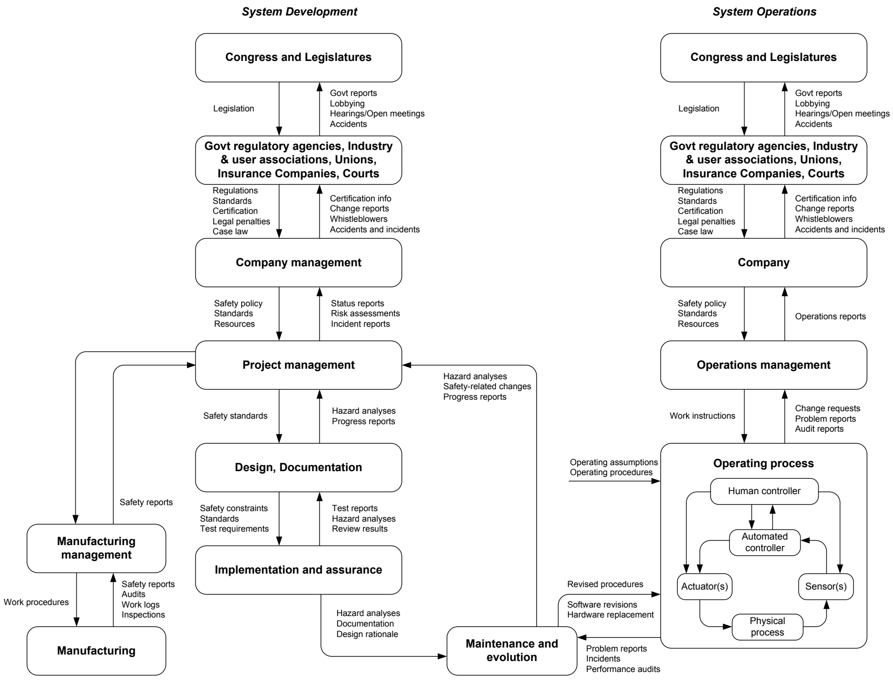

Figure 3. STAMP's control failure taxonomy and generic complex sociotechnical system control structure (adapted from Leveson, 2004).

Methods comparison study: Mangatepopo gorge walking tragedy

To compare the three methods each was applied independently by separate analysts to analyse the recent Mangatepopo gorge walking tragedy. A brief description of the incident is given below, following which the methodology and results are presented.

Incident description

The Mangatepopo tragedy occurred on the 15th April 2008 when a group of 10 college students and their teacher, led by an instructor from the Sir Edmund Hillary Outdoor Pursuit Centre (OPC), were completing a gorge walking activity in the Mangatepopo gorge in the Tongariro National Park, New Zealand. Due to heavy rain in the area, a flash flood occurred which led to increased river flow and a rising river level in the gorge. As a result, the group had to abandon the gorge walking activity and became trapped on a small ledge above the water. Fearing the group would be washed off the ledge, the instructor decided to attempt to evacuate the group from the ledge and gorge by entering the river, with poor swimmers tied to stronger swimmers, following which the instructor would extract them downstream using a 'throwbag' river rescue technique (whereby a bag attached to a length of rope is thrown to the person in the water and used to pull them to the river bank). After initiating the evacuation plan, only the instructor and two students managed to get out of the river as intended, with the remaining eight students and teacher being swept downstream and then over a spillway. Six students and their teacher eventually drowned, with only 2 of those swept over the spillway surviving.

In the aftermath of the incident, the coroner and an independent investigation initiated by the activity centre involved identified various failures on behalf of the instructor, her manager, the activity centre itself, the local weather service and government legislation and regulation (e.g. Brookes, Smith & Corkill, 2009; Davenport, 2010). The immediate causal factors included the increased river flow and level and the instructors decision to leave the ledge and enter the river in an attempt to get the group out of the gorge. According to the inquiry report, the group entered the water at the worst possible time, with the flood at its peak. Once the group had left the ledge, the water level did not rise further, leading the inquiry team to conclude that they would have likely survived had they remained on the ledge and awaited rescue. The instructor's decision to leave the ledge was, however, shaped by various factors. She was inexperienced and was in charge of a group containing non-confident swimmers. The water level was also visibly rising, the group were cold and uncomfortable, and some were questioning the decision to stay on the ledge (Brookes et al., 2009). She also had no means of contacting other instructors or the centre's field manager, having made an unsuccessful attempt at contacting the centre using the one radio in her possession.

Various other causal and contributory factors are identified in the inquiry and coroners reports. The evacuation plan formulated by the instructor and the instructions given to the group were inadequate (Brookes et al., 2009). The plan entailed the instructor entering the water first, followed by the group either individually or in pairs (connected together by cow tails and karabiners) in staggered five minute intervals. The instructor would then use the throwbag technique to rescue each pair from the water. The connection of individuals to one another was inappropriate, failing to consider that the linkage of two individuals could make them more vulnerable to drowning. No contingency plan was devised to cater for the instructor being unable to reach the side of the river or drowning (Brookes et al., 2009). Finally, use of the throwbag technique given the conditions was inappropriate; the inquiry report states that, upon being washed over the spillway whilst holding rope, the holder would have been submerged and subject to great force, which in turn would have caused them to lose their grip (Brookes et al., 2009).

The instructions given to the students by the instructor were inadequate. The advice to adopt a defensive float when in the water and to paddle with a backstroke motion was inappropriate (an alternative approach involving swimming hard and left with a conventional front stroke is cited in the inquiry report). Further, no warning was given regarding the spillway, and no instructions were given regarding what to do in the event of being washed over the spillway (Brookes et al., 2009). As a result, the inquiry report concluded that the group did not appreciate the gravity of the situation. None considered that the instructor might not be able to retrieve them from the water, were aware of the hazards posed by the spillway, or understood that survival may be dependent upon getting as close to the left hand bank as possible (Brookes et al., 2009).

Once underway enactment of the evacuation plan was flawed. The first student entered the water 1 to 2 minutes after the instructor (not 5 minutes as requested by the instructor), which meant that the instructor was not ready to execute a throwbag rescue. The student was subsequently swept over the spillway. At this point the instructor made an emergency call to the activity centre via radio; however, she had no way of contacting the group on the ledge and so could not stop the evacuation. Three further pairs of students were swept over the spillway.

Various contributory factors which shaped the instructors performance in the gorge and decision to undertake the activity given the poor conditions were identified in the inquiry report. The instructor had little experience of gorge walking activities, was not fully signed off as competent for them, and had not experienced the gorge in adverse weather conditions. The group only had one radio with them and thus once the evacuation attempt was underway, the instructor could not contact the group on the ledge to abort the evacuation in the event of it failing. The radio, supposedly waterproof, was not, and hence was turned off and carried, disassembled, in a protective bag. This meant that the group were not contactable until they assembled the radio (which was not until they were trapped on the ledge) and also potentially led to the instructor not making contact with the centre prior to becoming stranded on the ledge, since she was unable to stop and put the radio together whilst walking in the gorge. Poor reception in the gorge also meant that centre radios often did not work during gorge activities, rendering any attempt to contact the centre during the activity useless.

Contributory factors related to other staff at the activity centre played a part. There was a generic failure on behalf of the instructor and other staff to assess and understand the hazards associated with conducting the gorge walk activity given the conditions in and around the gorge on the day in question. It is reasonable to expect that, given the adverse weather conditions, either the instructor, field manager, or other activity centre staff should have raised concerns regarding the increased hazards associated with the gorge walking activity. Further, all staff present on the day in question (including an independent auditor) failed to check more up-to-date weather forecasts throughout the day of the incident.

The centre's field manager played a key role in the unfolding events. According to the inquiry report, he was unaware that an audit of the centre would take place on his first day back at work after annual leave and described being preoccupied with the audit throughout the day of the incident (Brookes et al., 2009). During the morning staff meeting, in which it was his responsibility to present information regarding the weather for the rest of the day, the field manager failed to check the maps on the MetService weather fax, which meant that he, along with the other activity centre staff, were unaware of the impending bad weather. The weather fax used during the meeting was incomplete, having at least the word 'thunderstorms' missing from the sentence "Today rain with isolated and poor visibility at times" (Brookes et al., 2009). This led to the field manager and instructor forming the impression that the rain would ease in the afternoon (Brookes et al., 2009). A weather map on the reverse side of the fax did give the appropriate forecast for thunderstorms; however, this was not checked by the field manager. An updated forecast, describing likely heavy rainfall and isolated thunderstorms was available on the MetService website after 7.15am (Davenport, 2010); however, this was not checked following the morning meeting by the field manager, instructor, or other activity centre staff.

Unaware of the impending adverse weather conditions, the field manager did not cancel all gorge trips (which he would have done had he known about the impending heavy rain), nor did he state that the downstream gorge trip would be closed (which he had decided based upon the weather forecast). Also, having raised concerns with the instructor involved regarding the planned gorge walking activity, it appears that the field manager misunderstood the exact nature of the planned trip, believing that the instructor planned to not go too far into the gorge (no more than 100 metres). Had the field manager ascertained the exact nature of the trip, he may have taken measures to prevent it from going ahead.

A failure by the instructor to sign off on the centres risk assessment system, which provided information on environmental hazards, is important. The inquiry report states that knowledge of the risk assessment system was a pre-requisite for undertaking gorge activities and that the instructor had not signed the appropriate sign off sheet prior to engaging in the activity. In addition, the centre also failed to adequately ascertain the swimming capabilities of the students within the group, a requirement prior to engagement in water activities as stated by centre policy at the time (Brookes et al., 2009). This was critical since there were three non-confident swimmers in the group (one with a fear of water) who slowed down the group during the activity and who were attached to confident swimmers during the ledge evacuation attempt.

Various failures related to activity centres policies, procedures and programs were identified. The induction, mentoring, and training programs provided by the centre to the instructor involved were found to be inadequate (Brookes et al., 2009). The use of the Outdoors Mark as evidence of the centre's safety management was also criticised in the inquiry report as was the risk assessment and management system used by the centre. According to Brookes et al. (2009) the sign off system was inadequate and there was poor alignment with the accompanying instructor handbook. Further, the report states that the risk assessment system for the upstream gorge activity was flawed, lacking a map of the area, not identifying the spillway and intake structure hazards, and providing no information on previous accidents and near miss incidents (Brookes et al., 2009). In addition, there was no specific rescue procedure for incidents in the gorge, despite the fact that many incidents had occurred previously. The absence of an efficient accident and near miss surveillance system was problematic; a myriad of incidents had occurred previously in the gorge, many involving similar failures to the present incident. Although the centre kept a record of these, this information was not passed onto new staff members, was not included in any formal training programs, nor was it subject to analysis for incident trend identification (Brookes et al., 2009).

There were significant financial and production pressures imposed on operations at the centre, which ostensibly led to a poorly designed adventure program, a rush to get staff trained and competent for activities, and the use of only one instructor for activities during busy periods (Brookes et al., 2009). Further, the company was found to have had a high staff turnover, meaning useful knowledge and experience of previous incidents in the gorge was not maintained and staff with high levels of experience were not prevalent within the centre. The centre's culture was reported by the inquiry team to influence day to day activities; the centre adopted a 'rain or shine' culture which meant that all attempts would be made to complete activities regardless of the weather conditions.

Finally, factors outside of the activity centre are also important. At the time of the incident, there was no regulatory body or licensing body for outdoor activity centres. In addition, the Outdoors Mark auditing system came under scrutiny, since the auditor failed to speak up at any point during the day regarding the planned activities. Further, none of the failures were mentioned in the auditors report (Brookes et al., 2009). The Coroners report recommended that the organisation responsible for the Outdoors Mark safety audits review its policies and procedures for conducting safety audits and also the training provided to auditors. There was also no legislation to control outdoor activity centres. In closing his report into the incident, the coroner recommended that the Government consider licensing outdoor education/adventure operations.

Methodology

Three human factors analysts with significant experience in the application of accident analysis methods in various domains (e.g. military, mining, aviation, led outdoor activities, police armed response) performed the analyses independent of one another, each using either Accimap, HFACS or STAMP. Each analyst used the same data sources to support their unique form or analysis, including the independent inquiry report (Brookes et al., 2009) and coroners report (Davenport, 2010). Upon completion of the initial analyses, the three analysts exchanged and reviewed the outputs, with any discrepancies or disagreements' being resolved through discussion until consensus was reached. To ensure validity of the analyses produced, an experienced led outdoor activity instructor reviewed the final analysis outputs. Any disagreements were subsequently resolved through discussion between the expert and analysts.

Results

The Accimap output is presented in Figure 4. The HFACS output is presented in Figure 5. The STAMP outputs, including the control structure and an extract of the analysis showing the control failures related to the centre's field manager, training officer, and the instructor involved, are presented in Figures 6 and 7.

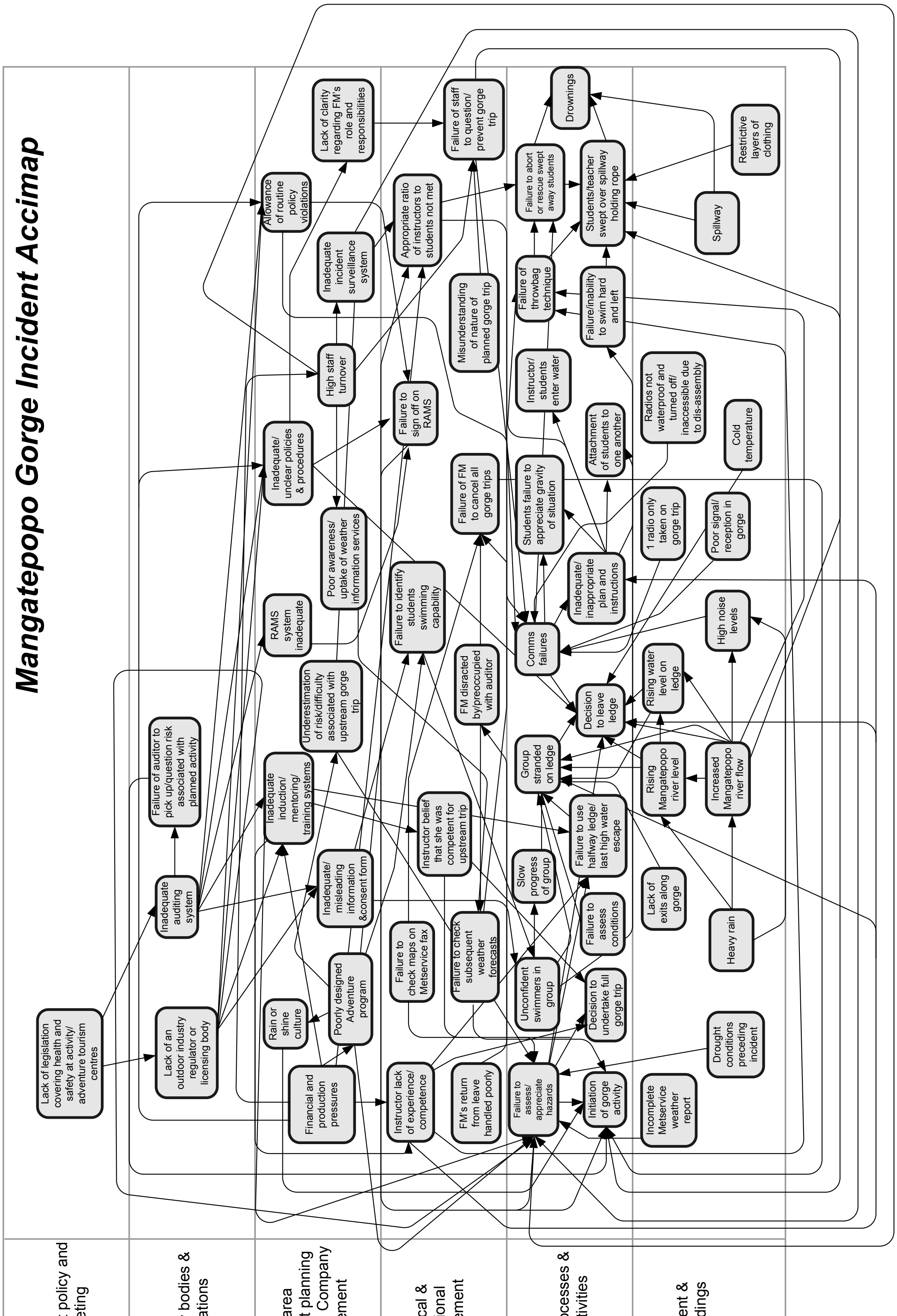
Mangatepopo Gorge Incident Accimap
ment policy and udgeting
atory bodies & sociations
ocal area ment planning ting, Company nagement
chnical & erational nagement
l processes & r activities
uipment & roundings
Lack of legislation covering health and safety at activity/ adventure tourism centres
Lack of an outdoor industry regulator or licensing body
Inadequate auditing system
Failure of auditor to pick up/question risk associated with planned activity
Financial and production pressures
Rain or shine culture
Poorly designed Adventure program
Inadequate induction/ mentoring/ training systems
Underestimation of risk/difficulty associated with upstream gorge trip
RAMS system inadequate
Inadequate/ unclear policies & procedures
Allowance of routine policy violations
Lack of clarity regarding FM's role and responsibilities
Inadequate incident surveillance system
High staff turnover
Poor awareness/ uptake of weather information services
Inadequate/ misleading information &consent form
Instructor lack of experience/ competence
FM's return from leave handled poorly
Failure to check maps on Metservice fax
Failure to check subsequent weather forecasts
Instructor belief that she was competent for upstream trip
FM distracted by/preoccupied with auditor
Failure to identify students swimming capability
Failure of FM to cancel all gorge trips
Failure to sign off on RAMS
Misunderstanding of nature of planned gorge trip
Appropriate ratio of instructors to students not met
Failure of staff to question/ prevent gorge trip
Failure to assess/ appreciate hazards
Unconfident swimmers in group
Slow progress of group
Group stranded on ledge
Comms failures
Students failure to appreciate gravity of situation
Instructor/ students enter water
Failure of throwbag technique
Failure to abort or rescue swept away students
Drownings
Initiation of gorge activity
Decision to undertake full gorge trip
Failure to assess conditions
Failure to use halfway ledge/ last high water escape
Decision to leave ledge
Inadequate/ inappropriate plan and instructions
Attachment of students to one another
Failure/inability to swim hard and left
Students/teacher swept over spillway holding rope
Incomplete Metservice weather report
Lack of exits along gorge
Rising Mangatepopo river level
Rising water level on ledge
1 radio only taken on gorge trip
Radios not waterproof and turned off/ inaccessible due to dis-assembly
Spillway
Drought conditions preceding incident
Heavy rain
Increased Mangatepopo river flow
High noise levels
Poor signal/ reception in gorge
Cold temperature
Restrictive layers of clothing

Figure 3. Mangatepopo incident Accimap.

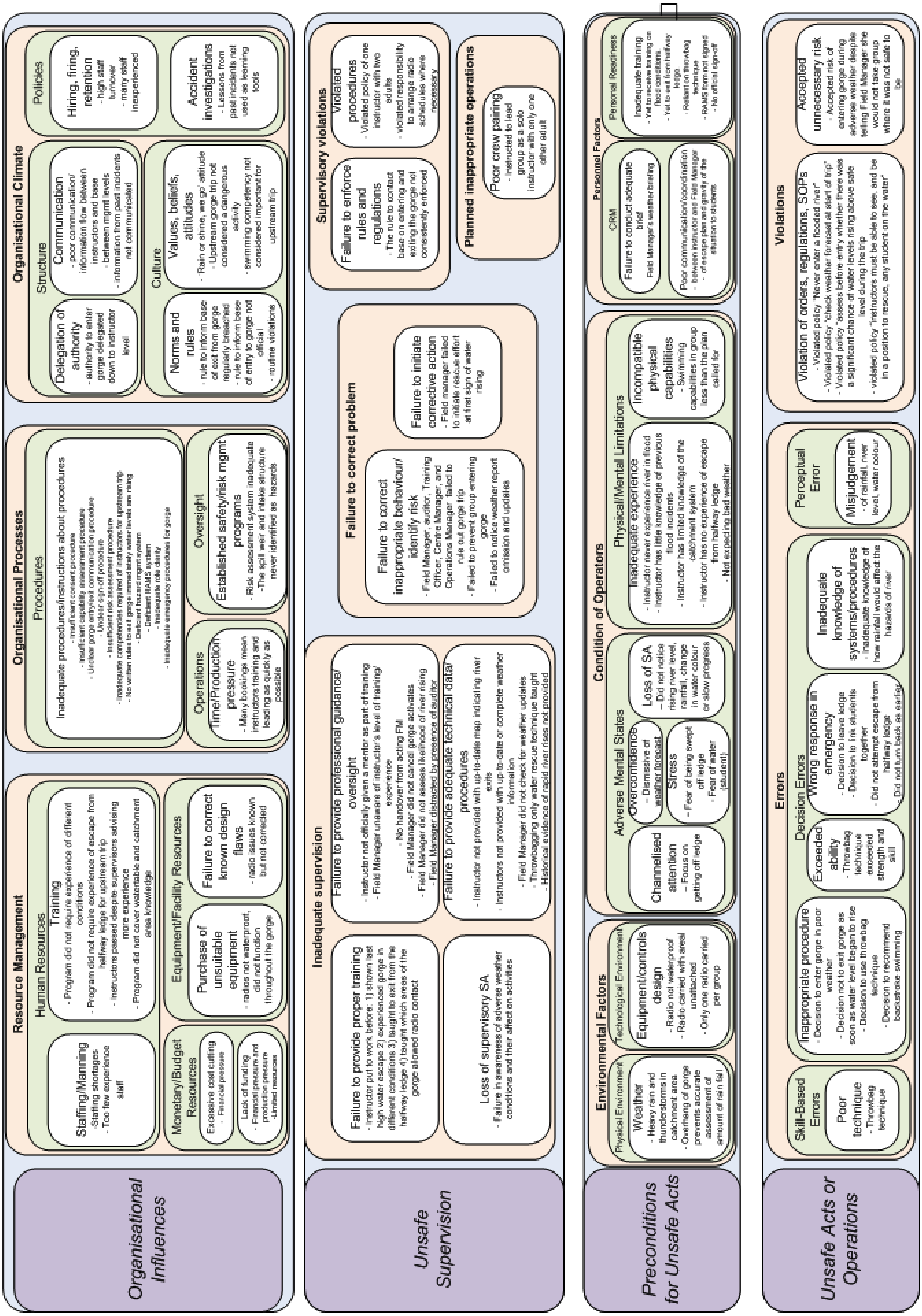

Figure 4. HFACS output

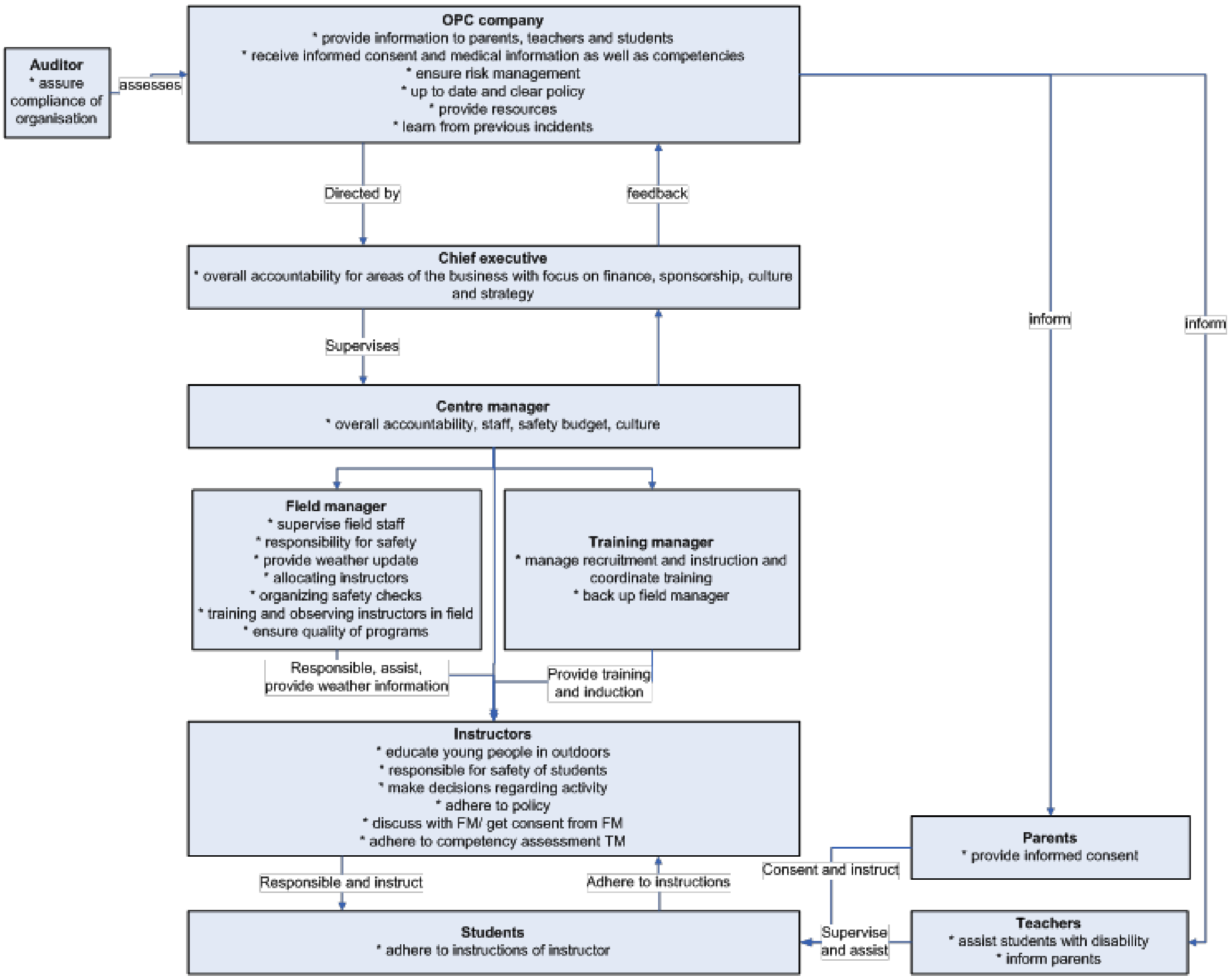

Figure 5. Mangatepopo incident: basic control structure diagram.

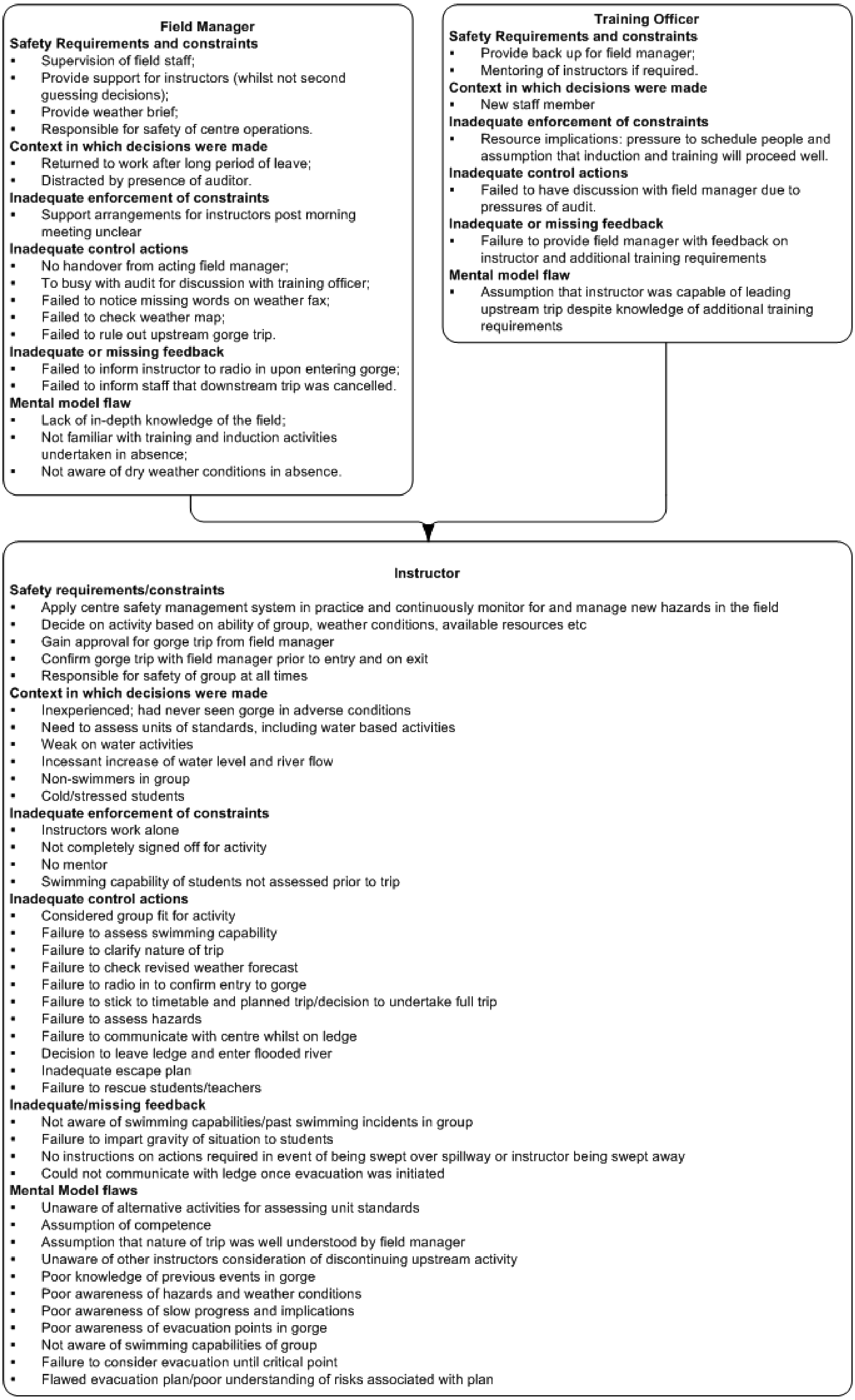

Figure 6. Example failures in field manager, training officer and instructor control structures.

Accimap

The Accimap output describes the failures involved and places them across six levels of the led outdoor activity system. Various contributory factors are placed at the equipment and surroundings level. These include the incomplete weather fax, the meteorological and environmental conditions prior to and on the day of the incident and the equipment used (e.g. only one non waterproof radio). At the physical processes and actor activities level, various failures related to the gorge walking activity itself and the instructor's response to the unfolding situation are represented. These include the generic failure of the instructor and other staff to assess and understand the hazards associated with conducting the gorge walk activity given the conditions in and around the gorge on the day in question and the initiation of the gorge walking activity. Other important factors at this level include the decision by the instructor to attempt to complete the full gorge walk activity, the slow progress of the group whilst in the gorge, the instructor's decision to attempt to evacuate the group from the ledge, and the resultant flawed evacuation plan, instructions, and enactment of the evacuation plan.

At the technical and operational management level the instructor's lack of experience of, and competence for, gorge walking activities, are key factors. These ostensibly had a bearing on various failures at the physical actor and processes levels, such as the decisions to undertake the full gorge trip given the conditions, to wait on the ledge, to leave the ledge, and the conception and enactment of the evacuation plan. Failures related to the field manager are also represented at this level, including his failure to check the weather map, to cancel all gorge trips and to communicate his decision to cancel the downstream trip. Failure of all staff (including the Outdoors Mark auditor) to check more up-to-date weather forecasts throughout the day of the incident, and to question the planned trip are also placed at this level. Other key failures at his level include the failure of the instructor to sign off on the centres risk assessment system, the centres failure to ascertain the swimming capabilities of the students within the group, and the use of only one instructor during gorge walking activities.

Various failures at the company management level played a role in the incident. There were significant financial and production pressures imposed on operations at the activity centre, which ostensibly led to a poorly designed adventure program, a rush to get staff trained and competent for activities, and the use of only one instructor for activities during busy periods (Brookes et al., 2009). The inadequate staff induction, mentoring, and training programs are represented at this level, as is the centres high staff turnover, which meant that useful knowledge and experience of previous incidents in the gorge was not maintained (Brookes et al, 2009). The risk assessment and management system and the lack of an adequate accident and near miss surveillance system are also placed at this level. Finally, routine policy violations by centre staff, such as failing to radio into the centre upon entering the gorge prior to engaging in gorge walking activities, are also included.

At the regulatory bodies and associations level, the absence of a regulatory body or licensing body for outdoor activity centres at the time in New Zealand is represented. Also represented at this level is the Outdoors Mark auditing system. Finally, at the government policy and budgeting level, the absence of legislation to control outdoor activity centres is included.

HFACS

The HFACS analysis involved classifying the failures involved across four levels of the outdoor activity system. At the unsafe acts level various decision errors on behalf of the instructor were classified. These are included in the failure modes ‘inappropriate procedures’, which includes the decision not to exit the gorge immediately on the water level beginning the rise; 'exceeded ability', which refers to the instructor using the throwbag technique which was beyond her capacity in the conditions; and 'inadequate knowledge or systems', which includes the instructor's lack of knowledge regarding how excessive rainfall would affect the hazards presented by the river and spillway. The failure mode 'wrong response in emergency' represents the instructor's decisions to leave the ledge, to tie the students together, to use the throwbag technique and to not attempt to evacuate the gorge via the halfway ledge. A skill-based error 'poor technique' is used to describe the failure of the throwbag technique to rescue the students, while a perceptual error describes the failure to immediately notice the rising river level and changing colour of the water during the activity.

At the pre-conditions for unsafe acts level, various failures were classified. In the condition of operator category and adverse mental states sub-category, stress on behalf of the instructor is represented, as are the instructor's loss of situation awareness in the gorge and channelized attention in focusing on leaving the ledge without assessing the potential hazard presented by the spillway. The instructor's overconfidence in her ability to lead the group in poor weather conditions is also represented in this sub-category. Also in the condition of operator category, the lack of experience and skill for the situation on behalf of the instructor is represented by the 'inadequate experience for complexity of situation' failure mode within the 'physical and mental limitations' sub-category. Incompatible physical abilities of both the instructor and the students are also represent by this sub-category. In the 'personnel factors' category, the failures 'failed to conduct adequate brief' and 'poor communication' from the 'Crew resource management' sub-category are represented. The former represents the failure by the activity centre's field manager to conduct an adequate weather brief at the staff meeting, whereas the latter refers generally to the poor communications throughout the day of the incident. From the 'personnel readiness' category, 'inadequate training', referring to the limitations in training/mentoring received by the instructor, is also represented.

Various failures were classified at the unsafe supervision level. The poor training/mentoring given to the instructor is represented by the 'failure to provide proper training' failure mode. The majority of the field manager's failures are represented at this level via the failure modes 'failed to provide professional guidance or oversight' (i.e. failure to cancel gorge activities or prevent the activity from going ahead). 'loss of supervisory situation awareness' (i.e. lack of awareness regarding the adverse weather conditions), 'failed to provide adequate supervision' (i.e. generic supervisory failures). Also, the failures 'failed to correct inappropriate behaviour' and 'failed to initiate corrective action' represent the continual, unchecked, policy violations by activity centre staff (i.e. not radioing into centre when entering gorge). Finally, the failure to make instructors aware of previous incidents in the gorge through the lack of an efficient accident and near miss surveillance system is represented by the 'failed to provide current publications/adequate technical data and/or procedures' failure mode.

The organisational influences level describes the failures in the running of the activity centre involved. From the 'human resources' category (within the Resource management category) the 'training' failure mode represents the inadequate induction, training, and mentoring system in use at the time of the incident. Also from the Resource management category, the sub-category 'Monetary/Budget resources' is represented through the 'excessive cost cutting' and 'lack of funding' failure modes, both of which refer to the financial pressures imposed on operations prior to the incident. The final failures from the resource management category are a 'failure to correct known design flaws' and 'Purchase of unsuitable equipment' which refers to the activity centres continued use of radios despite knowing that they were not waterproof and did not work well within the gorge. Six key failures are represented in the organisational climate category. In the 'Culture' sub-category, the centre's rain or shine culture is represented by the 'values, beliefs and attitudes' failure mode, while the routine violation of policy allowed by management are included in the 'norms and rules' failure mode In the 'Policies' sub-category the failures included the 'accident investigations' failure mode, which refers to the inadequate accident and near miss surveillance system in place at the time of the incident, and the 'hiring, firing, retention' failure mode, which refers to the high staff turnover at the activity centre involved. The final organisational climate failures fall within the 'Structure' category and include the various communications failures, represented by the 'communication' failure mode, and the delegation of authority to enter the gorge to individual instructors represented by the 'delegation of authority' failure mode.

A number of failures at this level come from within the Organisational Process category. These occur in the 'procedures/instructions about procedures' failure mode from the 'Procedures' sub-category, which includes the inadequate emergency procedures for activities in the gorge, and the 'established safety programs/risk management programs' failure mode from the 'Oversight' sub-category, which represents the inadequate risk assessment/management system used by the activity centre. The pressure to have instructors trained and active as rapidly as possible to cope with the number of bookings was represented in the 'Time/production pressure' failure mode in the 'Operations' sub-category.

STAMP

The STAMP analysis consisted of two phases. The first output was the control structure as depicted in Figure 5. The key personnel from the control structure were then selected for further analysis; the field manager, the training officer and the instructor. For these the safety requirements and constraints, context of decision making, mental model flaws, as well as inadequate enforcement of constraints, control actions and inadequate or missing feedback were determined.

The field manager was responsible for supervision of and support for instructors in the field, providing a weather brief and had the overall responsibility for safety during centre operations. The context in which his decisions were made affected his performance, namely he had just returned to work after a longer period of leave and was distracted by the presence of the auditor. The inadequate enforcement of constraints on behalf of the field manager was the lack of clarity of the support arrangements of instructors after the morning meeting. Inadequate control actions on behalf of the field manager were the lack of an efficient handover, the failure to notice missing words in the weather report and failure to rule out the trips within the gorge on the day in question. His failure to inform the staff of the downstream trip is an example of inadequate or missing feedback. Flaws in his mental model include his lack of familiarity with training and induction activities undertaken in his absence as well as the weather conditions prior to his return to work.

The training officer acts as a back up for the field manager, acting on his behalf in case the field manager is absent. The training officer was a relatively new member of the staff and resource implications meant there was pressure to schedule participants in with the assumption that the induction and training will proceed as well. This represents an inadequate enforcement of constraints on behalf of the training officer. An inadequate control action was the failure of the training officer to brief the field manager upon his return to work. The failure to provide the field manager with feedback regarding the instructors training development and requirements is considered inadequate or missing feedback. Furthermore, the assumption on behalf of the training officer to assume that the instructor was capable of undertaking the upstream trip despite the training requirements at the time, is considered a mental model flaw.

The instructors responsibility is to apply the safety management system in practice, decide on which activities to undertaken, gain approval for her decisions from the field manager, and oversee safety of the group being taught at all times. The context in which the instructor's decision making took place is important; she was inexperienced, not used to adverse weather conditions in the gorge, and had non-confident swimmers in the group. Examples of inadequate enforcement of constraints on behalf of the instructor are the fact that she did not assess the swimming capacity of the students and undertook an activity that she was not signed off for. Inadequate control actions include her assessment of the group as fit for the activity, failure to check revised weather forecast, failure to stick to timetable of trip and the decision to leave the ledge and enter a flooded river. Amongst the inadequate or missing feedback is the failure to communicate the gravity of the situations to the students, and the failure to communicate a contingency plan. Poor knowledge of previous incidents, poor awareness of hazards and weather conditions as well as of the slow progress of the group and the implications of that for the trip are examples of mental model flaws on behalf of the instructor.

Discussion

The aim of this paper was to compare and contrast three popular contemporary accident analysis methods based on their application to the analysis of the recent Mangatepopo gorge walking tragedy. The comparison reveals key differences between the methods in terms of approach and output. When using the Accimap method, analysts are essentially given free reign to identify contributing factors across the six levels specified. There is no taxonomy of errors or failure modes to guide the analysis, and the entire system, ranging from the environment in which the accident occurred, to the role of government in shaping the system of work, is considered. This makes Accimap potentially highly comprehensive in terms of its ability to identify all of the contributory factors involved in a particular accident, ranging from operator failures on the day of the incident to failures in government and local authority decision making and policy even many years before the accident. Provided sufficient data is available and the analyst is skilled enough, the Accimap method can potentially describe the entire accident trajectory in terms of failures across the system and the relationships between them. The linkage of failure within and between levels is also an important feature of Accimap, since this ensures that failures are considered in the context of the factors influencing them, and also supports the development of appropriate system wide countermeasures, as opposed to individual operator focussed ones. For example, in the present study the Accimap demonstrates that various factors across the system influenced the instructors decision to evacuate the ledge, including her inexperience and lack of competence for gorge activities, communications failures (i.e. inability to contact centre for advice), rising water level and river flow, cold conditions, and the students questioning the decision to stay on the ledge. In turn, the factors related to these linked factors are represented; for example, the various induction/mentoring/training failures linked to the instructor’s inexperience and lack of competence.

The Accimap structure can be problematic. For example, the physical processes and actor activities level does not specifically deal with failures in cognition of behalf of those involved; rather, flawed decisions are normally represented at this level without necessarily identifying the factors influencing them, such as poor situation awareness or operator mindset. The lack of taxonomies at each level also creates problems; since the analysis is entirely dependent upon analyst subjective judgement, the reliability of the method is likely to be limited. Differences in both the actual failures identified, and the way in which the failures are described, are likely to emerge across different analysts. Finally, the absence of taxonomic support renders Accimap more suitable to single case study analyses (as presented in this paper) as opposed to multiple case analyses. Without taxonomies of specific failure modes, it is difficult to aggregate Accimap analyses in order to derive a useful summary of multiple accident cases. Taxonomic approaches such as HFACS lend themselves to the analysis of multiple accident cases, since themes and trends in causal factors can be easily determined. This is evidenced by HFACS continued use in multiple accident case study analyses (e.g. Baysari et al., 2009; El Bardissi et al., 2007; Li & Harris, 2006; Li et al., 2008; Shappell and Patterson, 2010), whilst most published Accimap analyses focus on single accident cases (e.g. Cassano-Piche et al, 2009; Jenkins et al, 2010; Johnson & de Almeida, 2008; Salmon et al, 2010).

The taxonomic nature of HFACS is an important feature of the method. Reliability is enhanced since analysts are given guidance, albeit limited, in error and contributory factor classification. This is evidenced by various HFACS analyses which report statistics demonstrating acceptable to high levels of inter-rater reliability (e.g. Lenné et al., 2008; Li & Harris, 2006; Li et al., 2008). Also, as described above, the method lends itself to multiple accident case analyses, and so is perhaps more suited to inclusion in safety management systems than a more generic approach such as Accimap. The ability to link failures across the four levels is also important; when used for multiple accident case analysis this allows the associations between failures at the four different levels to be assessed statistically. This allows the higher systems level failures that are known to cause lower level operator errors and unsafe acts to be focussed on during accident prevention efforts.

There are, however, problems associated with the use of taxonomies in accident analysis methods. Although reliability is enhanced, the analyst is constrained in terms of the specific failures that can be classified. This problem becomes manifest when applying HFACS outside of aviation; since it was developed specifically for aviation, a number of the error and failure modes are aviation specific (e.g. lack of aptitude to fly, misinterpretation of traffic calls, hypoxia) which renders them unusable outside of the aviation context. Further, errors and contributing factors outside of the HFACS taxonomies cannot conceivably be classified by the method in its original format. In the present analysis, for example, various failures could not be classified, including the failure of the auditor to identify issues with the briefing, induction process or decision to undertake the gorge activity; and failures by the instructor that were not decision or skill errors but were not included in procedures so cannot legitimately be described as violations, such as the failure of the instructor to stick to her planned schedule when in the gorge. Finally, the use of only four levels in HFACS is problematic, since failures outside of the organisation involved (e.g. government policy, local authority level failures) are not considered. It is acknowledged, however, that more recent HFACS analyses have used additional 'outside factors' levels which include 'regulatory factors' and 'other' failure categories (e.g. Patterson and Shappell, 2010).

When using STAMP, the first thing to note is that there is an additional data and analysis requirement involved due to the need to construct the control structure diagram representing the safety control loops present in the domain in question. This involves going beyond merely collecting and analysing data regarding the accident itself, and requires that data on the domain in question be collected. An in-depth knowledge of the system in question, including factors such as Government policy and legislation, regulatory bodies, rules and regulations, company procedures and training programs, is required. Whilst on the downside this creates a much higher level of resource usage in terms of time invested and date required, it is also likely to be beneficial in enabling the analyst to develop a deeper understanding of the system under analysis.

STAMP provides an overview of how the system should have been controlled and how the accident in question should have been prevented from happening as well as the relations between actors, and the context in which the accident occurred. Since it also focuses on the entire sociotechnical system, STAMP is potentially as comprehensive as Accimap. Provided the initial control structure diagram is accurate, and all control loops are identified, failures across the entire system, including governmental and local authority levels, are considered. Like HFACS, STAMP provides a taxonomy of control failures; however, it is generic in nature (not restricted to a particular domain) and is thus less restrictive than that provided by HFACS. One notable aspect of the STAMP method is the inclusion of the context in which decisions were made as well as the mental model flaws category. This enables context to be considered when identifying and describing control failures, making it clearer why erroneous or inappropriate decisions were made.

The STAMP taxonomy and theoretical underpinning does create problems, however. In the present case study, initially the STAMP analyst, and then the other analysts when reviewing the outputs, found it difficult to place some of the human and organisational failures within the STAMP taxonomy. The language used, ostensibly borne out of its control theory and system dynamics origins, often makes it difficult to discriminate between control failure types, rendering STAMP more suitable for identifying and classifying technical control failures as opposed to complex human decision making and organisational failures. Further, it is worth noting that the STAMP theory and analysis approach has not yet gained acceptance outside of academic circles yet (i.e. with safety practitioners). Finally, the analysis demonstrated the difficulty in fully considering environmental conditions when using STAMP; in the present analysis the environmental conditions were only considered in the context of the decision making and did not appear in the basic control structure itself. The role of these could therefore be under represented and the focus is rather on what the actors did with the environmental conditions rather than any direct influence these could have had.

The question remains, which is the most suitable method for analysing accidents occurring in safety critical systems? Although Accimap and STAMP are likely to be the most comprehensive in terms of coverage of the overall sociotechnical system, for in-depth analysis of single, large scale, complex accidents, the present analysis suggests that the Accimap method is the most suitable. The entire system can be considered, and the analyst is not restricted by taxonomies of failure modes, making the approach the most comprehensive and easy to use out of the three methods compared. Further, the ability to consider failures, decisions and actions generally is likely to be simpler for safety practitioners and accident investigators not familiar with control theory and systems dynamics. For multiple accident case studies, however, a taxonomic approach such as HFACS is likely to be more useful;

however, it is recommended that additional higher systems levels (e.g. government, regulatory bodies) are included, and also that the taxonomies be developed specifically for the domain in question. One useful approach, as discussed in the following section, would be to add appropriate taxonomies to the Accimap method, which would enable it to be applied in multiple case study analyses.

The way forward for accident analysis in the led outdoor activity domain

The impetus for this case study arose from the need for the led outdoor activity industry in Australia to develop, through improved accident surveillance systems, a more in-depth understanding of the injury-causing accidents occurring in their domain. This discussion now returns to this domain to answer the question as to which of the approaches described represents the most appropriate for future accident surveillance systems in the led outdoor activity domain? In these authors opinion, the evidence suggests not that, for the reasons outlined above, the Accimap method stands out as the most suitable in terms of ease of use and utility of outputs; however, for use as part of an accident surveillance system in which multiple accidents are to be understood and trends identified, a modified approach, incorporating the main strengths of all three, is likely the best option. The Accimap and STAMP approach to taking the overall system as the unit of analysis is recommended, since this ensures that appropriate systems reform and countermeasures are developed. Failures at higher systemic levels are now accepted to play a critical role in accidents in the safety critical domains (e.g. Hollnagel, 2004; Rasmussen, 1997; Reason, 1990) and applying methods which do not identify such failures is likely to lead to the development of inappropriate remedial measures and countermeasures (Dekker, 2002; Reason, 1997). Based on this and other evidence (e.g. Salmon et al., 2010), the theoretical underpinning and philosophy of the Accimap approach seems suited to this domain; however, as described, its use as a multiple case analysis method is questionable. The solution to this, it seems, is to borrow from the HFACS approach and add taxonomies of failures across the six levels used. Provided these are developed appropriately, this should enhance the methods reliability when used by different analysts, and should also enhance its utility when applied to multiple accident cases as part of an overall accident surveillance system.

Conclusions

This article presented a case study-based comparison of three contemporary accident analysis methods: Accimap, HFACS, and STAMP. The comparison suggests that, although Accimap and STAMP are likely to be more comprehensive in terms of the contributory factors identified, the HFACS approach is likely to be more reliable due its taxonomic nature and also more useful in multiple case study analyses. The downside of this, however, is that, in the absence of domain specific taxonomies and taxonomies considering higher governmental and local authority failures, analysts are restricted in their ability to classify all failures involved, and contributing factors may be missed, particularly when applying the method outside of aviation. It is recommended that, for future accident analysis efforts, both in general and in the led outdoor activity domain, a modified Accimap approach incorporating flexible taxonomies across the six levels analysed, be developed.

Acknowledgement

This research was undertaken as part of a program of research funded through the Australian Research Council Linkage scheme, which includes funding contributions from the Australian Research Council and from various Australian led outdoor activity providers. The authors also wish to acknowledge the members of the project steering committee, who provided initial data for the analysis and also reviewed and refined the analysis presented. Dr Salmon's contribution to this article was funded through his Australian National Health and Medical Research Council post doctoral training fellowship. Miranda Cornelissen's contribution to this article was funded through the Monash Researcher Accelerator Program.

References

Baysari, M.T., McIntosh, A.S., Wilson, J. (2008). Understanding the human factors contribution to railway accidents and incidents in Australia. *Accident Analysis and Prevention*, 40, pp. 1750-1757.

Brookes, A., Smith, M., Corkill, B. (2009). Report to the trustees of the Sir Edmund Hillary Outdoor Pursuit Centre of New Zealand: Mangatepopo gorge incident, 15th April 2008.

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

Davenport, C. J. (2010). Mangatepopo Coroners report, Auckland, 30th March 2010.

El Bardissi, A. W., Wiegmann, D. A., Dearani, J. A., Daly, R. C., & Sundt, T. M. (2007). Application of the human factors analysis and classification system methodology to the cardiovascular surgery operating room. *Annals of Thoracic Surgergy*, 83, pp. 1412-1418.

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

Finch, C., Boufous, S., and Dennis, R. (2007). Sports and leisure injury hospitalisations in NSW, 2003-2004: sociodemographic and geographic patterns and sport-specific profiles. NSW Injury Risk Management Research Centre.

Hollnagel, E. (2004). Barriers and accident prevention. Ashgate, Aldershot, UK.

Jenkins, D. P., Salmon, P. M., Stanton, N. A. & Walker, G. H. (2010). A systemic approach to accident analysis: a case study of the Stockwell shooting. *Ergonomics*. 3:1. Pp 1 – 17.

Johnson, C.W. & de Almeida, I.M. (2008). Extending the borders of accident investigation: applying novel analysis techniques to the loss of the Brazilian space launch vehicle VLS-1 V03. *Safety Science*, 46:1. pp 38-53.

Lawton, R. & Ward, N. J. (2005). A systems analysis of the ladbroke grove rail crash. *Accident Analysis & Prevention*, 37, pp. 235-244.

Leveson, N. G. (2004). A new accident model for engineering safer systems. *Safety Science*, 42:4, pp. 237--270.

Leveson, N., Allen, P., and Storey, M. A. (2002). The analysis of a friendly fire accident using a systems model of accidents. In: Proceedings of the 20th international system safety society conference (ISSC 2003). Unionville, VA: System Safety Society, 345–357.

Leveson, N. G. (2009). The need for new paradigms in safety engineering. Safety-Critical Systems: Problems, Process and Practice (2009): 3-20. Proceedings of the Seventeenth Safety-Critical Systems Symposium, Brighton, UK, 3–5 February 2009

Levy, M. (2010). Tragedy of boy who drowned while swimming at school camp. http://www.theage.com.au/victoria/tragedy-of-boy-who-drowned-while-swimming-at-school-camp-20100218-oefo.html, accessed 15th April 2011.

Li, W.-C., & Harris, D. (2006). Pilot error and its relationship with higher organizational levels: HFACS analysis of 523 accidents. *Aviation, Space and Environmental Medicine*, 77, pp. 1056–1061.

Li, W.-C., Harris, D., & Yu, C.-S. (2008). Routes to failure: Analysis of 41 civil aviation accidents from the Republic of China using the human factors analysis and classification system. *Accident Analysis and Prevention*, 40:2, pp. 426-434

Ouyang, M., Hong, L., Yu, M. H., & Fei, Qi. (2010). STAMP-based analysis on the railway accident and accident spreading: taking the China-Jiaoji railway accident for example. *Safety Science*, 48:5, pp. 544-555.

Patterson, J. M., & Shappell, S. (2010). Operator error and system deficiencies: Analysis of 508 mining incidents and accidents from Queensland, Australia using HFACS. *Accident Analysis & Prevention*, 42:4, pp. 1379-1385

Rasmussen, J. (1997). Risk management in a dynamic society: A modelling problem. *Safety Science*, 27:2/3, pp. 183-213.

Reason, J. (1990). Human Error. New York, Cambridge University Press.

Salmon, P. M., Williamson, A., Lenne, M. G., Mitsopoulos, E., & Rudin-Brown, C. M. (2010). Systems-based accident analysis in the led outdoor activity domain: application and evaluation of a risk management framework. *Ergonomics*, 53:8, pp. 927-939.

Svedung, I., & Rasmussen, J. (2002). Graphic representation of accident scenarios: mapping system structure and the causation of accidents. *Safety Science*, 40, pp. 397-417.

Wiegmann, D. A., & Shappell, S. A. (2003). A human error approach to aviation accident analysis. The human factors analysis and classification system. Burlington, VT: Ashgate Publishing Ltd.