Identifying risks and emergent risks across sociotechnical systems: The NETworked Hazard Analysis and Risk Management System (NET-HARMS).

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Abstract

Accidents are a systems phenomenon and multiple methods are available to enable retrospective analysis of accidents through this lens. However, the same cannot be said for the methods available for forecasting risk and accidents. This paper describes a new systems-based risk assessment method, the NETworked Hazard Analysis and Risk Management System (NET-HARMS), that was designed to support practitioners in identifying a. risks across overall work systems, and b. emergent risks that are created when risks across the system interact with one another. An overview of NET-HARMS is provided and demonstrated through a case study application. An initial test of the method is provided by comparing case study outcomes (i.e. predicted risks) with accident data (i.e. actual risks) from the domain in question. Findings show that NET-HARMS is capable of forecasting systemic and emergent risks and that it could identify almost all risks that featured in the accidents in the comparison dataset.

Keywords: systems thinking, risk assessment, emergence, risk decision making, risk practitioner

Relevance to Human Factors/Ergonomics Theory

Methods which both support and enable application of a systems theoretical perspective to risk assessment are extremely limited. This paper outlines the development of a risk assessment method both underpinned by systems thinking and that was consciously designed to facilitate ease of use and application by the risk management practitioner.

Introduction

Accidents are now widely acknowledged to be a systems phenomenon, with the field of safety science now largely accepting that accidents are a result of multiple interacting contributory factors situated across entire work systems (Salmon et al, 2011; Dekker, 2011) This contemporary understanding mirrors an evolution of beliefs and subsequent models, developed to explain accident causation in safety-critical domains over the past century, e.g. Domino Theory, Heinrich, 1931; Normal Accident Theory, Perrow, 1984; Swiss Cheese Model, Reason, 1990; Risk Management Framework, Rasmussen, 1997; Systems-Theoretic Accident Model and Processes, Leveson, 2004, 2011; Functional Resonance Accident Method, Hollnagel, 2004). This explanation of accident causation, known as 'systems thinking', is philosophically underpinned by the assertion that accidents are produced by interactions between multiple human and technical elements, as opposed to the actions of one human, or one specific failure in isolation (Salmon et al, 2016a). The widespread acceptance of this philosophy is such that there is now a range of accident analysis methods available to support analysts in viewing accidents through this lens.

Whilst these methods have made a significant contribution to our understanding of risk and accident causation, the primary limitation of course, is that they are reactive, examining events that have already happened. In many domains, reductions in accidents and injuries are beginning to plateau (Dekker and Pitzer, 2016; Salmon, Walker, Read, Goode and Stanton, 2017; Walker, Salmon, Bedinger and Stanton, 2017). More worryingly, in other areas such as road safety, fatalities and injuries are beginning to rise once again (see National Safety Council, 2017; Transport Accident Commission, 2016). Reactive accident analysis approaches have been implicated in this (Leveson, 2011; Salmon et al, 2017), which in turn has led to calls for more emphasis on the use of methodologies that can forecast risk and accidents (Leveson, 2017; Salmon et al, 2017). Indeed, the ability to forecast accidents before they occur has been labelled the final frontier for ergonomics (Moray, 2008; Salmon et al, 2017; Stanton and Stammers, 2008). Within the field of safety science, the group of methods closest to enabling the prediction of adverse events, or at least the factors that contribute to them, are risk assessment methods (Dallat et al, 2017). Organisations use risk assessment methods to identify the foreseeable hazards and associated risks that may lead to adverse outcomes (Dallat et al, 2017; Escande et al, 2016).

Given the widespread acceptance of the systems thinking perspective on accident causation, it has been argued that risk assessment methods should a. be underpinned by the same perspective (Leveson, 2011; Salmon et al, 2017); and b. should examine the entire work system when attempting to identify the risks associated with different work activities (Dallat et al, 2017; Salmon et al, 2017). In practice, this means that as well as identifying risks at the sharp-end of system operation, risk assessment methods should also consider risks associated with supervisory, managerial, regulatory and even government actions and interactions.

Despite these assertions and the extensive literature on the need for a systems thinking approach to accident analysis and prevention (Waterson, 2009; Davis, Challenger, Jayewardene and Clegg, 2014), the majority of formal risk assessment methods are not underpinned by a systems view on risk (Dallat et al, 2017; Stanton and Harvey, 2017; Pasquini, Pozzi and Save, 2011; Eidesen, Sollid and Aven, 2009; Stanton and Stevenage, 1998). In a recent review, Dallat et al, (2017) used Rasmussen's (1997) tenets of accident causation to evaluate the extent to which over three hundred risk assessment methods, spanning a range of safety-critical domains, were underpinned by systems thinking. They found that the risk assessment methods they reviewed typically do not support the identification of risks outside of the front-line worker (e.g. pilot, control room operator, driver), nor do they support the identification of emergent risks (i.e. risks that emerge from the interaction of multiple risks across the system). In conclusion, Dallat et al (2017) reported that the majority of risk assessment methods reviewed adopted a linear, chain-of-events philosophy and were thus not consistent with contemporary systems thinking models of accident causation. Encouragingly however, a small number of the methods examined were underpinned by systems thinking. These included the System-Theoretic Process Analysis (STPA) (Leveson, 2011), and the Functional Resonance Accident Method (FRAM) (Hollnagel, 2004). These methods have made a major contribution to closing the gap between the currently accepted understanding of accident causation and risk assessment methods and provide a solid foundation upon which further development can occur.

Nonetheless, STPA (Leveson, 2011) and FRAM (Hollnagel, 2004) have not yet enjoyed widespread application in practice. Both methods have been criticised for being complex and time consuming to learn, understand and apply (e.g. Hollnagel and Spezali, 2008; Johansson and Lindgren, 2008). Further, both methods have been criticised due to a lack of evidence relating to their lack of reliability and validity (Underwood and Waterson, 2012). In general, these factors have been identified as key issues limiting the widespread application of systemic human factors methods in practice (Salmon, 2016; Shorrock and Williams, 2016; Underwood and Waterson, 2012).

Accordingly, it is these analyst’s opinion that new approaches to risk assessment are required. Importantly, to ensure translation of systems thinking principles in risk assessment practice, such approaches should embody key systems thinking principles whilst at the same time remaining easy to learn and apply. The authors have been engaged in a program of research that aims to develop and test such an approach. The aim of this article is to describe and demonstrate a new risk assessment method that is directly underpinned by systems thinking, and that was developed specifically for use by practitioners working in risk management. The NETworked Hazard Analysis and Risk Management System (NET-HARMS), was designed to enable the identification of risks across overall work systems, as well as the emergent risks that are created when different risks interact with one another. Further, to specifically address and remove the limitations of existing systems thinking risk assessment methods (e.g. Leveson, 2011, 2004), a key component behind the design of the NET-HARMS risk assessment method was that it must be easy to learn and quick to apply.

The article begins by providing a brief overview of the limitations of existing risk assessment methods, as well as outlining the requirements for a systems thinking based risk assessment method. Following this, an overview of NET-HARMS is presented along with a case study application within a specific context – the led outdoor education and recreation domain. This domain was selected as the first analyst has significant subject matter expertise in this field and further, within Australia, analyses of injury-causing incidents revealed inadequate risk assessment as a significant contributory factor (Van Mulken et al, 2017; Salmon et al, 2016a, 2017; Dallat et al, 2015; White, 2014). Following presentation of the case study analysis, the risks identified using NET-HARMS are compared with a dataset describing the contributory factors involved in injury-causing incidents within led outdoor activities (Van Mulken et al, 2017). In closing, the implications for applying NET-HARMS in practice are discussed, as well as the need for formal reliability and validity testing.

Current approaches to risk assessment

Risk assessment describes the process of determining the probability of a risk occurring within a work system, and the likely consequences of that risk (Ostrom and Wilhelmsen, 2012). Dallat et al (2017) reported that the most common methods currently described in the safety science literature are underpinned by quantitative (or probabilistic) approaches and further, that they focus largely on risks at the so called sharp-end of performance, predominantly viewing accidents as emerging from linear, or a chain-of-events process. Such an approach fails to consider the interactions between these factors; a key principle behind systems thinking in relation to accident causation (e.g. Leveson, 2011, Rasmussen, 1997, Reason 1990). Further, risks elsewhere in the system (e.g. procedural, policy, training and managerial risks) are not considered. Existing risk assessment methods are unable to identify the non-routine, emergent risks; those additional risks that arise as a result of the interaction between risks across the system. Of course, these are precisely the kinds of risks that interact to create large-scale catastrophes (Leveson, 2004; Reason, 1990). By way of an example, we can consider the Air France 447 crash of 2007 (see Salmon et al, 2016b) that involved a stalled A330 crashing into the Pacific Ocean, killing all on-board. Existing risk assessment methods would certainly be able to identify the risk of the pilot flying inadvertently putting the aeroplane into a climb and stalling. However, the extent to which they could identify earlier factors that created the situation in which the plane handed over control to the pilots, or the emergent properties that exacerbated the situation is questionable. These include the autopilot disconnecting after the pitot tubes froze and sent spurious airspeed information to the cockpit, or the fact that the aircrew associated the buffeting of the aircraft with an overspeed situation due to their previous training.

In short, the insight from the late twentieth century is that accidents emerge from relationships *between* parts, layers and components, and not from broken parts in isolation (Dekker, 2011). Whilst this is the dominant perspective for understanding accidents (see Underwood and Waterson, 2014), and despite recent calls for the need to adopt a similar perspective when attempting to proactively identify risks and accidents, such as those that contributed to the Air France example provided above, (see Salmon et al, 2017), this approach has not yet been widely translated across to the design of risk assessment methods (Dallat et al, 2017). This paper attempts to address that gap. The following section will explain the development of the NET-HARMS method to support the identification of risks across entire work systems.

NET-HARMS

Development of NET-HARMS

The aim of this program of research was to develop a systems thinking-based approach to risk assessment that was easy to learn and quick to apply in practice. The development of the method involved an initial review of two significant bodies of literature. First, the analysts reviewed over 100 human factors methods, as described in Stanton, Salmon and Rafferty, (2013) for a suitable approach to initially describe systems of work. This led to the identification of Hierarchical Task Analysis (HTA), (Annett, Duncan, Stammers and Gray, 1971; Shepherd, 1989; Kirwan and Ainsworth, 1992) as an appropriate methodology for describing the goals, tasks, operations and plans associated with work systems (Stanton, 2006). HTA was selected as it is arguably the most popular task analysis method and has extensive reliability and validity evidence associated with it (Stanton et al, 2013; Stanton, 2006). Next, existing human error identification (HEI) and human reliability analysis (HRA) methods were reviewed to identify which most suited the identification of risks across systems. This was considered a critical requirement as the overall aim was to develop a risk assessment method that was capable of identifying risks across the entire system of work, as opposed to the identification of risks associated with only sharp end operators and individual tasks. The Systematic Human Error Reduction and Prediction Approach (SHERPA) (Embrey, 1986), was identified as the most suitable for this. SHERPA was initially developed for application in nuclear processing domain (Harris et al, 2005), and has since been applied in numerous other domains, including aviation (Stanton et al, 2009), medication error (Lane, Stanton and Harris, 2006), and public technology (Stanton and Stevenage, 1998). An additional factor underpinning the selection of SHERPA included the fact that it uses HTA as its initial task description (along with a taxonomy) to identify credible errors associated with a sequence of human activity (Stanton and Baber, 2002). The technique works by the analyst indicating which of the errors from the error mode taxonomy (see Figure 1) is credible from each task under analysis from the bottom level of the HTA (Harris et al, 2005). SHERPA is one of the most commonly used HEI methods and has been found to require little training and to be relatively easy to use (Stanton et al, 2013; Harris et al, 2005). Further, it enjoys the most positive validation evidence of all HEI methods (Stanton, Young and Harvey, 2014; Stanton et al, 2013, Stanton and Young, 1999; Kirwan, 1992; 1990).

Action Errors
A1 Operation too long/short
A2 Operation mistimed
A3 Operation in wrong direction
A4 Operation too little/much
A5 Misalign
A6 Right operation on wrong object
A7 Wrong operation on right object
A8 Operation omitted
A9 Operation incomplete
A10 Wrong operation on wrong object
Checking Errors
C1 Check omitted
C2 Check incomplete
C3 Right check on wrong object
C4 Wrong check on right object
C5 Check mistimed
C6 Wrong check on wrong object
Retrieval Errors
R1 Information not obtained
R2 Wrong information obtained
R3 Information retrieval incomplete
Communication Errors
I1 Information not communicated
I2 Wrong information communicated
I3 Information communication incomplete
Selection Errors
S1 Selection omitted
S2 Wrong selection made

Figure 1. SHERPA (Embrey, 1986) External Error Mode Taxonomy

When used together in their original form, HTA and SHERPA would not typically support the identification of risks across overall work systems (by ‘overall work systems’, we are referring to the human and non-human actors throughout the organisation who influence the design, development and delivery of the desired outputs). For example, SHERPA is characteristically used to predict error associated with operator tasks at the sharp end, e.g. in an aviation context, ‘Pilot dials in wrong airspeed’, or in healthcare, ‘Drug name read incorrectly’. Further, even though HTA can be used as a systems analysis method, it is rarely used in this manner. Rather, it is mostly used to describe work at the sharp end (e.g. see Stanton et al, 2013).

Consequently, the next stage of methodological development involved extending HTA and SHERPA to support the identification of risk across overall work systems. For this purpose, HTA was extended to describe the goals, tasks and operations for an overall work system, from the process of initial work design and development of the work activity, through to work delivery and review. Accordingly, critical aspects such as work design, development of procedures, work planning and contingency planning were described in the HTA (see Figure 2).

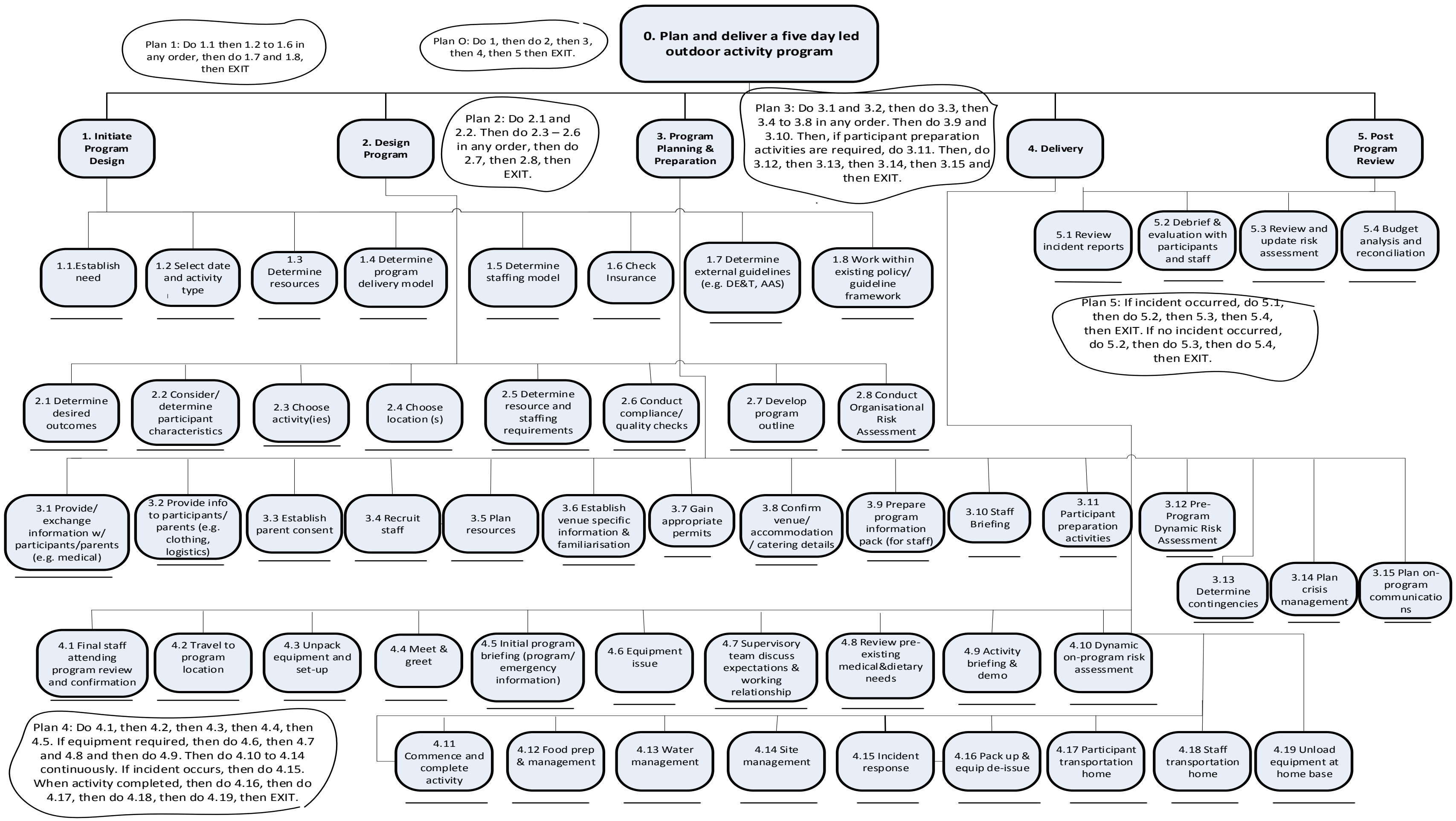

Figure 2. Hierarchical Task Analysis to reflect the system behind the process of design, planning, conducting and reviewing a five-day led outdoor education program

Extension of SHERPA

Next, initial testing of the SHERPA taxonomy found it to be limited when used to identify risks (the taxonomy was originally developed to identify human errors). Example issues encountered were that there were too many error modes (some of which did not relate to foreseeable risks), rendering the risk assessment process complicated, repetitive and very time consuming (which also raised concerns regarding reliability). Additional issues included several error modes which did not seem applicable to systemic risk assessment (e.g. 'Wrong operation on wrong object' or 'Right check on wrong object'). Accordingly, the taxonomy was refined to reduce the number of modes and to make them risk focussed (see. Figure 3). The term 'error mode' in SHERPA was also changed to 'risk mode' to reflect the focus of the NET-HARMS tool on risk assessment. Figure 4 provides an overview of the development of the NET-HARMS method along with explanations of the issues initially encountered and adjustments that were made.

NET-HARMS Risk Modes
T1 – Task mistimed T2 – Task omitted T3 – Task completed inadequately T4 – Inadequate task object T5 – Inappropriate task
C1 – Information not communicated C2 – Wrong information communicated C3 – Inadequate information communicated C4 – Communication mistimed
E1 – Adverse environmental conditions

Figure 3. NET-HARMS Taxonomy, developed for system risk assessment

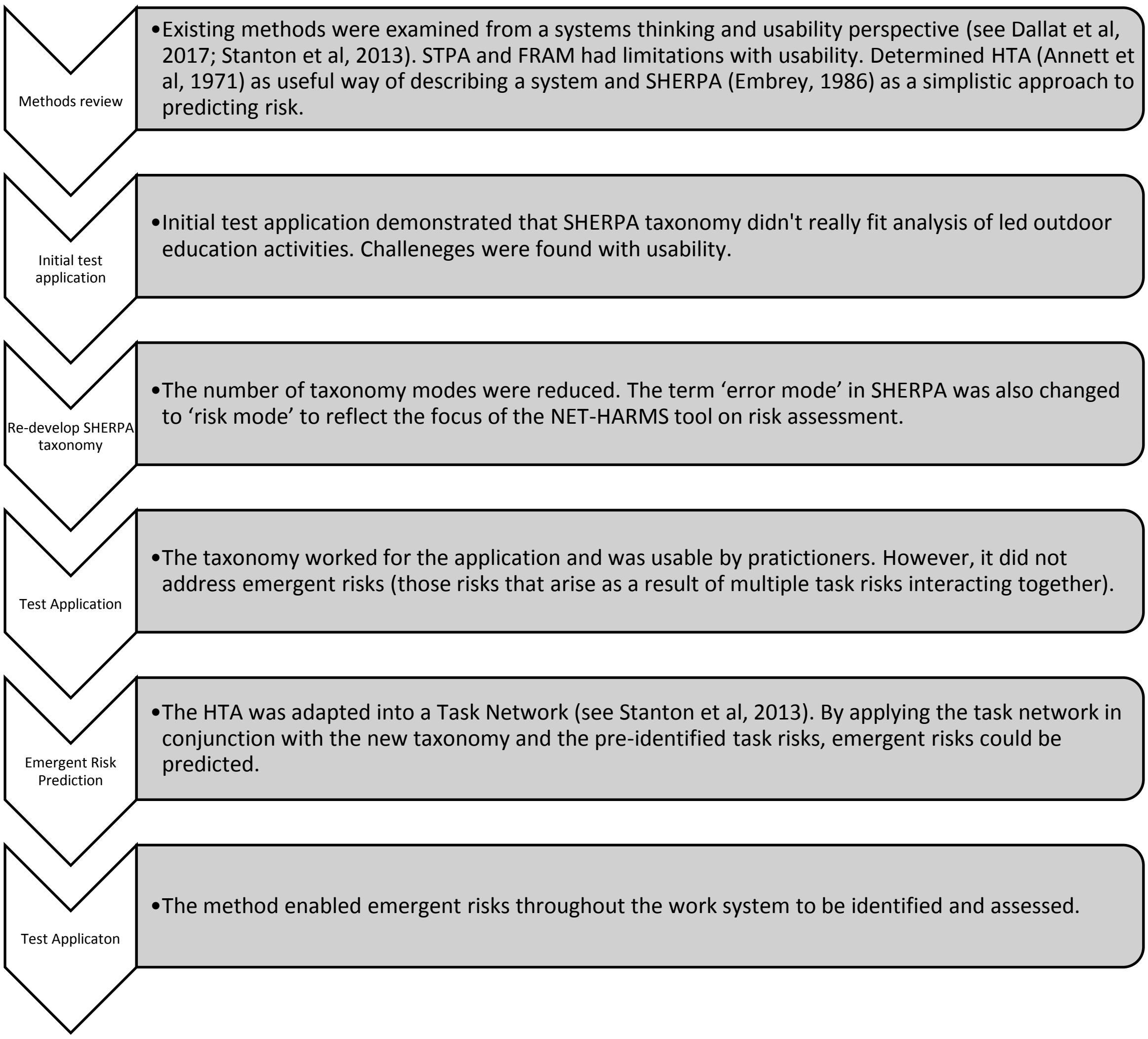

Figure 4. Development of NET-HARMS Risk Assessment method

Conceptually the NET-HARMS method follows that of a standard SHERPA analysis in that the task is first described and then the risks are identified based on specific domain expertise and analyst subjective judgement. The primary extensions are, a. that the HTA description focusses on the system of work; and, b. that first, tasks risks are identified and second, emergent risks (those risks that arise as a result of multiple task risks interacting together), are then identified by first constructing a task network. A task network is a representation of the HTA outputs that is then used to demonstrate and depict key tasks and relationships between them within a particular work system (Stanton et al, 2013; Walker et al, 2006). Based on subject matter expertise, those specific tasks where a dependent relationship existed in terms of successful completion on a subsequent task, were identified. Next, the task network was then used in conjunction with the NET-HARMS taxonomy to identify emergent risks. Figure 5 provides a flowchart outlining how a NET-HARMS risk assessment should be conducted.

NET-HARMS Case study: Risk assessment for a five-day led outdoor education school program

As a case study demonstration, NET-HARMS was used to identify the system risks associated with a five-day led outdoor education school program where rafting and camping were the primary activities. Led outdoor education school programs are defined as facilitated or instructed activities that have a learning goal associated with them (Salmon, Williamson, Lenne, Mitsopoulos-Rubens and Rudin-Brown, 2010). Activities conducted in led outdoor education programs may include for example, camping, canoeing, rafting, bushwalking, teamwork activities and, cycling (Dallat, 2009). The five-day program considered represents a common led outdoor activity in terms of program content and length (Dallat, 2009). Design, planning, conduct and review of these programs would commence many months prior to program delivery and would involve numerous actors across the system of work. These include actors at regulatory level, for example, Workplace Health and Safety agencies who regulate and communicate the relevant Acts and the Department of Education who specify policies and procedures for the school to follow. Actors at the local government level are also represented, e.g. Land managers determine compliance requirements surrounding land use, group sizes and accommodation, and issue permits. Further, local councils may also be involved, for example, in determining food handling requirements. Parents/guardians are also a key influence and have specific roles in the planning of a led outdoor education school program. They are engaged in communication with the school regarding the foreseeable risks involved (Dallat, 2009), and in turn, provide informed consent for their child's participation. Additional organisations may also be contracted by the school - e.g. they may hire an external organisation to provide specific activity management expertise (e.g. rafting guides). The school itself contains multiple actors – for example the school council who hold governance responsibility for approving the program (Dallat, 2009) and the Principal who must also approve the program based on Department of Education requirements being met (e.g. risk assessments, emergency planning). Further actors include teaching and/or ancillary staff who are providing direct supervisory responsibilities, the students themselves who are participating, as well as the overall teacher-in-charge. Non-human actors include the equipment being used, communications devices, the food, water and clothing.

The following section will provide a description of the method adopted when applying NET-HARMS to identify risks for the five -day program.

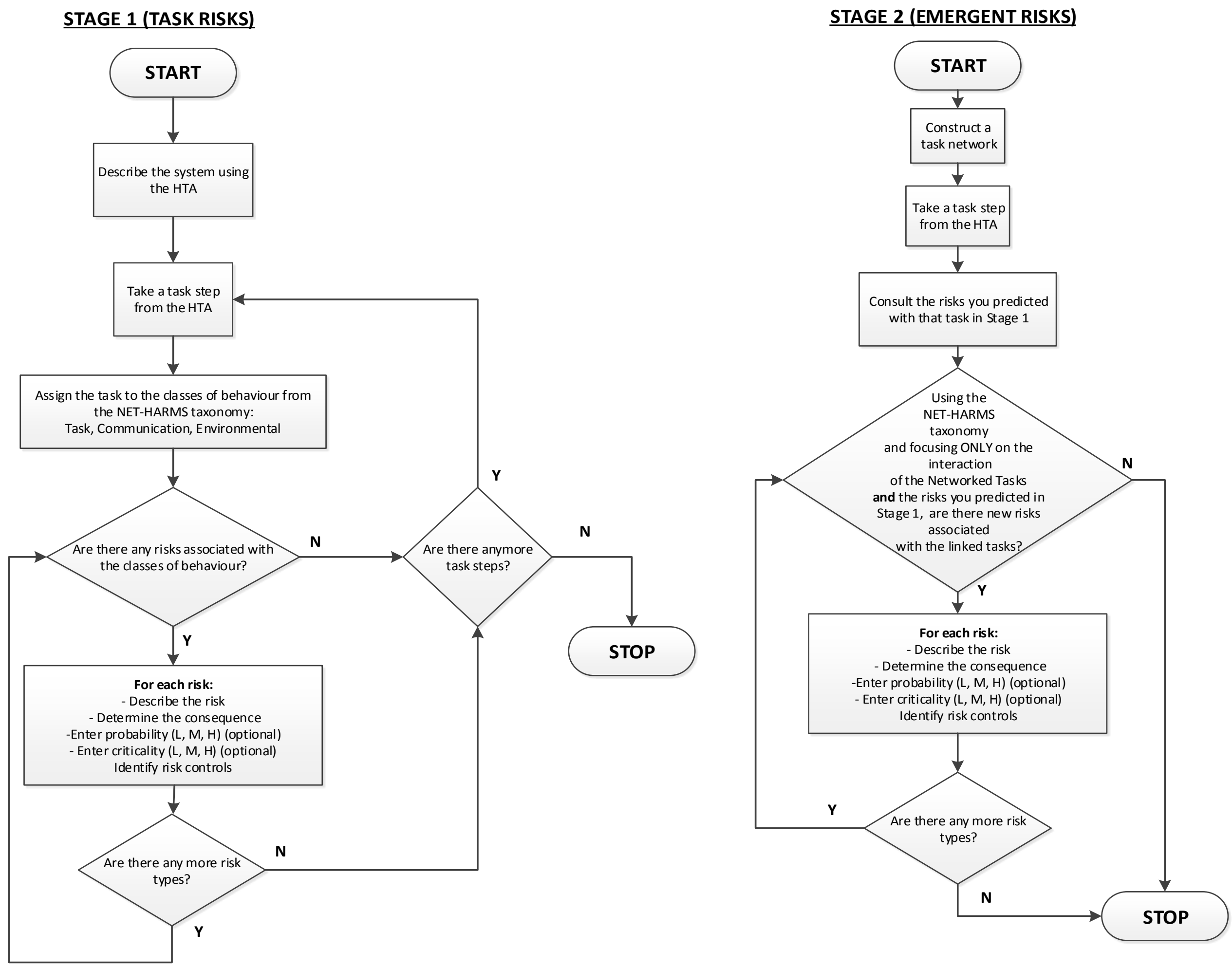

Figure 5. NET-HARMS methodology flowchart

Step 1 Describe the system using the HTA

The first two analysts, one with twenty years of domain specific expertise and who works for a major led outdoor education provider which employs over 500 staff and works with some 40,000 participants annually, and the other with extensive human factors experience, constructed a HTA of a typical five-day led outdoor education school program. The program was to be conducted in a semi-remote environment during bushfire season in Australia (e.g. December – March). Rafting and camping were the two planned activities. Notably, the HTA was constructed (see Figure 2) to reflect the entire system involved in the design, planning, conduct and delivery of the five-day program (as opposed to merely designing the goals, sub-goals and operations involved in delivering the program). Within the HTA, delivery of the rafting or camping activity is not represented until Plan 4, sub-goal 4.11, ‘Commence and complete activity’. As way of an example, Plan 1 described the sub-goals associated with ‘initiate program design’ – operations in this sub-goal included, ‘determine program activity model’, referring to for example, the task of identifying whether the school would be subcontracting any planning or delivery aspects (e.g. hiring a specialist rafting company to provide activity oversight). For a further example, Plan 2 described the sub-goals associated with ‘design program’. A sub-goal in this plan was ‘2.2 consider/determine participant characteristics’. This involves the program planning team identifying the known or expected level of pre-existing experience or specific requirements of the participants involved. Such information is critical to the design of a program that is appropriate to the specific group. For example, a program plan which has novice participants rafting on a river with Grade IV water (water internationally classified to pose moderate to high risk of injury to swimmers, and where water conditions may make self-rescue difficult (Walbridge and Singleton, 2005), would be inappropriate and unacceptably risky. A key contribution of the NET-HARMS method is that it considers such activities and the risks associated with them.

The system HTA resulted in 54 sub-goals under the main plans of ‘initiate program design’, ‘design program’, ‘program planning’ and ‘preparation’, ‘delivery’, and, ‘post-program review’. Three further analysts (all with more than ten years’ experience in planning and instructing rafting and camping programs in school outdoor education programs) reviewed the HTA and provided comment and feedback.

Step 2 Identify Task Risks

The next stage involved the two primary analysts taking each of the 54 sub-goals in the HTA (Figure 5) and working through each risk mode using subjective judgement to determine whether each risk mode, documented in the NET-HARMS taxonomy (see. Figure 3) was applicable or not. For each foreseeable risk identified, the risk was described along with the consequences associated with the risk. Next, the optional steps of assessing the ordinal probability of the risk occurring (low, medium, high), as well as the predicted criticality (low, medium, high), is estimated based on the analyst's experience. Although this was not conducted as part of this case study, the method permits it if users require a simple way of prioritising identified risks. Finally, risk control measures are considered and documented for the identified risks.

Table 1 provides an extract of the initial task risk assessment. The example illustrates the risk assessment outputs associated with the HTA sub-goals of, 'provide information to participants/parents (e.g. clothing, logistical)', 'establish parent consent', and 'recruit staff'. As Table 1 shows, risk modes selected by the analyst using the NET-HARMS taxonomy may generate different types of risks, however in some cases, the consequences of those risks will in fact be similar. For example, if the task of recruiting staff is conducted too late or conducted inadequately, (Risk Modes T1 and T2, see Figure 3), the consequences of both risks include the potential for inadequate staff provision, and inappropriately qualified, experienced staff overseeing the activity. However, in the case of the risk mode, T1, the task of recruiting staff is conducted too late, an additional risk in the form of inadequate preparation of staff, is also identified.

HTA Sub-goal	Risk Mode and Description	Task Risk Description	Task Risk Consequences	Risk Controls
3.2. Provide information to participants/parents (e.g. clothing, logistical)	C1 Information not communicated	Information not communicated	• Participants/parents not aware of requirements e.g. equipment, clothing, activities, timings, food, behavior • May lead to emergent risks on trip e.g. wrong, incorrect equipment	• Implement a process and timeframe for information exchange to occur with parents/participants. • Confirm process has been actioned.
	C2 Wrong information communicated	Wrong information is communicated	• Participants/parents not aware of requirements e.g. equipment, clothing, activities, timings, food, behavior • May lead to emergent risks on trip e.g. wrong, incorrect equipment	• Implement a process and timeframe for information exchange to occur with parents/participants • Confirm process has been actioned.
	C3 Inadequate information communicated	Information communicated is inadequate	• Participants/parents not aware of requirements e.g. equipment, clothing, activities, timings, food, behavior • May lead to emergent risks on trip e.g. wrong, incorrect equipment	• Implement a process and timeframe for information exchange to occur with parents/participants • Confirm process has been actioned.
3.3. Establish parent consent	T1 Task mistimed	Consent is established too early	• Parents may not have complete information on which to provide fully informed consent • Parents not fully aware and therefore are unable to provide informed consent • Parents not aware of potential risks	• Implement a process and timeframe for parent consent to be obtained • Confirm process has been actioned.
	T1 Task mistimed	Consent is established too late	• Parents may provide consent based on pressures created around limited alternative options (e.g. no plan for alternative supervision of child in place should they not attend the outdoor program)	• Implement a process and timeframe for parent consent to be obtained • Confirm process has been actioned.
	T3 Task completed inadequately	Consent is established but not for all activities within program	• Parents/participants not fully aware and therefore are unable to provide informed consent • Parents/participants not aware of potential risks	• Implement a process and timeframe for parent consent to be obtained • Confirm process has been actioned.
	C2 Wrong information communicated	Wrong information is communicated to participants and parents	• Parents/participants not fully aware and therefore are unable to provide informed consent • Parents/participants not aware of potential risks	• Implement a process and timeframe for parent consent to be obtained • Confirm process has been actioned.
	C3 Inadequate information communicated	Inadequate information is communicated to participants and parents	• Parents/participants not fully aware and therefore are unable to provide informed consent • Parents/participants not aware of potential risks	• for parent consent to be obtained • Confirm process has been actioned.
3.4. Recruit staff	T1 Task mistimed	Staff are recruited too late	• Potential for inadequate staff provision • Inappropriately qualified/skilled/experienced staff overseeing activity • Inadequate preparation of staff	• Implement a process and timeframes around staff recruitment.
	T3 Task completed inadequately	Staff recruitment is inadequate	• Potential for inadequate staff provision • Inappropriately qualified/skilled/experienced staff overseeing activity	• Implement a process around staff recruitment that clarifies and ensures recruitment of staff with required knowledge, skills and attributes.

Table 1. Excerpt from NET-HARMS Task Risk Assessment of a five-day led outdoor education program. The table depicts the selected sub-goal and corresponding number from the HTA (Figure 5),

the risk mode and description from the NET-HARMS Taxonomy (Figure 3), the task risk description, and the task risk consequences.

Step 3 Construct Task Network

Task networks are used to represent HTA outputs in the form of a network so that key tasks and relationships between them within a particular work system are depicted (Stanton et al, 2013). The intention is to show the interaction of tasks as well as their coupling. Within a task network, nodes represent discreet tasks and lines linking the nodes, represent the relationships between the tasks. The next step involved developing a task network for the five-day led outdoor education program. The Task Network (Figure 6) was constructed by taking each of the sub-goals identified in the HTA (Figure 2), and then identifying where a dependent relationship was present in terms of successful completion on a subsequent task (see Salmon, Lenne, Walker, Stanton and Filtness, 2014; Stanton et al, 2014). This was conducted using subjective judgement based on domain expertise and was subsequently checked by comparing the relationships with those specified in the original HTA plans. For example, HTA sub-goal '1.3. determine resources' is linked to HTA sub-goal '4.12 food preparation and management'. This is because food preparation and management during the conduct of the outdoor education program is directly impacted by the determination of resources required during the design of the program. To illustrate, if appropriate food resources (e.g. food that will satisfy pre-existing allergy requirements) have not been considered in the planning stages of the program, there will not be appropriate (or safe) food on the program for those participants with food-related allergies. Figure 7 provides a discreet example of one node depicting a sub-goal (3.5 Plan Resources) with the lines linking to the linked sub-goals.

Following the development of the task network, it was subsequently reviewed by three further analysts (two of whom were the same analysts who reviewed the initial HTA), all who possessed at least ten years led outdoor education program planning expertise. The task network was further refined until mutual agreement was reached between all analysts. This process resulted in two additional task links being identified and added.

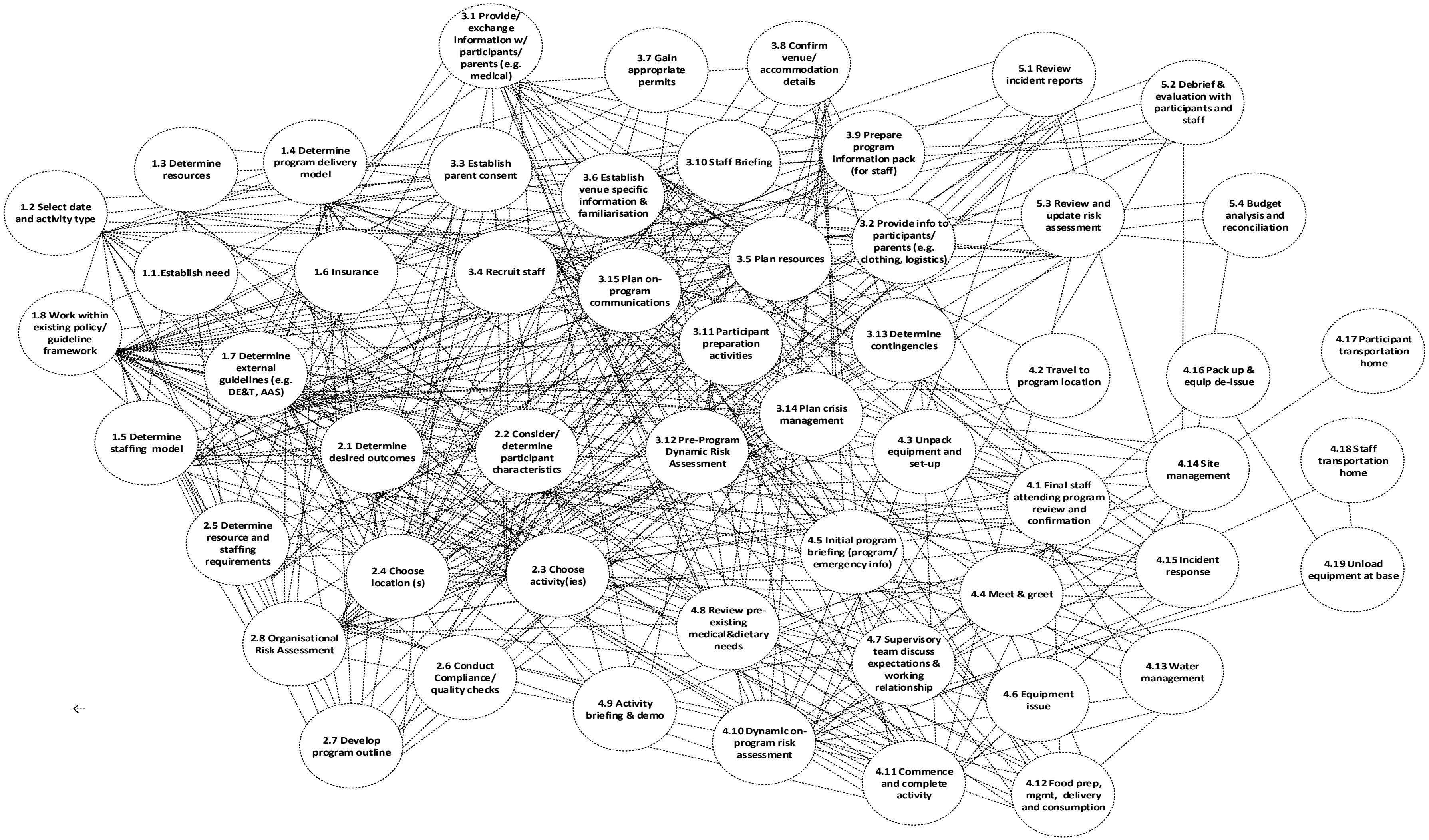

Figure 6. Task network of five-day led outdoor education program. The HTA sub-goals are depicted as circular nodes and the lines between the nodes represent dependent links between the sub-goals (tasks).

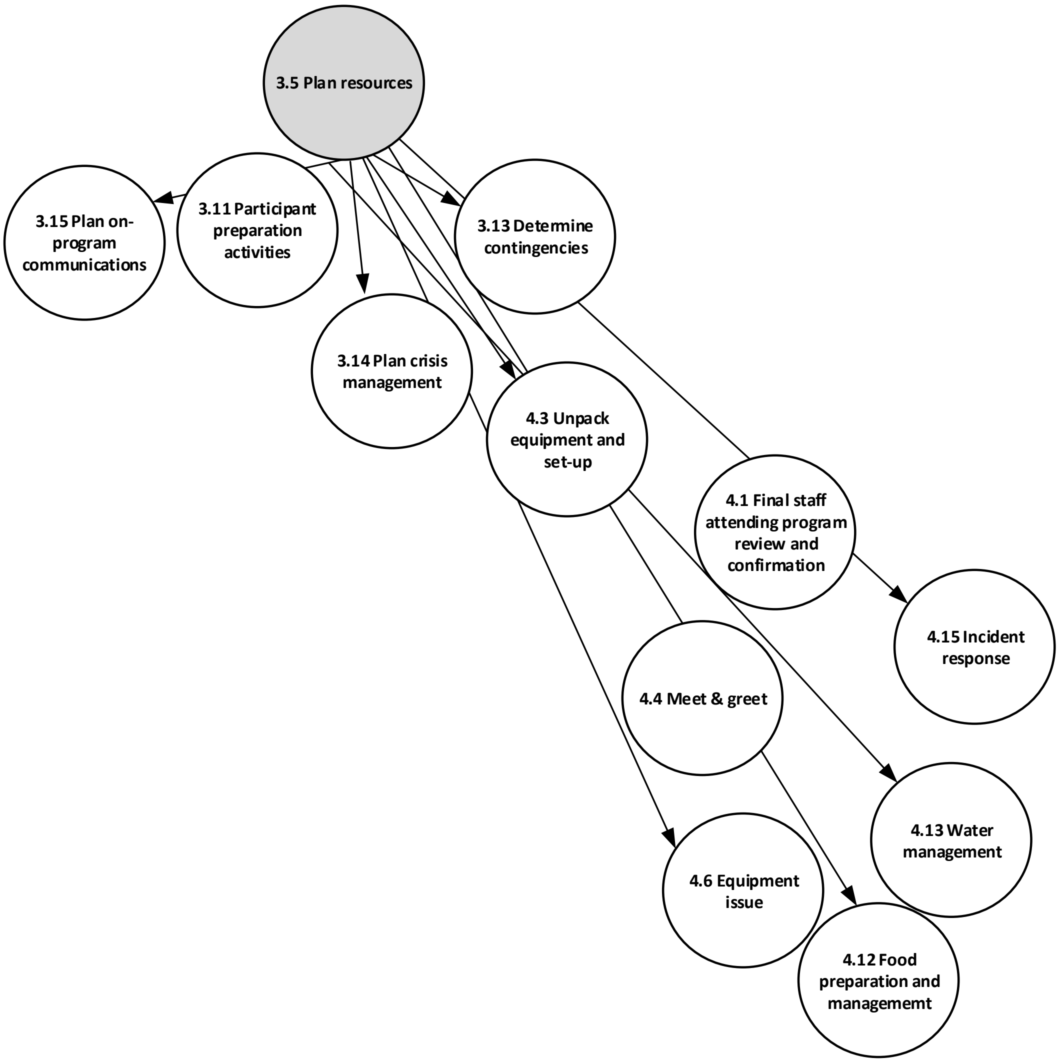

Figure 7. Illustrative example of one node depicting the discreet sub-goal of 'Plan resources' (3.5) and the lines representing its linked sub-goals.

The importance of the design and planning tasks was highlighted through the number of linked tasks identified during Step 3 (Construct Task Network). The top ten sub-goals that had the highest number of related sub-goals were directly related to the design, planning and preparation of the led outdoor education program (See Table 2).

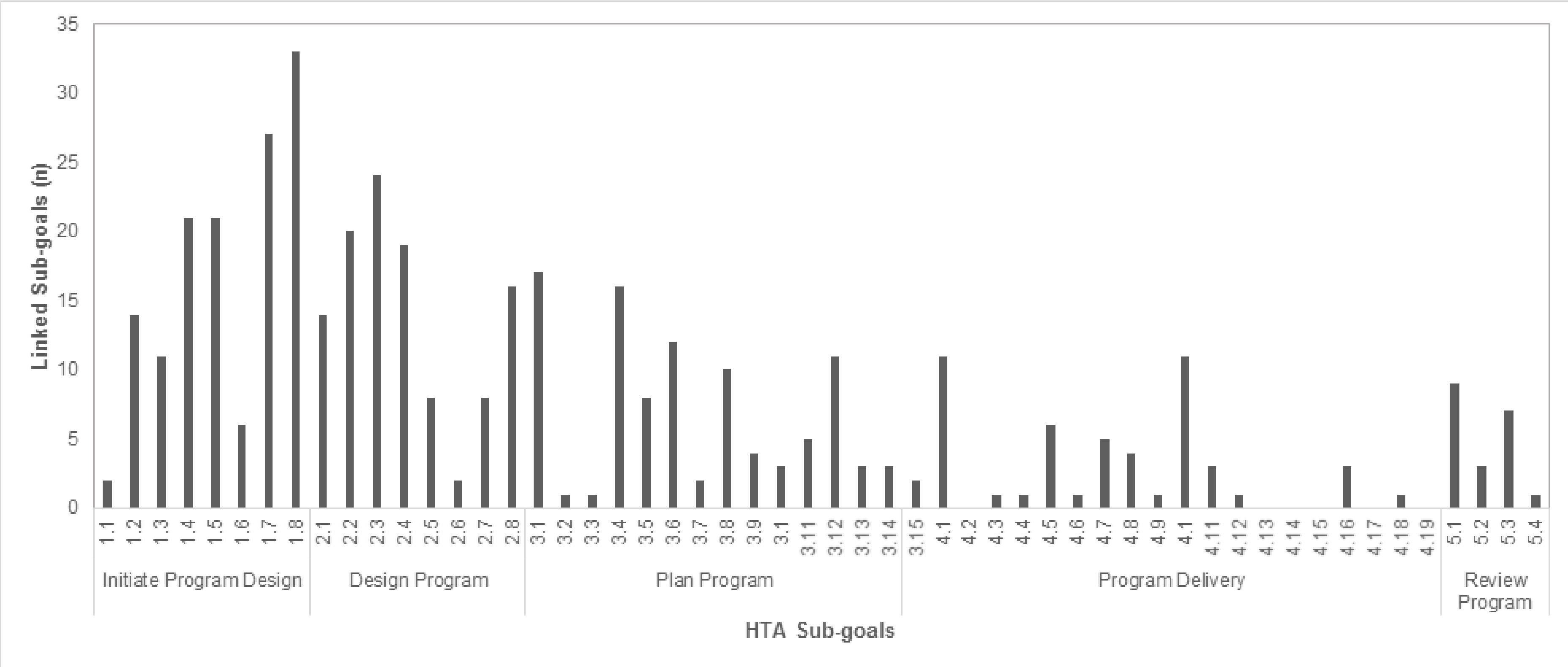

Table 2. HTA sub-goals, stages of program development and identified number of links associated with those sub-goals.

Step 4 Identify Emergent Risks

During Step 4, the NET-HARMS taxonomy is used in conjunction with the task network to identify emergent risks. Emergent risks represent additional risks that arise as a result of the interaction between the risks identified during step 2. This step involves identifying the risks that arise when a task is impacted by a risk that has played out during a related task. Here the analyst asks the question, 'What is the impact of this risk happening at task X on the related task Y?' The underlying principle in relation to linked tasks is that they will interact and, in the event that the initial task risks identified are not managed appropriately (as identified through the NET-HARMS taxonomy, see Figure 3), additional emergent risks arise as a consequence of the interaction between the linked tasks. These linked tasks are then assessed using the NET-HARMS taxonomy (Figure 3). For example, the sub-goal of 'plan resources' (3.5) had eleven related sub-goals within the task network (Figure 6). The task risks identified in Stage 1 associated with 'plan resources' (3.5) are then traced through to the eleven related sub-goals and, using the NET-HARMS taxonomy (Figure 3), emergent risks associated with the interaction of those sub-goals, are identified. For example, the task risk of 'resources are not planned' was identified in Stage 1 at the HTA step (3.5) This risk is then transferred to the related sub-goal of 'determine contingencies' (3.13), and by applying the NET-HARMS taxonomy (Figure 3), a risk mode of T2 (Task omitted) was identified, with the associated emergent risk being identified as, 'there will not be sufficient contingencies due to lack of planning – e.g. no bus available for emergency shuttles during fire season'. This is an emergent risk as it arises from the interaction of the task risk of 'resources not being planned', with the task of 'determine contingencies'. The lack of planning around resources creates the risk that the determine contingencies task cannot be undertaken. Notably, the emergent risk identified was dependent on the interaction of the task risk *and* the identified linked sub-goal. On its own for example, the task risk could identify that there may not be enough vehicle resources. However, it is only when the task risk *and* the dependent operation of ‘determine contingencies’ interact, that the lack of resources and the foreseeable environmental conditions under which the contingencies must be considered, are identified (e.g. time of year - bushfire season - and subsequent the need for a bus versus vehicles with less seats which would inappropriately delay the evacuation). Table 3 provides an excerpt of the emergent risks and risk controls identified as a result of the interaction between task risks initially identified, for example with the sub-goal, ‘plan resources’ (3.5) and the sub-goals identified to be linked with it.

HTA Operation	Risk Mode and Description	Task Risk Description	Linked Task(s) (Operation and number from HTA) (Figure 5)	Risk Mode and Description	Emergent Risk Description	Risk Controls
3.5. Plan Resources	T2 Task Omitted	Resources are not planned	3.13 Determine contingencies	T2 Task Omitted	There will not be sufficient contingencies due to lack of planning – e.g. no bus available for emergency shuttles in fire season	Prior to approving the program contingency plan, a sign -off mechanism for ensuring that the required resources have been confirmed, must be actioned.
	T2 Task Omitted	Resources are not planned	3.14 Plan crisis management	T2 Task Omitted	Crisis management system will be deficient as there will not be resources available - e.g. no satellite phones	Prior to approving the program crisis management plan, a sign -off mechanism for ensuring that the required resources have been confirmed, must be actioned.
	T2 Task Omitted	Resources are not planned	3.15 Plan on-program communications	T2 Task Omitted	On-program communications planning will not be adequate	Prior to approving the program communication plan, a sign -off mechanism for ensuring that the required resources have been confirmed, must be actioned.
	T2 Task Omitted	Resources are not planned	4.3 Unpack equipment and set-up	T2 Task Omitted	Insufficient equipment available for program	Prior to the program equipment being packed, a sign -off mechanism for ensuring that the required equipment resources have been confirmed, must be actioned.
	T2 Task Omitted	Resources are not planned	4.6 Equipment issue	T2 Task Omitted	Insufficient equipment available for program	Prior to the program equipment being packed, a sign -off mechanism for ensuring that the required equipment resources have been confirmed, must be actioned.
	T2 Task Omitted	Resources are not planned	4.12 Food prep & management	T2 Task Omitted	Insufficient food resources available for program	Parents are not sent the food allergy and anaphylaxis emergency care template until the program resources planning document has identified and confirmed agreed staff and food/equipment resources.
	T2 Task Omitted	Resources are not planned	4.13 Water management	T3 Task completed inadequately	Insufficient water resources available for program	Prior to the program water management equipment being confirmed (e.g. chemical treatment, barrels, up to date knowledge of fresh water availability) a sign -off mechanism for ensuring that the required water resources have been confirmed, must be actioned.
	T2 Task Omitted	Resources are not planned	4.15 Incident response	T3 Task completed inadequately	Incident response is insufficient – e.g. not appropriate resources of people or equipment.	Prior to approving the program's incident response plan, a sign -off mechanism for ensuring that the required resources have been confirmed, must be actioned.

Table 3. Example of emergent risks and controls identified as a result of the interaction between task risks identified with the sub-goal, 'Plan resources' (3.5), and the identified linked tasks (sub-goals and numbers are from the HTA - Figure 5).

The emergent risk identification was initially conducted by the first analyst, and reviewed by the two domain-specific analysts who also reviewed the HTA (Figure 2), and the task risks. A process of revision was undertaken until all analysts reached mutual consensus. Six additional emergent risks were identified and added during this process.

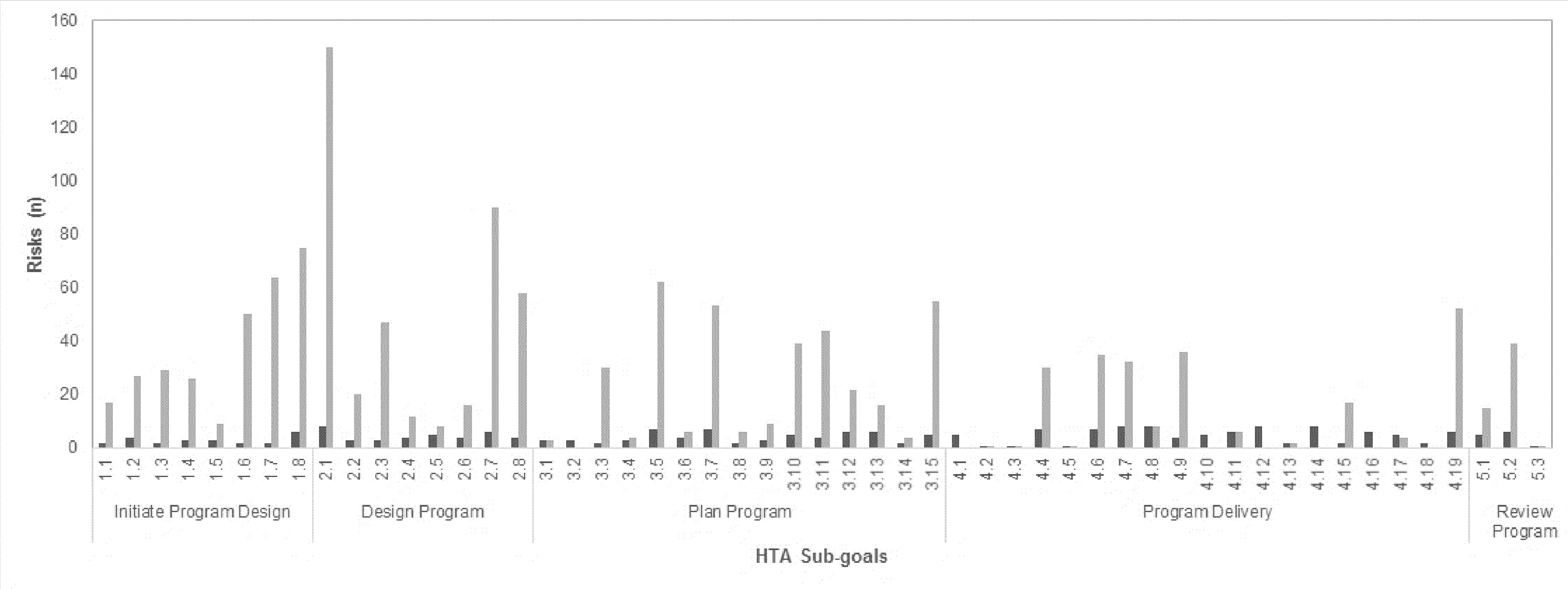

Figure 8. Graph depicting predicted NET-HARMS task (dark grey) and emergent (light grey) risks for a five-day rafting and camping program.

Step 5 Identify Risk Controls

The final step in applying NET-HARMS involves identifying appropriate risk control measures for the task and emergent risks identified. The aim of this step is to identify a series of strategies or countermeasures that are either designed to prevent the risk from occurring in the first place, or to mitigate the risk if it is realised. Following the identification of the risk controls by the two lead analysts, they were subsequently reviewed by three further analysts (two of whom were the same analysts who reviewed the initial HTA), all who possessed at least ten years led outdoor education program planning expertise.

As way of example, for the task risk, 'resources are not planned', the task risk control could be to, 'Implement a process to ensure resources are planned'. However, if that risk control has not been implemented, when that risk interacts with the linked task of 'Food preparation and management', additional emergent risks are created. These include, 'a lack of appropriate (or safe) food on the program for those participants with food-related allergies', and 'Unqualified staff are rostered on the program to manage pre-existing allergies". To mitigate against this, additional risk controls become necessary for both the interacting task of 'Food preparation and management', and for the emergent risks created. In this example, one risk control for the task of 'Food preparation and management' would be to, 'Ensure that the food allergy and anaphylaxis emergency care plan has been received from parents two months before program start date'.

At this stage both the initial task risk and the linked task have risk controls developed which are designed to manage those risks. However, the emergent risks created by these two interacting tasks are additional (and different) to the initial risks and therefore, require emergent risk controls. In this example, an emergent risk control would be that, 'Parents are not sent the food allergy and anaphylaxis emergency care template until the program resources planning document has identified and confirmed agreed staff and food/equipment resources'. This emergent risk control addresses the interacting risks of 'resources not being planned' with the linked task of, 'Food preparation and management'.

Comparison of NET-HARMS assessment with incident data

To conduct an initial test of the validity of the NET-HARMS method, the risks identified in the present analysis were compared to the contributory factors identified in an existing analysis of led outdoor activity injury incident data (Van Mulken et al, 2017). This data was sourced from a major program of research within the LOA domain established to develop and implement an incident reporting and learning system underpinned by systems thinking models of accident causation. Known as UPLOADS (Understanding and Preventing Led Outdoor Accidents Data System, see Salmon et al, 2017), this system provides led outdoor activity providers with a means of reporting and analysing adverse outcomes (e.g. injuries, illnesses, equipment, environmental damage and psychological impacts) and near miss incidents. A key contribution of UPLOADS is that it enables incidents to be analysed from a systems perspective in line with Rasmussen's (1997) risk management framework.

As part of the test, a total of 119 specific contributory factors were extracted from 351 UPLOADS incident reports provided between the 1st June, 2015 to 31st May, 2016 (see Van Mulken et al, 2017). The lead analyst had no access to this dataset prior to the present comparison. Although the incident dataset was not solely based on the same program type used as the basis for the NET-HARMS analysis (five-day rafting and camping program), it does nonetheless provide a reasonable point of comparison. As the case study was concerned with identifying foreseeable risks associated with led outdoor activity programs, it enabled a comparison with the risks identified by the NET-HARMS method.

The risks predicted via NET-HARMS were compared to the 119 contributory factors within the UPLOADS data (Van Mulken et al, 2017). The signal detection paradigm was then used to assess the extent to which NET-HARMS could predict the risks that played a role in the UPLOADS incidents. This approach has previously been used to calculate the sensitivity of risk assessment methods (Baber and Stanton, 1994; Stanton et al., 2009; Stanton and Young, 2003). It involved calculating hits (risks identified by NET-HARMS and the same contributory factor identified in the incident data), misses (contributory factors identified in the incident data but not identified by NET-HARMS) and false alarms (risks identified by NET-HARMS but not identified in the incident data). A hit rate was then calculated by taking the total number of hits (n = 115) and dividing this by the total number of hits (n = 115) plus misses (n = 4), resulting in a hit rate of 0.96. The results of this analysis are presented in Figure 9, and further extrapolated in Table 4.

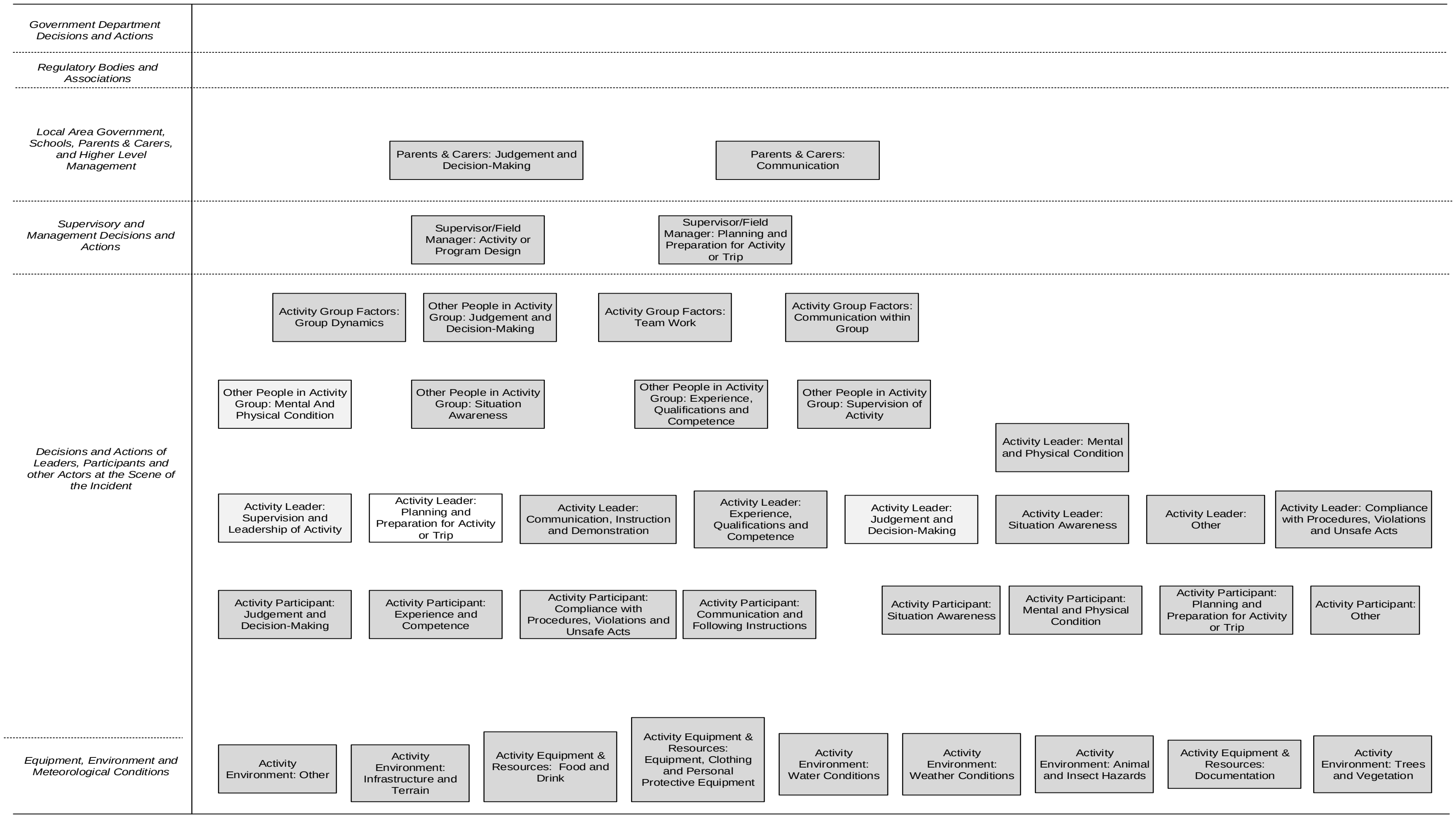

Figure 9. Categories containing factors identified as contributory to injury-related incidents (n = 351), (Van Mulken et al, 2017). The factors that NET-HARMS correctly predicted (hits) are depicted in the categories shaded dark grey (n=34). Factors not identified by NET-HARMS (misses) are in non-shaded categories (n=1), and categories with factors containing both hits and misses are shaded in light grey (n=3).

	Hits	Misses	False Alarms
Total (N)	115	4	1476
Rate	0.96		

Table 4. Number of hits, misses and false alarms, as well as the hit rate associated with the NET-HARMS method analysis against 119 injury-causing contributory factors (Van Mulken et al, 2017).

Whilst a high hit rate was achieved, a significant number of false alarms were also identified, with 1476 risks predicted via NET-HARMS that were not found in the injury incidents analysed by Van Mulken et al (2017).

Discussion

The majority of current risk assessment methods are not aligned with the contemporary perspective on accident causation, and those that are (e.g. STPA, Leveson, 2011; FRAM, Hollnagel, 2004) have been criticised regarding their ease of use and application in practice (Dallat et al, 2017; Stanton and Harvey, 2017). This paper described and demonstrated a new approach that is consistent with systems thinking (see Rasmussen, 1997). The case study has demonstrated that NET-HARMS can be used to predict task and emergent risks across an overall work system. This goes beyond existing risk assessment approaches which have been criticised for being reductionist in nature and primarily focused on risks at the sharp end (Waterson et al, 2015; Stanton et al, 2013; Stanton and Stevenage, 1998).

What does NET-HARMS offer over and above existing risk assessment methods?

The NET-HARMS method is underpinned by existing and well accepted human factors methods, namely HTA, (Annett et al, 1971), SHERPA, (Embrey, 1986) and Task Networks (Stanton et al, 2013). The first part of the NET-HARMS method involves the task risks associated with the sub-goals in the HTA being identified and assessed. The NET-HARMS taxonomy provides ten different risk modes thus enabling a broad analysis of potential task risks to be identified. Moreover, it is Stage 2 of the NET-HARMS method that significantly extends capabilities around risk assessment, in that it enables emergent risks to be identified and assessed. Such development more closely connects current knowledge about how accidents occur in complex sociotechnical systems with the identification of risks. The NET-HARMS extends existing systems risk assessment methods (e.g. STPA, System-Theoretic Process Analysis; Leveson 2011, and FRAM, Functional Resonance Analysis Method; Hollnagel, 2004) in three specific ways. Firstly, it provides a simplistic approach usable by practitioners with little knowledge of systems thinking. Secondly, it offers a broader and more usable taxonomy than the STPA method. Finally, it permits the concept of emergence to be both described and predicted. The application of the NET-HARMS method to the selected case study yielded some noteworthy insights about the importance of considering emergent risks and consequently, demonstrated significant divergence with the current approach to risk assessment within the led outdoor education domain (see. Dallat et al, 2015). Current risk assessment methods and practice largely focus on the identification, assessment and control of risks situated at the so-called 'sharp end' of practice; those risks located at the delivery part of led outdoor education programs (Dallat et al, 2015). Notably, NET-HARMS identified 1131 emergent risks associated with the design, planning and review tasks (Sections 1, 2, 3 and 5 of the HTA), whereas in the program delivery tasks (Section 4 of the HTA), 232 emergent risks were predicted. Within the task risks (Stage 1), 1.5 times (n=141) as many task risks were predicted in the design, planning and review tasks (Sections 1, 2, 3 and 5) in the HTA. Moreover, tasks at the program delivery stage of the program, (Section 4 of the HTA), had 91 risks predicted. These numbers make a compelling statement. The largest amount of emergent risks reside within the tasks not associated with delivery of the activity. Put another way, the tasks related to the design, planning and review of the program have the most potential for introducing risks into the system. If risk is not managed in these pre-activity stages, a significant number of emergent risks are created.

This feature of NET-HARMS goes beyond the majority of risk assessment approaches which focus primarily on the sharp-end of performance (Dallat et al, 2017; Dallat et al, 2015).

As an example, the sub-goal of 'Consider/determine participant characteristics' (2.2) had eight identified task risks, and 150 emergent risks. This highlights the importance of adequately managing the risks associated with that specific task (for example, the consideration of participant experience level, pre-existing illnesses, injuries, psychological well-being etc., and the subsequent design and planning of the program to align with these). However, if those task risks are not managed adequately, that specific task has 150 emergent risks associated with it. An example of an emergent risk associated with the task of, 'consider/determine participant characteristics' emergent risks (created by its identified task risks and the interaction with its linked tasks) is that, 'resources and staffing requirements are determined without consideration of participant characteristics'. A consequence of this emergent risk is that, staff (e.g. skill sets/ numbers) and resources (e.g. raft type) will be inadequate (e.g. raft type is unsuitable for students with behavioural concerns, or staff recruited for the program do not have expertise in working with children with significant pre-existing behavioural conditions. Due to the initial task risks associated with the task of, 'Consider/determine participant characteristics', not being addressed in the design phase of the program, *and* the interaction of the subsequent task of 'Determine resource and staffing requirements', this additional emergent risk was created.

Overall, the case study demonstrated the existence of 5.8 times more emergent risks (NET-HARMS Stage 2) in the system than task risks (NET-HARMS Stage 1, see

Figure 5). This is a sobering finding given that existing risk assessment methods do not attempt to identify emergent risks.

The results of the initial validity test also yielded promising insights. The NET-HARMS method accurately predicted all but 4 of the 119 contributory factors identified in the injury dataset (See Table 4), (Van Mulken et al, 2017). Worthy of mention also were the very high number of false alarms (n=1476) in the analysis. Echoing Stanton et al. (2006), it is prudent to consider that a false alarm could indeed represent risks that have not yet played a role in injury-causing incidents. Further, the UPLOADS data set does not yet contain many higher-level factors due in part to poor reporting and limitations in practitioners' understanding around systems thinking (Van Mulken et al, 2017; Salmon et al, 2016a; Dallat et al, 2015). Finally, it is notable that further contributory factors similar to some of the false alarms identified here have been identified in analyses of fatal incidents associated for example, with auditing bodies, risk assessment, government legislation and regulation, and weather forecasting (Brookes et al, 2009; Davenport, 2010). It is concluded then that it would be unwise to dismiss the false alarms without further analysis. It is these analysts view that they represent foreseeable risks worthy of consideration and management.

What are the implications for led outdoor activity practice?

The results of this study suggest that there are significant implications for the safety of the program participants if risks have not been addressed at the relevant stage in the HTA where they have been identified. The prediction of the subsequent emergent risks, created by to the interaction of previously identified risks, with subsequent linked tasks, serves as a stark reminder of the importance of effective risk management in all stages of the work system. In contrast however, Dallat et al (2015) reported that the led outdoor education domain identifies and focuses on the risks situated at the so-called sharp end of the work system; those related to the activity participants, equipment and environment. Notably, in analyses of multiple injury-causing incidents within the led outdoor education domain, both Salmon et al (2017) and Van Mulken et al (2017) identified multiple contributory factors throughout the work system, for example, factors related to schools, activity centre management, parents, activity leader supervision, risk assessment, and program design. The NET-HARMS risk assessment method is a promising methodological development to permit a broader lens to be placed over the whole system being analysed.

Future development, testing and applications

The NET-HARMS risk assessment method was designed to enable the identification of task and emergent risks throughout the system of work, thus extending the focus beyond those risks solely situated at the sharp-end of practice. Initial application and validity results have been positive in this regard and consequently, further development work, as part of a wider program of research, is planned. This will include formal reliability and validity testing, as well as tests to determine the effectiveness of the method when used by other analysts and practitioners. To assess the method's utility, future testing is also planned with both novice analysts and alternative work contexts. Further, the method requires further testing and applications in other domain areas, e.g. road and rail transport safety. Additionally, future work is recommended in relation to development and guidance as to what risks organisation should focus on. As a case study demonstration, we acknowledge that there are some limitations with this present study.

The application was undertaken by its creators. As a result, this may have led to optimal performance whereas novice analysts may not have achieved the same outputs.

Conclusion

This paper set out to present a new risk assessment method, the NETworked Hazard Analysis and Risk Management System (NET-HARMS), which is directly underpinned by systems thinking, and therefore enables the identification of task and emergent risks across entire work systems. Initial results of the method demonstrate an ability to achieve these aims and, as such, could represent a new paradigm for the identification and assessment of risk in complex sociotechnical systems. The method's initial development and continued future work to formally test it, represent a genuine opportunity to close the significant gap between what we know about how accidents occur in complex systems, with the capability of the very methods designed to prevent them.

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