Exposing resistant problems in complex systems: a review of accident causation tenets

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ABSTRACT

The plateau of incident rates in many domains, including road and rail transport, aviation and workplaces indicates that system-based ergonomics models used to understand accident causation are either underutilised or underperforming in preventing adverse events. Whether this plateau is due to an increase in system complexity or out-of-date toolkits, the problems are seemingly resistant to the current ergonomics methods that pursue them. With this knowledge it is pertinent to ask what changes, if any, are required to capture contemporary system complexity and uncover resistant problems. Are current methods being used to their full advantage or are new methods required to progress safety science? The paper presents a review of the dominant contemporary safety science methods and underpinning models that could potentially provide a solution to uncovering resistant problems in complex systems.

Accident causation theorists with the greatest number of citations were identified from the safety science literature. The citation information was derived from Scopus (April 2016). These included, Nancy Leveson (3950 citations Scopus, April 2016) Jens Rasmussen (3486 citations Scopus, April 2016), Charles Perrow (2041 citations Scopus, April 2016), Sidney Dekker (789 citations Scopus, April 2016) and Erik Hollnagel (672 citations Scopus, April 2016). Over ninety published works were coded into categories of safe and unsafe system behaviours. The outcome of the review produced a list of principle tenets extracted from the literature. The review has shown that despite the diversity in approaches there is considerable agreement about the core tenets of system safety and accident causation. Using this information a research program is proposed to test the quality of the tenets extracted from the literature review and the extent to which they can be used to support a proactive approach to safety in complex systems. This will provide a test of sociotechnical systems theory when used to predict accidents.

Keywords: STAMP; FRAM; DRIFT; Normal Accident Theory; Rasmussen’s Risk Management Framework
1.0 INTRODUCTION

When incidents occur, accident analysis methods underpinned by a systems approach are traditionally applied retrospectively (Jenkins et al, 2010; Salmon et al, 2016). Retrospective analysis is intended to afford the identification of incident characteristics to (hopefully) learn from the past and prevent future accidents (Dekker and Leveson, 2014; Moura et al, 2016). A major challenge for safety scientists is the reduction of adverse events in the face of a safety ‘plateau effect’. Instead of declining over time incidents have reached a plateau in multiple fields that have been applying systems based accident causation methods such as road, rail and aviation (Leveson, 2012; Salmon et al, 2016). This suggests that retrospective analysis may be underperforming in the prevention of accidents (Leveson, 2011); traditional approaches may have reached a saturation point and are no longer reliable for improving safety.

Predicting adverse events before they occur seems to be a logical step and has been explored extensively. For example, there are methods that support the prediction of human errors (Stanton et al, 2013) and various quantitative accident prediction methods exist (Li et al, 2016; Jocelyn et al, 2016; Atwood et al, 2006; Harwood, et al, 2000; Miaou, 1996). Both forms of method, whilst used extensively to date, have limitations. For example, given our understanding of accidents, a key limitation of error prediction methods is that they typically only identify the end error event in what is actually a complex web of interacting factors. With quantitative methods, there are questions around the suitability of using mathematical models and formulae; in particular, their use by practitioners is questionable as is the extent to which a numerical value is useful (Fujita and Hollnagel, 2004).

Increasingly researchers are investigating the use of qualitative systems analysis methods for predicting performance and accident scenarios (e.g. Leveson et al, 2015; Salmon et al, 2014; Stanton et al, 2014); however, this has not yet produced a formal methodology developed specifically predicting accidents. Indeed, there remains uncertainty surrounding the design of a useful qualitative prediction method and how it can be pursued (Hollnagel 2014; Moray, 2008; Salmon et al, 2016; Stanton et al, 2008).

A useful starting point in exploring the design of an accident prediction framework is to examine what we currently know about accident causation. Specifically, we believe that the clues to accident prediction lie in what we currently know about accident causation. However, it is acknowledged that, firstly many accident causation models exist, secondly that there is not yet a universally accepted accident causation model, and thirdly that the different models available likely all have useful elements relating to understanding accident causation. To address this lack of conceptual clarity, a literature review was undertaken to extract the key features of contemporary accident causation models that might form the basis of a qualitative accident prediction method. As part of this process the authors engaged in a ‘synthesis workshop’ to further refine the key features of accident causation extracted from the model. The intention was to identify a common set of accident causation model tenets, referred to as “systems thinking tenets”. The systems thinking tenets represent the shared principles of accident causation extracted from contemporary accident causation models. The aim of this paper is to present the findings from the review and the synthesis workshop and to outline the set of systems thinking tenets derived from accident causation models.
2.0 METHOD

The most popular accident causation models were identified via examination of the number of citations of the works of well-known accident theorists. Specifically, citation information was sought for authors who have previously published an accident causation model in the safety science literature that has a basis in systems theory or systems thinking. The citation information was derived from Scopus (April, 2016). The accident causation models outlined in Table 1 were refined based on consideration of whether they represent systems thinking-based models. Based on this, the Swiss Cheese model (Reason, 1990; 2008) and The Wheel of Misfortune model (O’Hare, 2000) were removed from the literature review. Although there are elements of systems theory within the Swiss Cheese model, it does not fully comply with the principles of system theory. Whilst hugely popular and arguably containing many elements of systems thinking, the model has been criticised for being linear and failing to account for the dynamic and adaptive nature of systems, which forms the basis of systems theory (Dekker et al 2014; Hollnagel, 2004; Hollnagel 2014). O’Hare’s (2000) Wheel of Misfortune model was excluded as it is largely an error taxonomy that focuses on an end error event.

Following the refinement process the following accident causation models were selected for review: Leveson’s System Theoretic Accident Model and Processes (STAMP) (2004), Jens Rasmussen’s risk management framework (1997), Perrow’s Normal Accident Theory (1981; 1999), Dekker’s Drift into Failure model (2011) and Hollnagel’s Functional Resonance Analysis Method FRAM (2012). The results from this exercise are presented in Table 1 from highest citation count to lowest.

Table 1: Accident causation model and author citation

<table>
<thead>
<tr>
<th>Author</th>
<th>Accident causation model</th>
<th>Citations (Scopus, April 2016)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nancy Leveson</td>
<td>Systems Theoretic Accident Model and Processes (STAMP, 2004)</td>
<td>3950</td>
</tr>
<tr>
<td>Jens Rasmussen</td>
<td>Risk management framework (Rasmussen, 1997)</td>
<td>3486</td>
</tr>
<tr>
<td>Charles Perrow</td>
<td>Normal Accident Theory (1981; 1999)</td>
<td>2041</td>
</tr>
<tr>
<td>Sidney Dekker</td>
<td>Drift into Failure Model (2011)</td>
<td>789</td>
</tr>
<tr>
<td>Erik Hollnagel</td>
<td>Functional Resonance Analysis Method (FRAM, 2012)</td>
<td>672</td>
</tr>
</tbody>
</table>

2.1 Accident causation models

2.1.1 Leveson’s System Theoretic Accident Model and Processes

According to Leveson (2011), safety is an emergent property of systems, which arises when technical, physical and human components of a system interact successfully. A system consists of interrelated components kept in a state of dynamic equilibrium using feedback loops of information and control that use sets of constraints to enforce safety on system behaviour (Leveson, 2011). Accidents arise when there is a loss of control (for example managerial, organisational, technical or engineering) where interactions violate the constraints placed on a system that maintain safety.
Leveson’s (2004) System Theoretic Accident Model and Processes (STAMP) uses a functional abstraction approach, to model the structure of a system and describe the interrelated functions. In comparison to other accident analysis methods STAMP’s aim is to understand control failures in a way that supports the implementation of new controls that enforce safe operation and prevent future accidents. To do this STAMP utilises a hierarchical control structure to describe existing controls, and a taxonomy of control failures to identify the control failures involved in the incident under analysis.

2.1.2 Rasmussen’s Risk Management Framework

Rasmussen’s (1997) model for risk management describes complex sociotechnical systems as a hierarchy. The model is underpinned by the idea that adaptive and dynamic sociotechnical systems are subject to a fast pace of change, and accidents occur because actors within the system adapt to change in unpredictable ways (Vicente & Christoffersen, 2006). For Rasmussen (1997), risk management in this context is a control problem and modelling techniques are required to appreciate the direct or indirect operational requirements of systems.

Rasmussen’s Accimap approach to accident causation outlined in Risk Management in a Dynamic Society (1997) is embodied in his model of abstraction that organises a system according to functions, roles and responsibilities in order to describe how they interact to produce the system. According to Rasmussen, the structure of work systems is hierarchical; actors, objects and tasks are modelled across levels of the sociotechnical system; their relationships to each other are linked to explain causal ties.

2.1.3 Perrow’s Normal Accident Theory

Perrow (1981; 1999) developed Normal Accident Theory (NAT) after the Three Mile Island incident in 1979. In response to the incident investigation and recommendations, Perrow (1981) presented the concept that a “normal accident” or system accident occurs because of the interaction of multiple failures that are not in direct operational sequence. This view identified system characteristics instead of human ones as the primary causes of accidents. A normal accident describes the inevitable failures caused by characteristics of a system where interactions between components behave in unpredictable ways and produce multiple and unexpected failures.

2.1.4 Dekker’s Drift into Failure Model

For Dekker (2011) system performance gradually shifts, leading them to adapt in unforeseen ways and to drift toward and ultimately across the boundary for safe performance. Dekker’s approach to accident causation is largely a cultural and philosophical one. He explains that reductionist approaches to cause and effect developed at the beginning of the scientific revolution have rooted themselves as factual discourse in everyday life (Dekker, 2011). When accidents occur investigations typically look for the “broken component” or “bad apple” based on the assumption that effects cannot occur without a direct cause. The Drift models central argument is that the traditional reductionist, component based, linear models of accident causation are unsuitable for current systems that are increasingly complex, emergent and non-linear (Dekker, 2011). While Drift does not specify methodologies, approaches, or practical steps, it provides a set of philosophies that explain the nature of drift within a system.
2.1.5 Hollnagel’s Functional Resonance Analysis Model

Hollnagel developed the Functional Resonance Analysis Model (FRAM; 2012) largely based on his dissatisfaction with safety assessment approaches and the methods used to address safety issues such as see fault tree analysis (Vesley et al, 1981) and Human Reliability Assessment (Kirwin, 1994). FRAM is not a model of system behaviour, rather it is a method that allows analysts to identify and define systems functions and variability within a system. Because Hollnagel (2009) believes variance is systematic and not random, safety is underpinned by different forms of variability. An important concept in FRAM is functional resonance, which is a detectable signal of variance from multiple interactions as a direct consequence of the way a system functions (Hollnagel, 2012).

2.2 Identification of systems thinking tenets

As touched on above, each of the models discussed has a set of tenets or central beliefs about accident causation. The aim of the review was to extract these tenets from the selected accident causation models in order to develop a common set. In order to identify the tenets associated with each model, the review involved examining the literature regarding each of the models using literature from the authors listed above. This included articles describing the models and articles describing applications of the models. To be included in the review, it was required that the creator of the accident causation model was the primary author of the published material. Further, it was required that either accident causation, safety or systems theory were addressed in the context of Human Factors literature (for example Perrow’s (1970) work on organisational theory was not included).

To obtain relevant literature a series of academic databases (Science Direct, Taylor and Francis Online, Web of Science, Sage Journals Online, IEEE Xplore and Google Scholar) were searched based on the author name (no limitations on year of publication were used). In all, ninety authored books, peer reviewed journal articles and technical reports were included in the final review process.

Each text was then reviewed by the first author who extracted accident causation tenets. The qualitative coding software Nvivo 10 was used to firstly categorise the literature based on the author’s descriptions of system properties or behaviours in either a safe form or unsafe form. Three categories were used, these were;

1. safe system properties;
2. unsafe system properties; and
3. system definitions (i.e. how author’s defined whole system properties).

Identifying safe and unsafe system properties was essential to determine how each tenet performs in both states as it was the authors’ opinion that the tenets, which could do both, had the potential to predict system vulnerabilities. The first level of coding required that authors’ descriptions of a concept or principle were coded to either safe system properties, unsafe system properties or system definition. Once this first level was completed the descriptions were attributed to a ‘tenet’ or systems based principle (as seen in Table 2). The first author analysed the literature and coded material based on the above structure. On completion of the coding task, a set of twenty-six tenets of accident causation were identified. The two co-authors then independently reviewed the list of tenets, making one addition, resulting in a final list of twenty-seven tenets based on the review of the literature.
2.3 Refining the systems thinking tenets
A workshop was held to evaluate and synthesize the twenty-seven systems thinking tenets identified from the literature. The authors, all of which have extensive experience in human factors research and accident causation approaches, were presented with the twenty-seven system thinking tenets, including a definition and a short background on each accident causation method selected to review. The evaluation required identifying those tenets, which were key factors in existing accident or incident analysis and appear to apply to accident prediction.

As there was considerable overlap between the tenets, one of the key aims of the workshop was to synthesize them into a set of distinct and well-defined tenets. The workshop participants were asked to create a simplified description of each tenet to ensure that they could be easily understood and interpreted by non-human factors practitioners. This is desirable as human factors based analytic tools often experience a significant gap between academic understanding of concepts and practical applications in the field (Underwood and Waterson, 2013). The tenets were then reviewed according to how they applied to systems theory, accident analysis, and the scope and similarity between each tenet. For example, “control mechanisms”, “resource scarcity and competition”, “work system constraints” and “constraints” contain similarities to each other and were combined under the tenet “constraints”. To be included in the final list, tenets were required to be judged by the participants to play a role in either safe or unsafe system performance and also to align with systems thinking. For example, “functional abstraction” and “hierarchical control structures” were removed as tenets because they describe an approach to the organization of information rather than provide information about system states. Inclusion or exclusion of systems thinking tenets was agreed upon based on the criteria above; any disagreements were discussed until a consensus was met amongst the authors.
3.0 RESULTS

Of the twenty-seven tenets originally identified from the literature, fifteen remained after the workshop. The final list of systems thinking tenets are presented in Table 3 along with definitions extracted from the literature. In most cases, each of the tenets were common across all accident causation models. For example, “vertical integration” is common to all methods used in the review as each categorises interactions between components in a system in some form or another, either by referring to an interaction itself or using a specific term related to the method (STAMP uses feedback loops, NAT uses coupling and FRAM describes the links between upstream and downstream functions).

Two tenets did not have uniform representation across all approaches: performance variability and modularity. Performance variability was present in all except for Normal Accident Theory (1981; 1999). This may be due to the terminology used to describe variability. Efforts were made to search Perrow’s work for different terms that may be related to performance variability (for example: adaptation, variance, variation), however these were not identified. Modularity was also not uniformly identified across all approaches included in the review. Two authors refer to modularity, the most obvious being Perrow as it plays a significant role in recent adaptations to Normal Accident Theory (2011) and Rasmussen (1990; 2000) who proposes the idea of functional de-coupling to minimise the need for informational exchange. The tenets themselves represent a wealth of knowledge about accident aetiology based on decades of retrospective systems analysis of accident causation. Furthermore the systems thinking tenets represent a shared and mutual understanding between models about accident aetiology.
Table 3 provides an explanation of the fifteen systems thinking tenets that remained after the refining and simplifying exercise. It details how each author explains the systems thinking tenets in the context of their own accident causation model.

### Table 3: Definitions of each fifteen system thinking tenet by author/accident causation model

<table>
<thead>
<tr>
<th>Vertical integration</th>
<th>Leveson</th>
<th>Rasmussen</th>
<th>Perrow</th>
<th>Dekker</th>
<th>Hollnagel</th>
</tr>
</thead>
<tbody>
<tr>
<td>STAMP (2004; 2012)</td>
<td>Feedback loops that allow information to be passed and control to be enforced between hierarchical levels of the system</td>
<td>Interaction between levels in the system hierarchy</td>
<td>Interaction in complex systems is determined by the degree of coupling between components</td>
<td>Interactions between lower order components and their interaction with their environment</td>
<td>A system is defined in terms of functions and their potentialcouplings. Instantiations of upstream functions carry information to downstream functions, which may affect them</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Constraints</th>
<th>Leveson</th>
<th>Rasmussen</th>
<th>Perrow</th>
<th>Dekker</th>
<th>Hollnagel</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Control processes that limit system behaviour to ensure safe operation and adaptations</td>
<td>The boundaries that the system must work within, in order to achieve acceptable performance</td>
<td>The structure of the organisation and the external political and economic conditions in which the system must operate, buffers and redundancies are part of system design.</td>
<td>Limitation in finite resources and resulting competition that occurs.</td>
<td>Legislative controls, production and economic pressures affect and influence operational goals. In FRAM, controls supervise or regulate functions to achieve the desired output.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Functional dependencies</th>
<th>Leveson</th>
<th>Rasmussen</th>
<th>Perrow</th>
<th>Dekker</th>
<th>Hollnagel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tracing system functions to individual components</td>
<td>Means-ends relationships</td>
<td>Interdependence between tightly coupled functions in complex systems</td>
<td>Path dependence in complex systems</td>
<td>The operation of one component may be functionally tied to another</td>
</tr>
</tbody>
</table>
Table 3 (cont.): Definitions of each fifteen system thinking tenet by author/accident causation model

<table>
<thead>
<tr>
<th>Emergence</th>
<th>Leveson</th>
<th>Rasmussen</th>
<th>Perrow</th>
<th>Dekker</th>
<th>Hollnagel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Adaptive system or subsystem processes focused on achieving goals while adapting around constraints</td>
<td>Decisions and actions across levels of the system interact and shape behaviour and accidents</td>
<td>In complex and tightly coupled systems, interactions occur that cannot be foreseen or controlled.</td>
<td>Coupled, non-linear and context dependant interaction that cannot be obtained by summing behaviour from constituent parts</td>
<td>Variability of performance by people (singular and groups) and organisations where approximate adjustments effect system functions creating change that resonates throughout the system</td>
</tr>
<tr>
<td>Normal performance</td>
<td>Mechanisms generating behaviour in the actual dynamic context.</td>
<td>Boundaries of safe operation where complex adaptation of performance to work requirements are made (2000)</td>
<td>The limits of safe operation</td>
<td>System performance boundaries are made explicit to encourage skill development to cope with processes and pressures at the system boundaries</td>
<td>Actions emerge to create safe operation</td>
</tr>
<tr>
<td>Coupling</td>
<td>Interactive complexity between components. Tightly coupled interactions in complex system allow disruptions and dysfunctions in one part of the system to have far reaching effects.</td>
<td>Degree of integration where effects of a single decision can propagate rapidly and widely through the system</td>
<td>The degree that components in a system interact: In a tightly coupled system the operation of one part directly effects the other. In a loosely coupled system, parts act independently.</td>
<td>Interconnections and interactions between system components</td>
<td>Sub-systems and/or components are connected or dependent on each other in a functional sense. Coupling can be loose or tight, potential or existing.</td>
</tr>
</tbody>
</table>
Table 3 (cont.): Definitions of each fifteen system thinking tenet by author/accident causation model

<table>
<thead>
<tr>
<th>Non Linear interactions</th>
<th>Leveson</th>
<th>Rasmussen</th>
<th>Perrow</th>
<th>Dekker</th>
<th>Hollnagel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Interactions that arise from unpredictable sequences between components with high degrees of complexity and coupling</td>
<td>Dynamic unpredictable information flow structure</td>
<td>Interactions that are characterised by branching paths, feedback loops and jumps from one linear interaction to another. Units or subsystems serve multiple functions</td>
<td>Interactions among components that produce unfamiliar, unexpected or unplanned sequences</td>
<td>Unpredictable interactions that arise from normal performance variability (2008).</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Linear interactions</th>
<th>Leveson</th>
<th>Rasmussen</th>
<th>Perrow</th>
<th>Dekker</th>
<th>Hollnagel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Interactions that arise from predictable sequences between components with lesser degrees of complexity and coupling</td>
<td>Pre-planned strategies and prescriptive procedures</td>
<td>Procedures carried out in an anticipated production sequence units or subsystems serve only one function.</td>
<td>Interactions among components that produce expected, planned and familiar interaction sequences</td>
<td>Predicable interactions that are planned and familiar.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Modularity</th>
<th>Leveson</th>
<th>Rasmussen</th>
<th>Perrow</th>
<th>Dekker</th>
<th>Hollnagel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Functional decoupling minimising the need to exchange information between actors or components</td>
<td>The organisation of a system where the parts are designed independent of the system</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Feedback Loops</th>
<th>Leveson</th>
<th>Rasmussen</th>
<th>Perrow</th>
<th>Dekker</th>
<th>Hollnagel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Control structure components that provide information allowing the component to effect control actions and maintain safety</td>
<td>Communication structure and the information flow to evaluate control requirements of hazardous processes</td>
<td>Monitoring processes that provide frequent information about the operational state of the system</td>
<td>Information mechanisms that recognise the boundaries of safe operation by regulating interactions between system components</td>
<td>Maintaining order and controlling what the system does – it can be both anticipatory or feed forward driven</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Decrementalism</th>
<th>Leveson</th>
<th>Rasmussen</th>
<th>Perrow</th>
<th>Dekker</th>
<th>Hollnagel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Migration of systems where small deviations overtime allow the system to drift to a high risk state</td>
<td>Degrees of freedom allows adaptations to performance</td>
<td>Progressive deviations from routine tasks that accumulate overtime to produce an accident</td>
<td>Small deviations over time lead to big effects</td>
<td>Approximate adjustments to match conditions, resources and constraints</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sensitive dependence on initial conditions</th>
<th>Leveson</th>
<th>Rasmussen</th>
<th>Perrow</th>
<th>Dekker</th>
<th>Hollnagel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Changes and adaptations that migrate toward an accident over time</td>
<td>Effects of a single decision can have dramatic effects that propagate rapidly and widely</td>
<td>Everything is linked, changes in one system state can cause unpredictable effects elsewhere in the system (theoretically everything is potentially critical)</td>
<td>Systematic adaptation where small changes in one state of a complex system can result in large differences later</td>
<td>Upstream functions distribute conditions or information that are fed to respective functions downstream affecting performance.</td>
</tr>
</tbody>
</table>
Table 3 (cont.): Definitions of each fifteen system thinking tenet by author/accident causation model

<table>
<thead>
<tr>
<th>Unruly technologies</th>
<th>Performance variability</th>
<th>Contribution of the protective structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leveson</td>
<td>Rasmussen</td>
<td>Dekker</td>
</tr>
</tbody>
</table>

**Unruly technologies**
- New technologies may lead to an asynchronous evolution of the control structure.
- Boundaries shift, making it difficult to identify the potential for restructuring in response to changes in technology.
- The complicated and complex design of technology means that not all interactions can be anticipated.
- Technologies that introduce and sustain uncertainties about how and when things may fail.
- Modern technological systems are intractable and underspecified leading to possible variability.

**Performance variability**
- Objectives with many degrees of freedom in how those objectives are met.
- Quick change to new requirements shaped by the ‘degree of freedom’ in fluctuating and dynamic work conditions.
- People learning about and adapting to multiple goals, hazards and making trade-offs.
- Adjustments to work performance that are the basis of safety and productivity. Performance is always variable.

**Contribution of the protective structure**
- Regulatory structures designed to help the system meet its goals.
- Regulatory structures designed to help the system meet its goals (2000).
- No individual component (human or technology) is perfect.
- The web of relationships where the system maintains its own rules.
- Background functions, which provide the context or working environment – they provide the input, precondition, resources, and control and time aspects of functions downstream.
4.0 DISCUSSION

The aim of this review was to identify a set of core systems thinking tenets relating to accident causation. The purpose was to identify a set of tenets which could form the basis of a formal methodology for predicting accidents in complex systems. Based on a review of the most popular accident causation models twenty-seven accident causation tenets were identified. The tenets were reviewed and simplified by the five authors to provide a final set of fifteen systems thinking tenets. Further analysis determined that almost all of the system thinking tenets were identifiable across the key accident causation literature used in the review despite variation in each author’s underpinning theory and accident causation model (Table 3). As such, the tenets presented provide a synthesised view of the central beliefs around accident causation within the discipline of Human Factors. In synthesising the key features from the most prominent models in the literature, the tenets represent a comprehensive view of contemporary thinking on accident causation. That is, the fifteen tenets represent aspects of system behaviour that, either together or in isolation, are thought to create accidents in complex sociotechnical systems. A key contribution of the review is to provide the first step toward a unified model of accident causation.

Other findings are of interest. Despite differences in how each model describes accident causation or is structured to collect and interpret information on accident causation the review indicates that there is significant agreement around the aetiology of accidents themselves. Indeed it is plausible that the systems thinking tenets represent key points of vulnerability where systems are most susceptible to changes in behaviour, leading them to shift toward the boundary of unsafe performance. The system thinking tenets could reliably be used in accident investigation given this finding.

A key outcome, and a goal of the wider program of research from which this review was undertaken, is that the tenets provide the basis for developing a formal methodology for predicting accidents in safety critical systems. For example, the authors are currently developing an approach that will assess the status of the 15 tenets in order to identify potential accidents. Historically, accident prediction methods have focussed on predicting end error events or on calculating a numerical probability of an accident occurring. These approaches either do not align with systems thinking and contemporary accident causation models, or they are difficult to apply in practice. Just as accident analysis methods have seen a departure from reductionist approaches, accident prediction methods must also follow suit (Dekker, 2011; Leveson, 2012). The systems thinking tenets identified in this review are an initial step to provide a holistic yet analytical attempt at addressing system properties to aid in prediction.

Study Limitations

The review had some limitations that are worth noting. The coding of the literature during the review may have been impacted by bias as only one author coded the literature. This was addressed by two independent human factors researchers with significant experience in accident reporting and analysis reviewing the list of tenets identified. Manual coding was required for a small number of texts due to a limitation in coding software regarding importing protected files. This restricted the ability of the analyst to search those documents for key terms or phrases. While every attempt was made to capture these, it is likely that some may have been overlooked.
5.0 CONCLUSIONS
While systems based accident causation approaches have been crucial to developing a holistic understanding of accidents and improving system performance over decades, this reactive approach to improving safety has been underperforming in terms of a reduction in accidents (Leveson, 2011; Salmon et al, 2016). As part of a program of research that aims to develop a formal accident prediction method that aligns with systems thinking, the aim of this review was to identify a set of key tenets from the contemporary accident causation literature. The intention was to identify a set of coherent tenets that could form the basis for the accident prediction methodology. Based on the accident causation approaches of Nancy Leveson (2011), Jens Rasmussen (1997; 2000), Charles Perrow (1981; 2011), Sidney Dekker (2011) and Erik Hollnagel (2009; 2012; 2014), fifteen systems thinking tenets were identified. It is our view that the fifteen tenets allow identification of essential characteristics related to system performance, and may well afford the first signs of predicting system performance.

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