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Review

Back to the future: What do accident causation models tell us about accident prediction?

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ABSTRACT

The prediction of accidents, or systems failure, should be driven by an appropriate accident causation model. Whilst various models exist, none is yet universally accepted, but elements of different models are. The paper presents the findings from a review of the most frequently cited systems based accident causation models to extract a common set of systems thinking tenets that could support the prediction of accidents. The review uses the term "systems thinking tenet" to describe a set of principle beliefs about accidents causation found in models proposed by Jens Rasmussen, Erik Hollnagel, Charles Perrow, Nancy Leveson and Sidney Dekker. Twenty-seven common systems thinking tenets were identified. To evaluate and synthesise the tenets, a workshop was conducted with subject matter experts in accident analysis, accident causation, and systems thinking. The evaluation revealed that, to support accident prediction, the tenets required both safe and unsafe properties to capture the influences underpinning systematic weaknesses. The review also shows that, despite the diversity in the models there is considerable agreement regarding the core tenets of system safety and accident causation. It is recommended that future research involves applying and testing the tenets for the extent to which they can predict accidents in complex systems.

1. Introduction

Increasing system safety through reducing adverse events remains a major challenge to safety scientists (Dekker & Pitzer, 2016; Salmon et al., 2011; Stanton and Stammers, 2008). In recent times accident causation models and analysis methods underpinned by systems thinking have emerged as the most prominent approaches for this purpose. The basis of systems thinking is that safety and accidents are the result of emergent behaviours in a system where interrelated components work to achieve common goals (Stanton et al., 2012; Leveson, 2013). The complexity of systems and the environments in which they operate means the process of safety is not straightforward or linear, but instead is driven by a complex web of relationships and behaviours between humans, technology and their environment (Underwood and Waterson, 2014). From a systems perspective, using approaches that reduce faults or failures to a 'bad apple' such as an individual worker or broken component can never truly elucidate the complexity of an accident or the system in which it occurred (Dekker, 2011; Leveson, 2012).

Accident analysis methods underpinned by a systems approach are traditionally applied retrospectively to analyse incidents (Jenkins et al., 2010; Salmon et al., 2016a). 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). Despite this, it is acknowledged that the reliance on extreme events for safety learning is both inappropriate and inadequate. Indeed, instead of declining over time, incident rates have reached a plateau (or an increase) in multiple fields that have been applying systems based accident causation methods such as road, rail and aviation (Leveson, 2012; Salmon et al., 2016a). This is reflected in Australian data on road and rail incidents where decreases some years are negated by increases in others and trauma numbers spanning over several years look to be the same (ATSB, 2012; BTIRE, 2017). Commercial aviation accidents in Australia also reveals a significant increase from just over 9 accidents per million departures in 2006 to 20 per million departures in 2014 (ATSB, 2017). This suggests that retrospective analysis may be underperforming in the prevention of accidents (Leveson, 2011; Salmon et al., 2016a; Walker et al., 2017); traditional approaches may have reached a saturation point and are no longer reliable for improving safety. Finally, the appropriateness in

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relying on major accidents to occur to improve safety raises both moral and ethical dilemmas where safety innovation is continually built upon the foundations of others hardship and adversity. These concerns are reflected by movements within safety science toward a focus on accident prediction (e.g. Salmon et al., 2016a) or studying incidents in which a catastrophic outcome was avoided (e.g. Hollnagel, 2014; Trotter et al., 2014).

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; Attwood et al., 2006; Harwood, et al., 2000; Miaou, 1996). A key limitation, given our understanding of accidents, is that error prediction methods typically only identify the end error event in what is a complex web of interacting factors. In addition, there are questions around the suitability of using mathematical models and formulae; their use by practitioners is questionable as is the extent to which a numerical value is useful (Fujita and Hollnagel, 2004).

Apart from Leveson's STAMP model (Leveson, 2015), applications driven by qualitative accident causation models have not been used predictively. Increasingly researchers are investigating the use of qualitative systems analysis methods for predicting performance, accident scenarios and assessment of risk (e.g. Salmon et al., 2014; Stanton et al., 2014; Stanton and Harvey, 2016); however, this has not yet produced a formal methodology for 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., 2016a; Stanton and Stammers, 2008).

With over half a century of progress in safety science, sociotechnical systems theory and human factors methods it seems pertinent to ask what can be learned about accident causation from our past to inform our next step into the future of prediction. It is these authors opinion that the clues to accident prediction lie in what we currently know about accident causation. However, it is acknowledged that, first many accident causation models exist, second that there is not yet a universally accepted accident causation model, and third that the different models have useful elements relating to understanding accident causation. The purpose of this review is to address the lack of conceptual clarity and in doing so recognise the extent that the core tenets of accident causation can be revealed across the leading accident causation models. To do so a review of the literature 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 contemporary accident causation models. 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 several contemporary accident causation models. Both safe and unsafe features of each systems thinking tenet are presented as a proactive approach to safety will require both knowledge of how a system works and of how its environment can develop and change (Hollnagel, 2012). The aim of this paper is to present the findings from the review and the synthesis workshop to outline the set of integrated systems thinking tenets.

2. 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 identified 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 (O'Hare, 2000) model were removed from the review. Although there are elements of systems theory within the Swiss Cheese model, it does not fully comply with the principles of system theory; the model has been criticised for being a reductionist and linear model that fails to account for a holistic representation of systems as dynamic and adaptive which forms the basis of systems theory (Dekker and Leaveson, 2014; Hollnagel, 2004; Hollnagel, 2014). Similarly, O'Hare's (2000) Wheel of Misfortune was excluded, as it largely an error taxonomy that focuses on an end error event. While models were excluded, their contribution to safety philosophy cannot be denied. Indeed, it is critical to note the importance of accident causation models from the past and how they have underpinned present day safety ideals, particularly affording a pathway to a systems approach to accident causation (Heinrich, 1931, Turner, 1976, 1979).

Table 1
Accident causation model and author citation.

Author	Accident causation model	Citations (derived from Scopus, 2016)
Nancy Leveson	Systems Theoretic Accident Model and Processes (STAMP, 2004)	3950
Jens Rasmussen	Risk management framework (Rasmussen, 1997)	3486
Charles Perrow	Normal Accident Theory (1981; 1999)	2041
Sidney Dekker	Drift into Failure Model (2011)	789
Erik Hollnagel	Functional Resonance Analysis Method (FRAM, 2011)	672

The refinement process left the following models for review (see Table 1): Leveson's Systems Theoretic Accident Model and Processes (STAMP, Leveson, 2004) 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, Hollnagel, 2012).

2.1. Accident causation models selected for review

2.1.1. Nancy 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. 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 from 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) STAMP model 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 identify the controls and feedback loops that enforce safe operation and then determine which failed to support the prevention of future accidents. To do this STAMP utilises a hierarchical control structure, which is a model explaining the regulation of a sociotechnical system. The control structure is divided into two models, one for system development and one for operations. Constraints limit system behaviour to ensure it operates within safe boundaries. Constraints can be both existing such as environmental or fiscal constraints or introduced constraints such as rules, procedures or design of equipment or technology. They represent control on behaviour to limit the degree of freedom on interaction between components (Dekker, 2014). These are imposed by actors at higher levels of the hierarchy onto those at lower levels. According to STAMP, system accidents occur not because of failures, but because constraints were not successfully enforced pushing the system closer to the edge of safe performance and reducing the margins of safe operation (Leveson, 2004; Dekker, 2014a).

2.1.2. Jens Rasmussen's risk management framework

Rasmussen's (1997) risk management framework describes complex sociotechnical systems as a hierarchy, accounting for the dynamic context in which systems operate. 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 and 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 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 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. Dynamic workflows are represented in the framework as interdependencies between the levels of the system, which are underpinned by feedback controls or vertical integration. For successful operation, information regarding controls from the higher levels of the hierarchy is filtered downward to the lower levels and conversely feedback on performance at the lower levels is fed upward carrying operational information to the higher levels of the system (Cassano-Piche et al., 2009). This information then informs appropriate decisions and actions at the higher levels of the system. Instability in the system can be caused by a lack of vertical integration, which ultimately leads to a loss of control. Loss of control means the system is vulnerable and more likely to perform outside the boundaries of acceptable performance where adverse events are more likely to occur.

2.1.3. Charles 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 is coupled with the incomprehensibility of the accident (Perrow, 1999). This view identified system characteristics, instead of human ones, as the primary causes of accidents. Perrow's research into the incident at Three Mile Island is noted as a significant turning point in safety science research (Hopkins, 2001).

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. Within complex systems, the relationships between components can be described in terms of the degree of "coupling" between them. Coupling is the interaction between components of a system that influences the intensity of the relationship between the two and as such their behaviour (Perrow, 2008; Hollnagel, 2012). Perrow (1999) makes the distinction between loose or tight coupling. Loose coupling describes interactions between components that are less controlled, less dependent on each other. Tight coupling describes the opposite, highly dependent interactions where one interaction sequence creates effects in the function or operation of other components. When applied to a system, a NAT matrix or typology determines the degree of coupling (as either tight or loose) and type of interaction (as either linear or complex) operating in a system (Perrow, 1999). The model posits that where systems have both complex interactions and tight coupling, failures become inevitable.

2.1.4. Sidney Dekker's drift into failure model

For Dekker (2011) systems gradually shift, leading them to adapt in unforeseen ways and to drift across the boundary to unsafe 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. According to Dekker (2011), this philosophy has become so deeply embedded in western approaches to accident causation, where it is taken for granted that failure can easily be reduced to a single "root cause" and thus it can be removed, fixed or made compliant returning the "system" to its safe state. Dekker's main argument in Drift (2011) 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. While Drift (2011) does not specify methodologies, approaches, or practical steps, it provides a set of philosophies that explain the nature of drift within a system. These embody key principles from complexity theory such as path dependence, decrementalism, non-linearity and the impact of protective structures.

2.1.5. Erik Hollnagel's Functional Resonance Analysis Model

Hollnagel developed the Functional Resonance Analysis Model (FRAM) (2012) largely based on his dissatisfaction with the methods used to address safety issues such as see fault tree analysis (Vesley et al., 1981) and Human Reliability Assessment (Kirwan, 1994). FRAM is not a model of system behaviour, rather it is a method that identifies and defines systems functions and variability and determines how variability may interact within a system in a manner that leads to adverse outcomes. As Hollnagel (2009) believes variance is systematic and not random, safety is said to be underpinned by different forms of variability. Philosophies of safety such as Safety II perspective (Hollnagel, 2014) are similar to that of high reliability theory (La Porte & Consolini, 1991, La Porte, 1996). However, Hollnagel's focus on systems engineering and human factors 'top down' systems thinking approach provide a distinguishing feature between the two (Leveson et al., 2009).

A FRAM analysis can be used to improve practices in a system or to investigate adverse events. In contrast to Rasmussen's Risk Management Framework (1997) and Leveson's STAMP (2012), FRAM does not explain systems hierarchically or by abstraction, instead it explains a system in terms of the mutually coupled or dependant functions relative to the whole system focusing on what a system does rather than what it is. The system is described by the functions required to complete its tasks and possible variability that may occur in those functions (Lundberg et al., 2009). Through understanding the functions, a system performs, a distinction can be made between the system and its environment and thereby identifying the system boundaries (Hollnagel, 2004).

2.2. Identification of systems thinking tenets

Each of the models described above contain specific tenets around safety and accident causation. To identify the core system thinking tenets associated with each model, the review involved examining the accident models using literature from the authors listed above. 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. This decision was made to preserve the integrity of the key safety related concepts in each model as the authors had originally intended. It was felt that using other descriptions or examples of the methods in practice could dilute rather than enhance the extraction of the systems thinking tenets, as many of the methods have been found to rely on subjectivity when performing analysis (Stanton et al., 2013).

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). A specific requirement was that either accident causation, safety or systems theory were addressed in the article (for example Perrow's (1970) work on organisational theory was not included). In all, ninety (90) authored books, peer reviewed journal articles and technical reports were included in the final review process. Each source was then reviewed and the accident causation tenets were identified.

The identification of the tenets involved first reviewing the article and identifying instances where a concept was described as a key mechanism for safe or unsafe system performance. The qualitative coding software Nvivo 10 was used to first categorise the literature based on the author's descriptions of system properties or behaviours in either a safe form or unsafe form. In this first level of coding three categories were used, these were; safe system properties; unsafe system properties; and system definitions (i.e. how author's defined whole system properties). This first coding pass created a list of safe and unsafe system properties derived from each accident causation model.

Next a second coding exercise was undertaken whereby the core tenets from the combined accident causation models were identified based on the descriptions of safe and unsafe and system definitions. Table 2 provides examples of the coding structure used. The first author analysed the literature and coded material based on the above structure. Two co-authors then independently reviewed the list of tenets making one addition to the list (performance variability). This addition was based on its absence from the original list, however a review of the coding structure exposed the possibility that it was concealed by other tenets. An example of this is outlined in Table 2 where the description of performance variability as a safe system example also includes a description of the tenet 'coupling'. The output of the coding process was a set of twenty-seven recurring tenets of accident causation.

2.3. *Refining the systems thinking tenets*

A workshop was held to evaluate and synthesize the twenty-seven systems thinking tenets. The workshop involved all the five authors, each of which have experience in applied human factors research and accident analysis in various domains including defense, transportation, workplace safety, sports and outdoor recreation, disaster management and urban planning (see Table 3).

In the workshop, the participants were presented with the twenty-seven system thinking tenets, their definitions and information on each accident causation model. The evaluation process involved discussing the tenets along with examples of their role in safe and unsafe system performance and identifying instances where tenets were either inappropriate or could be integrated. Finally, the potential for each tenet to be used in a predictive capacity was discussed.

As there was considerable overlap between the initial twenty- seven tenets an aim of the workshop was to synthesise them into a set of distinct and well-defined tenets (see Table 4). To do so, tenets were reviewed according to how they applied to systems theory, accident analysis, and the scope and similarity between each tenet. For example, "functional abstraction" and "hierarchical control structures" were removed as tenets early in the process because they describe an approach to the organization of information rather than provide information about system states. Similarly, the tenet "adaptation" was removed because of its broad scope; additionally, it is captured in other concepts such as performance variability and normal performance.

Once the set of twenty-seven tenets had been formally revised the next stage required simplifying the formal definitions from the literature to limit erudite language and design a description of each tenet to promote ease of understanding. This is desirable as human factors based analytic tools often experience a significant gap between academic understanding of concepts and the transfer to practical applications in the field (Underwood and Waterson, 2013). This simplification required that the key concepts were described appropriately to capture the underpinning theory of each tenet (e.g. simple but not simplistic). Further the authors were required to construct both a safe and unsafe description of the tenets, for example, providing a description of how each tenet would perform safely and unsafely (see Table 5). It is the perspective of the authors that safe and unsafe classifications of tenets provide a basis to forecast those properties that lead a system to operate toward the boundaries of unsafe performance. A central feature of the research program this work is associated with, is to use the tenets to determine where systems are more prone to weakness leading to unsafe behaviours through the identification of both safe and unsafe performance. More importantly this enables a methodology that on one hand recognizes the potential of unsafe performance within a system and on the other supports a system's return to its safe state. In other words, it utilises an understanding of safe and unsafe behaviours to predict accidents before they occur. To achieve this the properties that lead to both safe and unsafe behaviours for each tenet need to be acknowledged *a priori*.

At the conclusion of the workshop each systems thinking tenet had been assigned three classifications; a generic simplified definition, a description of that tenet in its safe form and a description of that tenet in its unsafe form. Inclusion or exclusion of systems thinking tenets was agreed upon based on the criteria above; any disagreements were discussed until a consensus was met. In the event that consensus was not met regarding inclusion or exclusion of a tenet judgments were to be based on a majority decision, however this was not required.

3. Results

The output of the workshop was a set of fifteen tenets of safe and unsafe system performance. Table 4 provides comparative definitions of the tenets as originally described in the accident causation models reviewed. This also provided a context to decide the levels of homogeneity between the methods when identifying the core tenets of system safety, as author's descriptions of tenet behaviour could be easily compared.

Table 5 presents the simplified definitions attributed to each tenet in addition to a description of its characteristics in both safe and unsafe states. To aid in clarity, Table 5 also provides examples from literature that best describe the safe and unsafe characteristics of the tenet in

Table 2
Example of coding structure.

Coding categories	First level coding (Authors descriptions)	Second level coding (Tenet extracted)
Safe system properties	Characterisation of performance variability is needed to understand how functions become coupled and can lead to unexpected outcomes (Hollnagel, 2012: 58)	Performance Variability
Unsafe system properties	It is difficult – if not impossible – for any individual to judge the safety of their decisions when it is dependent on the decisions made by other people in other departments and organisations (Leveson, 2012: 43)	Vertical integration
System Definition	Human actions always involve some interpretation of the person's goals and motives. The individuals involved may be unaware of their actual goals and motivation or may be subject to various types of pressures to reinterpret their actions (Leveson, 2012: 54)	Normal performance

Table 3
Author experience and qualifications.

Workshop participant	Qualification level	Years' experience in human factors and accident analysis	Number of published journal papers on accident analysis and prevention
Participant 1	BA (Hons. Sociology) First Class	3	1
Participant 2	MSc Applied Ergonomics, PhD Human Factors	16	100
Participant 3	Master (UrbRegPlan), PhD (UrbRegPlan)	4	3
Participant 4	BA (Hons. Psychology), PhD (Psychology)	6	10
Participant 5	BBsc, LL.B, PostGradDipPsych, PhD Human Factors	10	6

context of a near miss or accident scenario.

3.1. Results of review of literature and validated tenets

Table 4 presents the fifteen tenets that remained after the workshop with comparative definitions of each tenet according to accident causation method. Note: Some tenet definitions were not present in the available literature and in these cases 'Not found' is stated.

3.2. Simplified tenets list

Table 5 shows the simplified definitions attributed to each tenet after the workshop. It also provides descriptions of safe and unsafe system behaviours with examples retrieved from accident analysis literature to aid in clarity.

Almost all the systems thinking tenets were represented across the selected accident causation models (as seen in Table 4). Two tenets were not found in some models: 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 found in the literature of Leveson's STAMP (2004), Dekker's Drift into failure (2011) or Hollnagel's FRAM (2012). 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 results also confirm that each of the remaining fifteen tenets are applicable to both safe and unsafe systems states (see Table 5). This result has the potential to reveal when systems are shifting at increased points of vulnerability by making a distinction between normal and abnormal behaviours at these points. The tenets represent a significant body of knowledge about accident aetiology based on decades of retrospective systems analysis of accident causation. The description of safe system properties makes safety in complex systems distinct or "refer(s) to what safety is in a way that makes it open to inter-subjective verifiability" (Hollnagel, 2014: 21). A key factor to the predictive capacity of the systems thinking tenets is their ability to form a clear picture of what 'safe' looks like in complex systems, which in turn describes how a systems functions rather than how it malfunctions (Hollnagel, 2014).

4. Discussion

The aim of this review was to identify a set of integrated systems thinking tenets regarding accident causation. The intention was to synthesise the core features of contemporary accident causation models to form the basis for the development of a formal methodology for predicting accidents. Further analysis determined that almost all 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. This was perhaps surprising given the apparent differences in the models. An important contribution of the study is therefore a set of common accident causation tenets that represent the core philosophies of the five leading models presented in the literature (Dekker, 2011; Hollnagel, 2012; Perrow, 1981; Rasmussen, 1997; Leveson, 2004). It is the authors contention that the tenets represent a step toward a unified model of accident causation. Furthermore, despite differences in how each model is structured to collect and interpret information on accident causation the review indicates that there is significant agreement around the aetiology of accidents themselves. The system thinking tenets could conceivably provide a more comprehensive approach to accident investigation than the adoption of one model in isolation.

4.1. Contribution to the literature

In synthesising multiple models, the tenets represent a comprehensive view of contemporary thinking on accident causation. That is, the fifteen tenets in their unsafe mode represent aspects of system behaviour that, either together or in isolation, are thought to create accidents in complex sociotechnical systems. This research is conceptually novel, is it has first illuminated the common elements of accident causation shared between contemporary accident causation methods. The tenets themselves describe how and why accidents occur. Second, the research process has emphasised the concept of safe behaviours and its important role in accident prediction. For accident prediction to be useful there must be a way to see vulnerability but also guidance on how to return the system back to safety. The identification of unsafe tenets must also consider how the particular feature of performance can be made safe.

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. The analysis identifies plausible opportunities to predict system safety using existing principles from multiple accident causation models that identify accident scenarios, which could potentially emerge. The systems thinking tenets elucidate the key points of system vulnerabilities; however, the review has also shown that they are also key features in maintaining safe operation. The systems thinking tenets may provide an opportunity to identify system properties or behaviours as either safe or unsafe where a system is most vulnerable to change before it crosses the boundaries toward unsafe performance. Given that approaches to system safety are moving away from counting accidents to counting safe performance (see Hollnagel, 2012), the systems thinking tenets are a practical means to achieve this undertaking.

Historically, accident prediction methods have focussed on predicting end error events or on calculating a numerical probability of an accident occurring. From a systems perspective, this is unsustainable. Without addressing the systematic properties that underpin accidents, they will likely recur. Moreover, because systems theory is departing from reductionist approaches, accident prediction methods must also follow suit (Dekker, 2011; Leveson, 2012). The systems thinking tenets provide a holistic yet analytical attempt at addressing system properties

Table 4
Comparative definition of tenets according to accident causation model.

	Leveson STAMP (2004; 2012)	Rasmussen Risk Management Framework (1997; 2000)	Perrow Normal Accident Theory (1981; 1999; 2007)	Dekker Drift (2011)	Hollnagel FRAM (2012)
Vertical integration	Feedback loops that allow information to be passed and control to be enforced between hierarchical levels of the system	Interaction between levels in the system hierarchy	Interaction in complex systems is determined by the degree of coupling between components	Interactions between lower order components and their interaction with their environment	A system is defined in terms of functions and their potential couplings. Instantiations of upstream functions carry information to downstream functions, which may affect them
Constraints	Control processes that limit system behaviour to ensure safe operation and adaptations	The boundaries that the system must work within, in order to achieve acceptable performance	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	Limitation in finite resources and resulting competition that occurs	Legislative controls, production and economic pressures affect and influence operational goals. In FRAM, controls supervise or regulate functions to achieve the desired output
Functional dependencies	Tracing system functions to individual components	Means-ends relationships	Interdependence between tightly coupled functions in complex systems	Path dependence in complex systems	The operation of one component may be functionally tied to another
Emergence	Adaptive system or subsystem processes focused on achieving goals while adapting around constraints	Decisions and actions across levels of the system interact and shape behaviour and accidents	In complex and tightly coupled systems, interactions occur that cannot be foreseen or controlled	Coupled, non-linear and context dependant interaction that cannot be obtained by summing behaviour from constituent parts	Variability of performance by people (singular and groups) and organisations where approximate adjustments effect system functions creating change that resonates throughout the system
Normal performance	Mechanisms generating behaviour in the actual dynamic context	Boundaries of safe operation where complex adaptation of performance to work requirements are made	The limits of safe operation	System performance boundaries are made explicit to encourage skill development to cope with processes and pressures at the system boundaries	Actions emerge to create safe operation
Coupling	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	Degree of integration where effects of a single decision can propagate rapidly and widely through the system	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	Interconnections and interactions between system components	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
Non Linear interactions	Interactions that arise from unpredictable sequences between components with high degrees of complexity and coupling	Dynamic unpredictable information flow structure	Interactions that are characterised by branching paths, feedback loops and jumps from one linear interaction to another. Units or subsystems serve multiple functions	Interactions among components that produce unfamiliar, unexpected or unplanned sequences	Unpredictable interactions that arise from normal performance variability
Linear interactions	Interactions that arise from predicable sequences between components with lesser degrees of complexity and coupling	Pre-planned strategies and prescriptive procedures	Procedures carried out in an anticipated production sequence; units or subsystems serve only one function	Interactions among components that produce expected, planned and familiar interaction sequences	Predicable interactions that are planned and familiar
Modularity	Not found	Functional decoupling minimising the need to exchange information between actors or components	The organisation of a system where the parts are designed independent of the system	Not found	Not found
Feedback Loops	Control structure components that provide information allowing the component to effect control actions and maintain safety	Communication structure and the information flow to evaluate control requirements of hazardous processes	Monitoring processes that provide frequent information about the operational state of the system	Information mechanisms that recognise the boundaries of safe operation by regulating interactions between system components	Maintaining order and controlling what the system does – it can be both anticipatory or feed forward driven
Decrementalism	Migration of systems where small deviations overtime allow the system to drift to a high risk state	Change is a modelling issue: degrees of freedom allow adaptations to performance which can lead to a loss of control	Progressive deviations from routine tasks that accumulate overtime to produce an accident	Small deviations over time lead to big effects	'Approximate adjustments' in the system are made to match conditions, resources and constraints
Sensitive dependence on initial conditions	Changes and adaptations that migrate toward an accident over time	Effects of a single decision can have dramatic effects that propagate rapidly and widely	Everything is linked, changes in one system state can cause unpredictable effects	Systematic adaptation where small changes in one state of a complex	Upstream functions distribute conditions or information that are fed to respective

(*continued on next page*)

Table 4 (*continued*)

	Leveson STAMP (2004; 2012)	Rasmussen Risk Management Framework (1997; 2000)	Perrow Normal Accident Theory (1981; 1999; 2007)	Dekker Drift (2011)	Hollnagel FRAM (2012)
			elsewhere in the system (theoretically everything is potentially critical)	system can result in large differences later	functions downstream affecting performance
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	Not found	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 that restrict behaviour of the system by enforcing safety constraints	Regulatory structures designed to help the system meet its goals	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

to aid in prediction. Accident prediction in this context is an opportunity to locate variations or weaknesses across a system based on the system's production of either the safe and/or unsafe behaviours.

4.2. *Limitations*

The coding of the literature during the review may have been impacted by bias as it was undertaken by only one author. 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, there is potential that some may have been overlooked.

Additionally, the assembly of safe system examples was more difficult due to the extremely small amount of detailed near miss analyses available in the literature. This is perhaps an area that requires attention within the safety science field and should see improvements given the burgeoning fields of resilience engineering (Woods, 2006; Hollnagel et al., 2007; Dekker, 2014) and safety II (Hollnagel, 2014).

4.3. *Research agenda*

A pertinent question to ask following this review is how we can move from the tenets identified to a formal methodology for accident prediction. First, testing of the tenets is required to establish their presence within a sub-set of accidents. Whilst they are derived from popular and widely accepted models of accident causation, which ensures some level of face validity, validation in terms of their role in previous accidents are required. Following this, a formal and structured methodology needs to be established around the tenets. Whilst inherently useful, the tenets alone will not predict anything and the reliance on analysts' subjective judgement should be minimised. A structured and formal methodology is required to support description of the system under analysis and then identification of each tenet and the current and future status of each tenet. The method then needs to provide a structured way of identifying systems failures from the tenets identified. Following methodological development, the accident prediction methodology will require robust reliability and validity testing; something often overlooked in accident analysis research (Stanton, 2016). Indeed, there are questions regarding the reliability and validity of existing accident analysis methods (Stanton et al., 2013; Stanton and Young, 1998). The review provided a survey of a select set of models, future surveys may extend a broader scope to include others outside the selection criteria presented here such as Heinrich (1931), Reason (1990, 2000), Turner (1976, 1979) and High Reliability theory (HRT) and High Reliability Organisations (HRO) (La Porte &, Consolini, 1991). Finally, to support use of the methodology by practitioners, training and guidelines for applying the method are required. This is an extremely important step given the noted research to practice gap in the area of accident analysis (Underwood and Waterson, 2014) and human factors generally (Chung et al., 2011).

5. Conclusions

While systems based accident causation approaches have been crucial to developing a holistic understanding of accidents and improving system performance over decades, they have also been underperforming in the prevention of accidents (Leveson, 2011; Salmon et al., 2016a). While many accident causation models exist, with useful elements relating to understanding accident causation, there is no universally accepted model. The aim of the research was to identify a set of core tenets from the contemporary accident causation literature that recognise system performance. Based on the accident causation models of Nancy Leveson (2011), Jens Rasmussen (1997, 2000),

Table 5
Definitions and descriptions of tenets in both safe and unsafe conditions.

	Simplified definition	Safe system	Examples of tenet in a safe system	Unsafe system	Example of tenet in an unsafe system
Vertical integration	Interaction between levels in the system hierarchy	Decisions and actions at the higher levels filter down to lower levels and impact behavior Information regarding the status of the system filters back up the hierarchy and influences higher level decisions and actions	Apollo 13: effective feedback across different levels of the system by prioritising information and needs between teams (Trotter et al., 2014)	Decisions and actions do not filter through the system and impact behavior on the front line. Information on the current status of the system is not used when making process decisions	Walkerton *E coli* outbreak: information on water quality does not filter through the system (Vincente and Christoffersen, 2006)
Constraints	Influences that limit the behaviours available to components within a system	Specific constraint introduced to control hazardous processes	Airbus A320 alternate law flying modes (the pilot has no direct control) where it is not possible for human pilot to stall the plane	A constraint which restricts the appropriate performance variability	Mid-air collision: constraints produced a mismatch between perception and control of the developing situation (de Carvalho, 2011)
Functional dependencies	The necessary relationships between components in a system	Relationships between functions are expected and sustained	AA DC-10: Pilot self-trained flying techniques in decompression scenario (Leveson, 2002)	Dependencies that are not wanted or expected	Kimberly Ultra marathon: satellite telecommunications systems do not work in locations due to lack of reception (Grant et al., 2015)
Emergence	An outcome or property that is a result of the interactions between components in the system that cannot be fully explained by examining the components alone	Emergent behaviours that support the goals of the system	Hudson river landing whereby the pilot was able to land the plane safely in the Hudson River following a bird strike (Hollnagel, 2013)	Emergent behaviours that undermine the goals of the system	US Army friendly fire: the migration towards the efficiency of procedures without controls and checks on potential adaptations (Leveson et al., 2002)
Normal performance	The way that activities are actually performed within a system, regardless of formal rules and procedures	Behaviour is flexible enough to cope with adverse conditions	The pilot improvises a sequence of actions and identifies deficiencies to adapt to an unusual situation in landing where auto pilot malfunctions (Nouvel, et al., 2007)	Behaviours which cannot cope with the unfolding situation	The throwbag technique used for the attempted rescue in the Mangatepopo Gorge is unsuited to conditions (Salmon et al., 2012)
Coupling	An interaction between components that influences their behaviour; both tight and loose interactions	Tight: connections between components are evident Loose: recovery from disturbances in the system is possible	Tight: The use of colour coding on male and female adaptors to reduce wiring errors (Marais et al., 2004) Loose: BAC 1–11 incident: Co-pilot and flight crew regain control of plane after loss of windscreen, autopilot and radio mid-flight (Reason, 2008)	Tight: Cascading failures when one component breaks down Loose: Loss of control regulating behaviours. Too much independence. The duplication of functions leading to inefficiencies	Tight: Three Mile Island, a stuck coolant valve begins a wave of cascading failures in a nuclear power plant (Perrow, 1981)Loose: Kimberly Ultra Marathon, limited interaction between state authorities and event organisers leads to disorganisation, lack of information and confusion (Grant et al., 2015)
Non Linear interactions	Interactions are complex. Relationships between components where the outcome is not predictable	Allows for adaptations in the system	Apollo 13: adaptations achievable based on *a priori* relationships between crew, flight controllers and support personnel (Trotter et al., 2014)	Inconsequential events have large effects, and cannot predict the effect of changes	Columbia space shuttle: failure of redundant 0 ring components were not independent, but lead to unpredictable and catastrophic changes (Leveson et al., 2009)
Linear interactions	Direct cause effect relationships between components where the outcome is predictable	Actions and outcomes are predictable and dependable	Safety barriers installed to inhibit accidents used in occupational settings (such as scaffolding and machinery guards) (Jørgensen, 2016)	Interactions are predefined and fixed with no allowances for adaptations when alternatives are required	Brazilian launch vehicle: Conflicting priorities in the system are created by hierarchically structured teams managing the development of the vehicle (de Almeida and Johnson, 2008)
Modularity	The organisation of a system where sub systems and components interact but are designed and operate largely independently of each other	The system is resilient to breakdowns, replacement or substitutions of components and organisation of sub systems can be easily made	Apollo 13: escape craft unaffected by original shuttle fault providing alternative action and getaway (Trotter et al., 2014)	The system is tightly integrated and complex, substitutions cannot be made	Malware attacked Nuclear power plants and other electricity suppliers through operating systems, which were all the same. No substitutions for operating systems were available (Perrow, 2008)
Feedback Loops			Apollo 13: Feedback on system failures is received quickly allowing fast	Communication structures are not in place to provide or receive system feedback	

(*continued on next page*)

Table 5 (*continued*)

	Simplified definition	Safe system	Examples of tenet in a safe system	Unsafe system	Example of tenet in an unsafe system
	Communication structure and information flow to evaluate control requirements of hazardous processes	Feedback is received on system breakdowns allowing for the control of hazards	evaluation and control over situation (Trotter et al., 2014)		Milstar Satellite loss: no tests of load tape prior to launch, assumptions that others had done so (Leveson, 2004)
Decrementalism	Small changes in normal performance that gradually result in large changes	Complex systems need to adapt, small adaptations are required to maintain optimisation	Job rotations on naval aircraft carriers demanded constant training and system diversity (Dekker, 2011)	Constant small organisational changes create conflicts and pressure	Walkerton E coli outbreak: constant migration of work practices over 20 years increased the likelihood of unsafe behaviours (Vincente and Christoffersen, 2006)
Sensitive dependence on initial conditions	Characteristics of the original state of the system that are amplified throughout and alters the way the system operates (interconnected webs of relationships)	Mechanisms for monitoring changes are available	GPS collision avoidance warning and control systems that monitor spatial changes outside automobiles	No understanding of initial conditions and their influence on the system	Kerang Train collision: existence of rail crossings in the first place – they are inherently unsafe yet remain in the system
Unruly technologies	Unforeseen behaviours or consequences of technologies	Technology that supports adaptation through a mechanism that is beyond the scope of what is was designed for affording flexibility	The use of social media applications (e.g. Twitter/Facebook) in emergent disaster response situations to divert resources to those most in need (Bruns et al., 2012)	Technology that introduces and sustains uncertainties about how and when things may fail	Air France AF447: Unknown to the crew, frozen pitot tubes disconnect the autopilot system (Salmon et al., 2016b)
Performance variability	Systems and components change performance and behaviour to meet the conditions in the world and environment in which the system must operate	Performance varies to meet the needs of changing conditions	Aviation near miss: Pilot varies flight procedure to adapt to incorrect information received from the plane (Nouvel et al., 2007)	Performance does not change when conditions change	Stockwell shooting: organisational structure did not support information flow in a rapid-paced operation (Jenkins et al., 2010)
Contribution of the protective structure	The organised structure and system control that are intended to optimise the system, instead they do the opposite	Protective structures are effective, flexible and adaptable in maintaining controls	Apollo 13: flexible and changeable task and team structure enable changes that maintain control (Trotter et al., 2014)	Protective structure inhibits performance variability. Introduces new tasks that do not contribute to the goal. Unnecessary controls.	Greyrigg train derailment: Local track policies restricted the time available to conduct inspections (Underwood and Waterson, 2014)

Charles Perrow (1981, 2011), Sidney Dekker (2011) and Erik Hollnagel (2009, 2012, 2014), fifteen core systems thinking tenets were identified. There review exposed that indeed, the foundation for a unified model of accident causation can exist based on the presence of the systems thinking tenets across the five models reviewed. Further, the tenets afford the identification of essential characteristics related to system performance, which may provide a suitable approach for predicting system states. That is, any prediction method would have to be able to identify each of the systems thinking tenets to successfully predict accidents. A final important conclusion from the literature review was the fact that little literature was found where by the dominant models had been tested in a predictive context. Apart from Leveson's STAMP model (Leveson et al., 2015), predictive applications driven by the models reviewed were not identified in the peer-reviewed literature.

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