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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