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Review

What do applications of systems thinking accident analysis methods tell us about accident causation? A systematic review of applications between 1990 and 2018

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A R T I C L E I N F O

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FRAM

A B S T R A C T

Introduction: This systematic review examines and reports on peer reviewed studies that have applied systems thinking accident analysis methods to better understand the cause of accidents in a diverse range of sociotechnical systems contexts.
Methods: Four databases (PubMed, ScienceDirect, Scopus, Web of Science) were searched for published articles during the dates 01 January 1990 to 31 July 2018, inclusive, for original peer reviewed journal articles. Eligible studies applied AcciMap, the Human Factors Analysis and Classification System (HFACS), the Systems Theoretic Accident Model and Processes (STAMP) method, including Causal Analysis based on STAMP (CAST), and the Functional Resonance Analysis Method (FRAM). Outcomes included accidents ranging from major events to minor incidents.
Results: A total of 73 articles were included. There were 20, 43, six, and four studies in the AcciMap, HFACS, STAMP-CAST, and FRAM methods categories, respectively. The most common accident contexts were aviation, maritime, rail, public health, and mining. A greater number of contributory factors were found at the lower end of the sociotechnical systems analysed, including the equipment/technology, human/staff, and operating processes levels. A majority of studies used supplementary approaches to enhance the analytical capacity of base applications.
Conclusions: Systems thinking accident analysis methods have been popular for close to two decades and have been applied in a diverse range of sociotechnical systems contexts. A number of research-based recommendations are proposed, including the need to upgrade incident reporting systems and further explore opportunities around the development of novel accident analysis approaches.

1. Introduction

Accidents are increasingly being examined through a systems theoretic lens (Salmon et al., 2011; Waterson et al., 2015). Since the turn of the century, four systems thinking accident analysis methods have been widely used in the human factors and safety science literature: (i) AcciMap (Rasmussen, 1997; Rasmussen and Svedung, 2000); (ii) the Human Factors Analysis and Classification System (HFACS) (Shappell and Wiegmann, 2001); (iii) the Systems Theoretic Accident Model and Processes (STAMP) model and associated Causal Analysis based on STAMP (CAST) method (Leveson, 2004; Leveson et al., 2009); and, (iv) the Functional Resonance Analysis Method (FRAM) (Hollnagel, 2004, 2012). In recent times, the capability of these methods to address and resolve resilient accident-related problems has been a topic of much scholarly conversation (Leveson, 2011; Dekker and Pitzer, 2016; Salmon et al., 2017a). Arguments have centred on the impending shift in the nature of safety-critical sociotechnical systems, such as increased levels of advanced automation, artificial general intelligence and the use of robotics (e.g., Banks et al., 2018; Hancock, 2017, 2018) which together are likely to expose further theoretical and methodological flaws in contemporary accident analysis methods (Salmon et al., 2017a; Stanton and Harvey, 2017; Walker et al., 2017).

Given that applications of these state-of-the-art methods now span almost 20 years, as well as the fact that they have recently been

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criticised (Leveson, 2011; Salmon et al., 2017a), it is timely to subject this body of accident analysis research to a detailed systematic review. Aside from other comprehensive reviews published in areas such as occupational safety (Khanzode et al., 2012), or reviews that focus on a specific method (e.g., AcciMap; Waterson et al., 2017), there is a need for a systematic and thorough overview of systems thinking accident analysis applications in the broader peer reviewed literature. Such a review is required to not only gain an overview of the applications and their implications for accident prevention, but also to ascertain what they are adding to the knowledge base around accident causation and prevention more generally. Reporting on unique study features and characteristics, such as the addition of analyses or statistical techniques to supplement base applications, can provide a historical account of how systemic accident analysis research has evolved over time. Therefore, the aim of this systematic literature review is to examine and report on peer reviewed studies that have applied AcciMap, HFACS, STAMP-CAST, and FRAM to analyse and understand the cause of accidents across a diverse range of sociotechnical systems contexts.

1.1. Structure of this review

This review is structured as follows. First, an overview of the included accident analysis methods is provided. This overview, albeit brief in scope and scale, describes the main features of the methods and models reviewed. Second, a methods section outlines the electronic search terms, study eligibility criteria, as well as how information and data were extracted and synthesised. Third, the results section is divided into four methods categories according to the study groups identified, the key findings of which are presented qualitatively and quantitatively. Fourth, the discussion describes the results and methods categories, of which a number of key findings are identified and research-based suggestions proposed.

1.2. Methods overview

Based on recent discussions around the advancement of accident analysis theory and approaches (Salmon et al., 2017a), this review restricted article inclusion to reflect a core set of systems thinking methods only. Consistent with their underlying theoretical basis and original intended purpose, the aim of these methods is to identify and/or conceptualise a range of interacting contributory factors or functions from across a sociotechnical system.

1.2.1. AcciMap

An overview of the AcciMap method requires a brief introduction to Rasmussen's (1997) Risk Management Framework (RMF). The RMF is predicated on the idea that sociotechnical systems comprise various hierarchical levels (e.g., government, regulators, company, management, staff, and work), each of which contain actors, organisations, and technologies that share responsibility for production and safety. Decisions and actions occurring across levels of the system interact to shape behaviour, meaning that organisational safety and health are influenced by all elements in a system. The RMF describes the concepts of organisational migration and vertical integration. Specifically, the behaviour of a complex sociotechnical system shifts, over time, towards or away from acceptable boundaries of safety and performance depending on external pressures (e.g., financial pressures) and the nature of the communication and feedback between actors across the system hierarchy.

Based on the RMF theory, Rasmussen and Svedung (2000) outlined the AcciMap technique which is used to graphically represent the system-wide failures, decisions, and actions involved in accidents (Waterson et al., 2017) (Fig. 1). AcciMap analyses typically focus on decisions and actions across the following six organisational levels: (i) government policy and budgeting; (ii) regulatory bodies and associations; (iii) local area government planning and budgeting (including company management); (iv) technical and operational management; (v) physical processes and actor activities; and, (vi) equipment and surroundings. The output is a map of contributory factors and their interrelationships across the system. AcciMap is a generic approach that does not use a taxonomy of failure modes and has since been applied in a diverse range of safety-critical domains.

1.2.2. HFACS

HFACS was developed based on Reason's (1990) theory of latent and active failures (i.e., the so-called Swiss cheese model). Latent failures include factors such as deficient organisational management practices, inadequate or missing resources, supervisory violations, poor equipment design, and insufficient staff training protocols and procedures. Conversely, active failures include unsafe acts that occur closer to the moment at which an accident happened. Reason's (1990) model is theoretical in nature, and at the height of its popularity, lacked a taxonomy to classify contributory factors. In response to this, Shappell and Wiegmann (2001) formalised an aviation specific method incorporating categories of failure modes across four levels: (i) unsafe acts; (ii) preconditions for unsafe acts; (iii) unsafe supervision; and, (iv) organisational influences. Each of the four levels contain at least three independent categories of contributory factors, with a total of 17 original categories that were later extended to 19 via the addition of environmental factors (Li and Harris, 2006) (Fig. 2). When applying HFACS, analysts classify the human (active) errors and the related latent failures across levels of the work system.

1.2.3. STAMP-CAST

The STAMP model (Leveson, 2004; Leveson et al., 2009) takes the view that accidents result from the inadequate control or enforcement of safety-related constraints – when disturbances, failures, and/or dysfunctional interactions between components are not handled by existing control mechanisms. STAMP considers safety as a control issue that is managed through a control structure, with the primary goal of enforcing constraints on the actors, organisations, and technologies across the sociotechnical system (Fig. 3). Various forms of control are considered, including managerial, organisational, operational, manufacturing-based, and even social controls (Leveson et al., 2009). That is, overall system behaviour is dictated not only by appropriately designed and engineered systems, but also by policies, procedures, shared values, and other aspects of the surrounding organisational culture. Similar to AcciMap, STAMP adopts a broad, holistic view of the entire system and includes a congress and legislatures, as well as government level.

The STAMP model has associated risk and hazard assessment (Systems Theoretic Process Analysis: STPA) and accident analysis (i.e., CAST) methods. When used for accident analysis purposes, applying CAST involves developing a control structure model of the system under analysis, and then using the associated taxonomy to identify control and feedback failures that played a role the accident. Leveson's (2004) classification taxonomy of control flaws includes failures related to: (i) the inadequate enforcement of safety constraints (control actions); (ii) the inadequate execution of control actions; and, (iii) inadequate or missing feedback. CAST analyses can include 'context', 'mental model flaws', and 'coordination' as classification taxonomy categories in order to cater to the human element since the method originated in the engineering domain (Leveson, 2004).

1.2.4. FRAM

FRAM (Hollnagel, 2004, 2012) provides the means to develop an overall understanding of how a complex sociotechnical system operates. FRAM is able to facilitate a risk and hazard analysis by describing the relationships among factors according to their functional dependencies (Hollnagel, 2012). The method is unique in the sense that work organisations are not conceptualised as having multiple system levels as is the case when modelling human and non-human interactions across an abstraction hierarchy. Consequently, FRAM is focussed

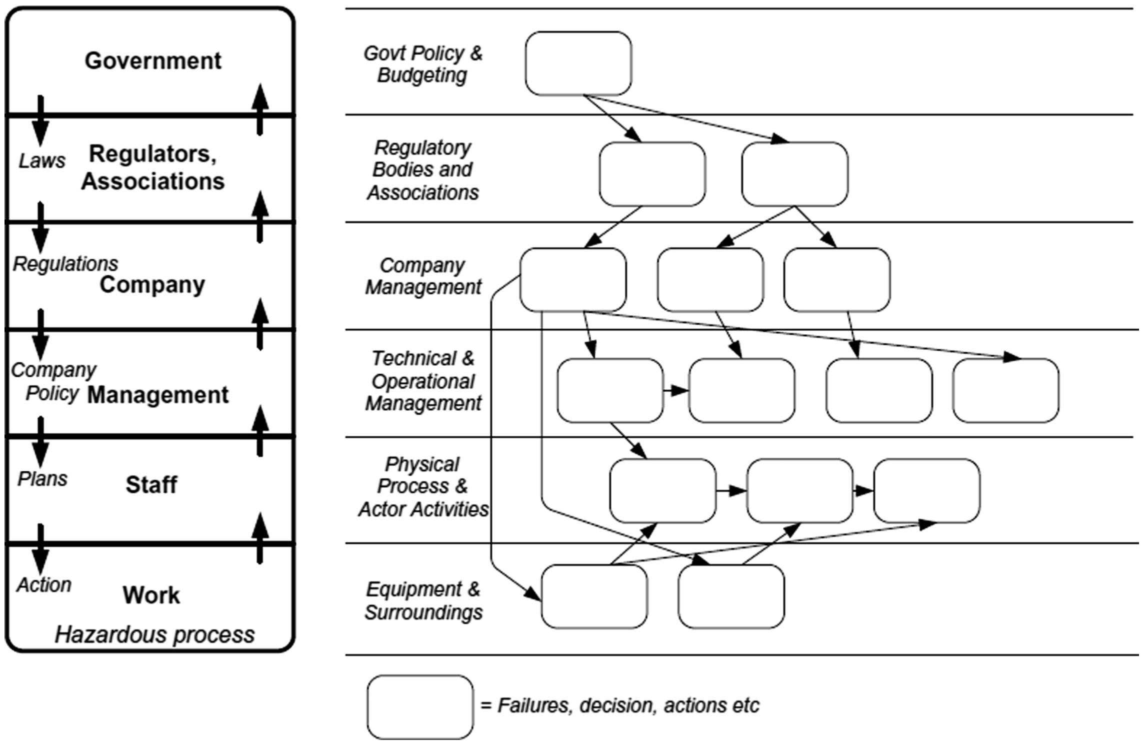

Fig. 1. Rasmussen's (1997) RMF and the associated Accimap technique (Rasmussen and Svedung, 2000).

on understanding how combinations of everyday normal performance variability may lead to unexpected (and usually unwanted) outcomes, rather than to trace the propagation of a failure or malfunction (Hollnagel, 2016).

The first step of a FRAM analysis is to identify system functions, whether human, technological, organisational, or otherwise. Each function is described from the perspective of six FRAM aspects: (i) the *input* that a function uses or transforms; (ii) the *output* that that a

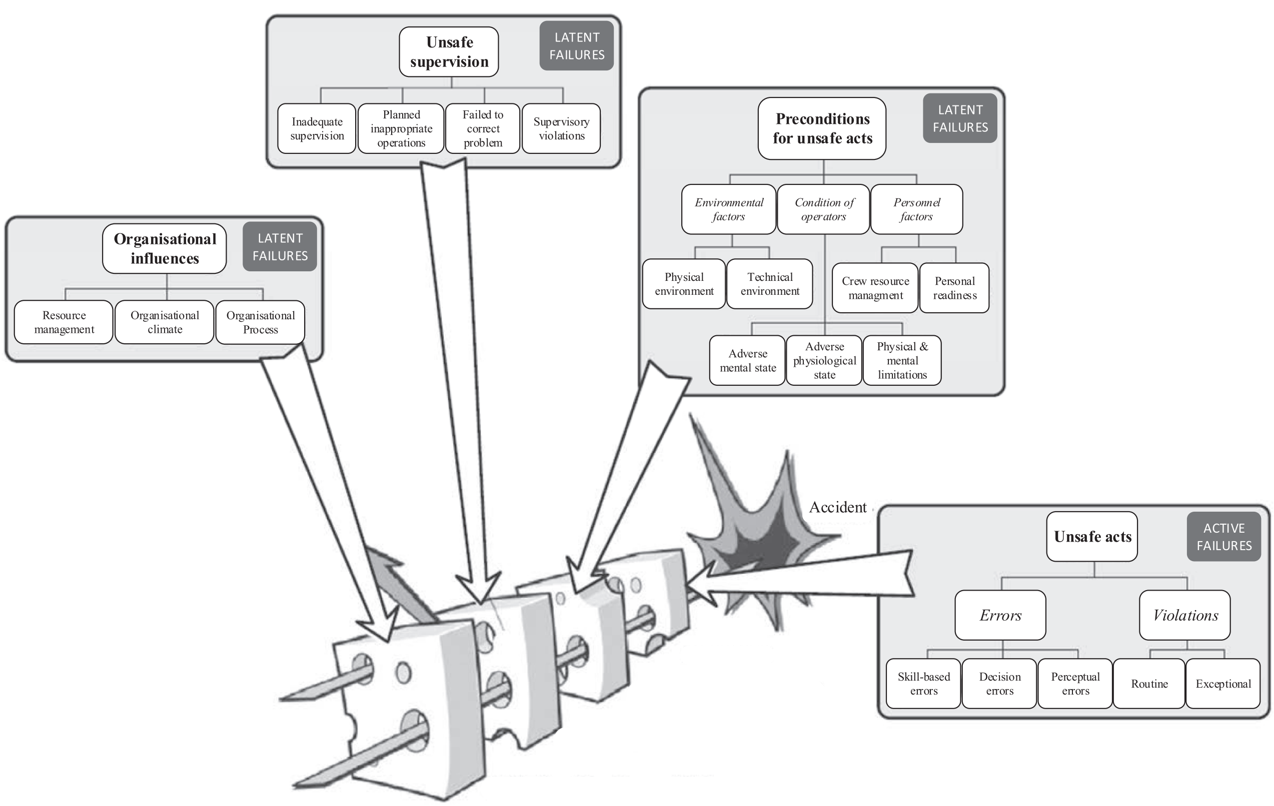

Fig. 2. HFACS taxonomies overlaid on the Swiss Cheese model.
adapted from Salmon et al., 2012

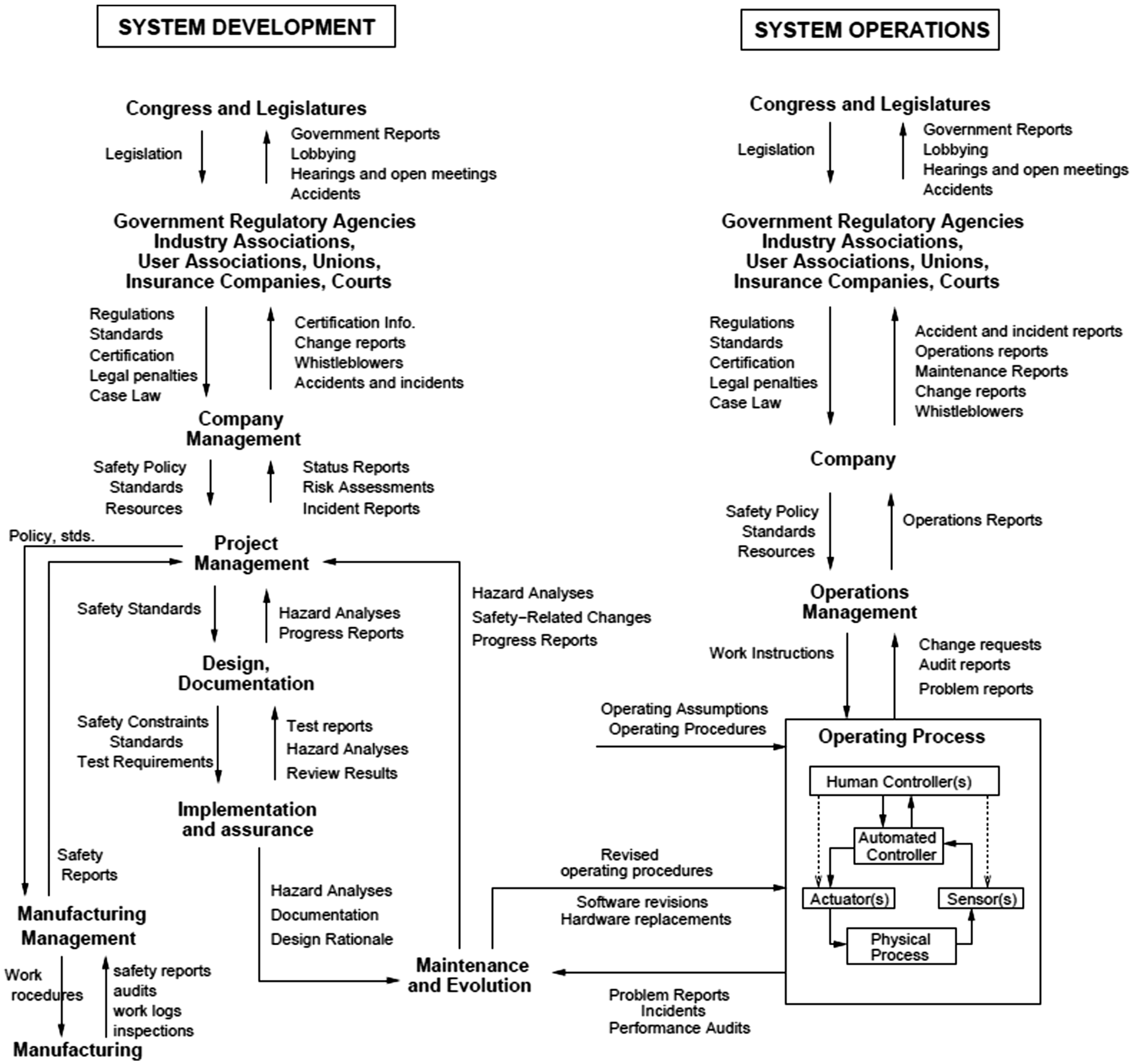

Fig. 3. Leveson's (2004) and Leveson et al. (2009) STAMP control structure model.

function produces; (iii) a function's *preconditions* that must be fulfilled to perform its function; (iv) the *resources* that a function needs or consumes; (v) a function's *time* that affects time availability; and, (vi) the *control* required to supervise or adjust a function's behaviour (Hollnagel et al., 2008). The second step involves characterising the context-dependent observed and potential variability of the identified system functions (Hollnagel et al., 2008). Step three involves linking the different functions from step one, whilst considering the identified factors and circumstances in step two, to produce a FRAM diagram depicting aggregate variability (Fig. 4). When the links among functions are modelled using the FRAM Model Visualiser (FMV; http://functionalresonance.com/), it is possible to specify where the variability in a system has occurred, as well as how this variability contributed to an accident. Accordingly, FRAM gets its name from the propagation of variability through a system which can result in what has been termed *functional resonance* – or the point at which an expected level of 'noise' oscillates and becomes a 'signal' representing a non-specific accident cause (Hollnagel, 2012). The fourth and final step is to examine the variability depicted across the FRAM model (i.e., variability is visualised across the six FRAM aspects, as well as the links between aspects) to identify solutions to maintain work operations within an acceptable boundary of safety and performance. The idea of this step is to propose new ways of monitoring and/or dampening unwanted performance variability (Hollnagel, 2016). Further information about how to conduct a FRAM analysis can be found elsewhere (Hollnagel, 2012).

2. Methods

2.1. Electronic search

Four databases (PubMed, ScienceDirect, Scopus, Web of Science) were searched by the first author for published journal articles during the dates 01 January 1990 to 31 July 2018, inclusive. Citation software (EndNote for Windows 6.0.1) facilitated the searching process. Limiters were applied when searching databases. The search aimed to retrieve

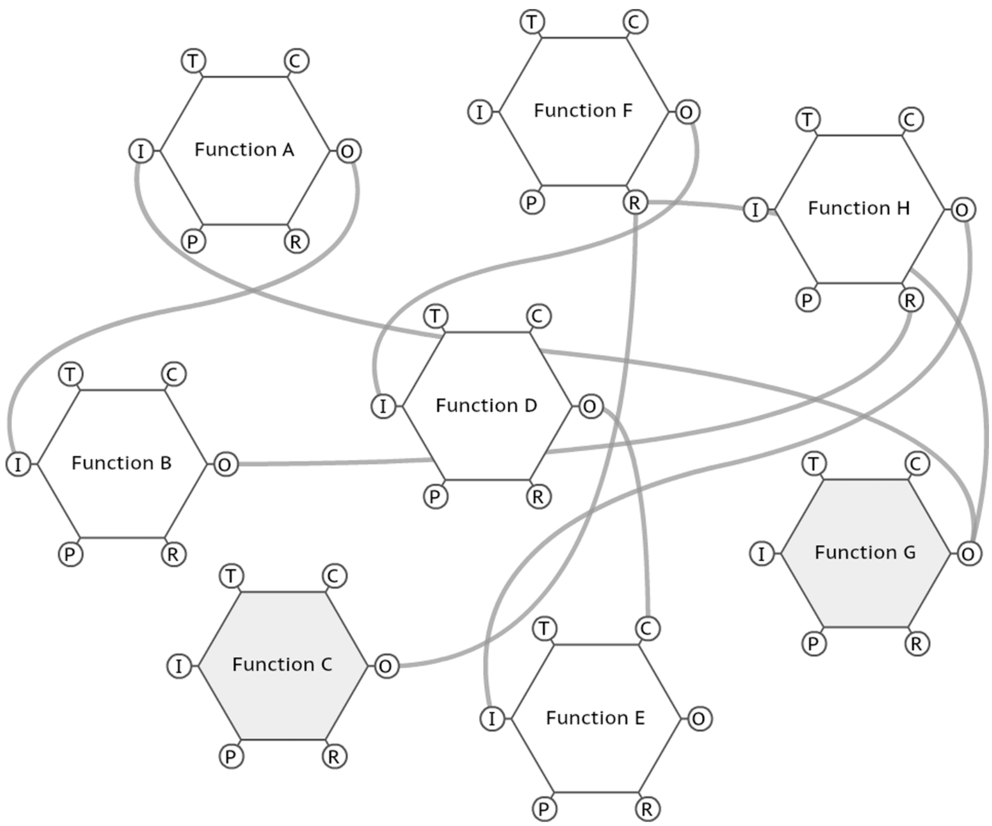

Fig. 4. Generic example of a FRAM model (Hollnagel, 2004, 2012). The hexagonal shapes represent individual functions that contain the six FRAM aspects, indicated by I (input), O (output), P (precondition), R (resource), T (time), and C (control). Systems exhibiting high variability and resonance can be modelled using the FRAM Model Visualiser (FMV; http://functionalresonance.com/). The FMV is a computer-based tool that can assist analysts to develop models and conceptualise where in the system performance variability has occurred.

Table 1
Key words and applied limits associated with each of the four databases.

Database	Search terms and applied filters
PubMed	Search (((((“human factors analysis and classification system”)) OR “rasmussen’s risk management framework”) OR AcciMap) OR (“systems theoretic accident model and processes”)) OR “functional resonance analysis method” Filters: Publication date from 1990/01/01 to 2018/07/31; English
Scopus	TITLE-ABS-KEY (“human factors analysis and classification system” OR “rasmussen's risk management framework” OR AcciMap OR “systems theoretic accident model and processes” OR “functional resonance analysis method”) AND DOCTYPE (ar) AND PUBYEAR > 1989 AND (LIMIT-TO (LANGUAGE, “English”))
ScienceDirect	“human factors analysis and classification system” OR “rasmussen’s risk management framework” OR AcciMap OR “systems theoretic accident model and processes” OR “functional resonance analysis method”
Web of Science	TOPIC: (“human factors analysis and classification system”) OR TOPIC: (“rasmussens risk management framework”) OR TOPIC: (AcciMap) OR TOPIC: (“systems theoretic accident model and processes”) OR TOPIC: (“functional resonance analysis method”) Refined by: DOCUMENT TYPES: (ARTICLE) AND LANGUAGES:(ENGLISH) Timespan: 1990–2018. Indexes: SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI, CCR-EXPANDED, IC.

articles from 1990 onwards as this predates the development of the methods to be included (see Section 2.2.1). Database limits were imposed on both the published language and document type to maintain a manageable and highly relevant search strategy (e.g., the search in the Scopus and Web of Science database was restricted to include peer reviewed journal articles only). The complete search strategy including key terms, can be viewed in Table 1.

2.2. *Eligibility criteria*

2.2.1. *Inclusion criteria*

To be eligible for inclusion, studies were required to comply with the following criteria:

i. Analyses involved an application of AcciMap, HFACS, STAMP-CAST, and FRAM. Domain-specific adaptations to the original terminology and/or taxonomy were permitted (e.g., HFACS-RR is a modified version of HFACS for railroad accidents (Reinach and Viale, 2006)).
ii. Analyses aimed to understand the cause of accidents (singular events or aggregated datasets) from a systems thinking perspective (i.e., systemic contributory and proximal causal factors could reside across the work system).
iii. Outcomes included documented accidents ranging from major events (e.g., large-scale nuclear disasters impacting on global economies, environments, populations) to relatively minor incidents and anomalies (e.g., component failures, exposure to hazardous substances, personal injury).
iv. Information sources were original peer reviewed journal articles published in English.

2.2.2. *Exclusion criteria*

Studies were excluded if they complied with the following criteria:

i. The use of traditional error and hazard analyses (e.g., fault tree inspired analyses, human error identification and human reliability analysis techniques), teamwork and performance assessment methods that have been used in an accident analysis capacity (e.g., Event Analysis of Systemic Teamwork (EAST)), Distributed Situation Awareness (DSA), and communications analyses.

ii. Analyses describing work-as-done as a basis to identify organisational or systemic frailties with the end goal of recommending redesign and/or new engineering resilience activities (i.e., the absence of a documented accident).
iii. The theoretical and/or analytical enhancement of another accident analysis method via the integration of certain aspects associated with AcciMap, HFACS, STAMP-CAST, and FRAM. Doing so fundamentally changed the use of methods resulting in a hybridised approach (i.e., an approach that does not involve a complete application of the method for accident analysis purposes).
iv. Books, conference or symposium presentations or papers, systematic and narrative reviews of the literature, industry reports, and articles published in a language other than English.

Following the initial search, the first author inspected the titles and abstracts of all retrieved articles against the inclusion criteria. For the remaining potentially eligible articles, two authors (AH and PS) independently conducted the screening of abstracts and, in cases of insufficient detail, the full-texts. Eligibility disagreements were resolved during discussions involving two authors (AH, PS).

2.3. Data extraction

Eligible studies were grouped into one of four methods categories: (i) AcciMap; (ii) HFACS; (iii) STAMP-CAST; and, (iv) FRAM. Extracted study information differed according to the method used, however the following categories provide a general overview of the information that was obtained: (i) study/date; (ii) accident context; (iii) data sources/year; (iv) the version of the method (e.g., HFACS-RR; AcciMap with five levels); (v) outcome/severity (i.e., accident details, injuries and fatalities); (vi) accident/error/category frequency; (viii) relationships among factors; and, (ix) unique features of the methods applied, including the use of additional theories, methods, analyses, and statistical techniques.

2.4. Data organisation and interpretation

This section describes how study data and information were synthesised so that conclusions about methods applications could be formulated.

2.4.1. AcciMap

Information and data were summarised qualitatively (Table 2) and quantitatively. A quantitative synthesis of the mean (Fig. 6) and total number of contributory factors identified (Fig. 7) (i.e., errors and failures across the AcciMap model) was performed. Information regarding the modelling of relationships among AcciMap factors was extracted regarding whether links were qualitative or quantitatively described.

2.4.2. HFACS

A qualitative HFACS study synthesis is provided (Table 3). The non-weighted and weighted mean proportion of a given HFACS category was computed (Figs. 8 and 9). Calculating a weighted mean proportion (Eq. (1)) and weighted standard deviation (Eq. (2)) was performed as the number of accidents varied across studies. Studies providing information about the frequency of the presence of each HFACS category, as well as the number of accidents analysed, were eligible for a quantitative synthesis:

$$\bar{x}_w = \sum_{i=1}^{n} \frac{(x_i * w_i)}{\sum_{i=1}^{n} w_i} \tag{1}$$

$$s_w = \sqrt{n \sum_{i=0}^{n} \frac{w_i (x_i - \bar{x}_w)^2}{\sum_{i=0}^{n} w_i}} \tag{2}$$

where x is the frequency of a HFACS category for a given study (calculated manually where necessary), and w is the weighted factor based on the total number of accidents. The relative quality of the data, as well as the nature and severity of accidents, were treated as equal given that the purpose was only to understand where classification efforts have been concentrated on HFACS. For this review, there were 18 HFACS categories across four levels (i.e., unsafe acts, preconditions for unsafe acts, unsafe supervision, organisational influences). The violations category under the unsafe acts level was not divided into its constituent ‘routine’ and ‘exceptional’ behaviours as studies do not always report this distinction (Fig. 2).

2.4.3. STAMP-CAST

A written synthesis elaborating on extracted data and information from each study is provided to supplement tabulated information (Table 5). A quantitative summary of the number of control structure levels and controllers (e.g., equipment, physical components, technologies, environments, weather conditions, people, organisations) is provided (Fig. 10) in addition to the number of control flaws from Leveson’s (2004) classification taxonomy (Table 6).

2.4.4. FRAM

A written synthesis is provided to supplement tabulated information (Table 7). This general summary focusses on the identification of FRAM functions, and describes in further detail, any unique features of the investigations.

3. Results

3.1. Full-text selection

After searching four databases, a total of 690 articles were identified. After removing 197 duplicates and examining 493 titles and abstracts, 104 potentially eligible articles were retained. The decision to exclude 389 articles was based on: (i) method eligibility (n = 269); (ii) whether or not the analysis aimed to better understand accident causation from a sociotechnical systems perspective (i.e., n = 114 studies applied methods in an attempt to optimise sociotechnical systems from a design and/or engineering resilience standpoint); and, (iii) relatively few articles (n = 6) were reviews of the accident analysis literature. Articles not identified through the systematic searching process were later added according to the authors’ knowledge of the peer reviewed literature (n = 5). Closer examination of 109 full texts led to the exclusion of a further 36 articles. The reasons for exclusion at this later stage can be viewed in Fig. 5. Overall, this process resulted in a total of 73 articles for inclusion.

3.2. Overview of AcciMap studies

A total of 20 AcciMap studies were included (Table 2). There were five studies published between the years 2000 and 2009, and 15 studies published between the years 2010 and 31 July 2018, inclusive. Six studies were undertaken in the public health context, five of which aimed to identify the factors underpinning food contamination and infectious disease outbreaks (Woo and Vicente, 2003; Vicente and Christoffersen, 2006; Cassano-Piche et al., 2009; Waterson, 2009; Nayak and Waterson, 2016). The other public health study applied a systems analysis to investigate the cause of a firearms-related fatality involving a case of mistaken identity during police anti-terrorism activities (Jenkins et al., 2010).

There were four studies in the transport context, including commuter and high-speed rail (Salmon et al., 2013; Underwood and Waterson, 2014), freight road safety (Newnam and Goode, 2015), and off-road beach driving (Stevens and Salmon, 2016). There were four studies in the led outdoor recreation domain (Salmon et al., 2010; 2012, 2014a; 2017b), two of which examined the contributory factors underpinning student group fatalities (Salmon et al., 2010; 2012). The remaining contexts were maritime (Akyuz, 2015; Kee et al., 2017; Lee

Table 2
Overview of extracted information associated with 20 AcciMap studies ordered by ascending publication date. The column titled 'levels' refers to the number of AcciMap levels used. The column titled 'factors' indicates the total number of causal/contributory factors identified, including the specific number of factors on each level from the upper to the lower system. 'Relationships' indicates whether interactions among factors were modelled, and if so, the general approach undertaken. 'Unique features' includes modifications to the AcciMap. Hyphenated fields indicate that information was not provided or relevant.

Study	Context	Source/data	Levels	Outcome/severity	Accidents	Factors	Relationships	Unique features
Woo and Vicente (2003)	Public health; Battleford, Saskatchewan, Canada	Inquiry report containing mixed methods; 2002	6	Drinking water contamination; ~6500 affected/sick	1	56 (3, 13, 9, 9, 10, 11)	Qualitative	Integration of logic gates in AcciMap
Vicente (2006)	Public health; Walkerton, Ontario, Canada	Formal commission inquiry report; 2002	6	Drinking water contamination; ~2300 affected/sick; 7 fatalities	1	32 (4, 7, 4, 3, 11, 4)	Qualitative	Integration of logic gates & decision trees in AcciMap
Johnson and de Almeida (2008)	Aerospace; Brazil	Official Servico Publico accident report; 2006	6	Space vehicle explosion; 21 fatalities & damage	1	33 (6, 2, 5, 9, 9, 2)	Qualitative	No distinction made between direct & indirect causes
Cassano-Piche et al. (2009)	Public health; UK	BSE inquiry report & EEA report; 2000–2001	6	Food supply chain contamination (BSE); sickness & fatalities	1	46 (6, 17, 5, 3, 9, 6)	Qualitative	Addition of critical event in the AcciMap
Waterson (2009)*	Public health; Maidstone & Tunbridge Wells, UK	NHS healthcare commissioners report; 2007	6	Hospital outbreak of *Clostridium difficile*; sickness & 90 fatalities	1	7 (not level specific)	No	Use of RMF rather than standard AcciMap
Jenkins et al. (2010)	Public health; Stockwell, London, UK	IPCC investigation report; 2007	6	Firearm (shooting), mistaken identity; single fatality	1	44 (2, 7, 7, 8, 12, 8)	Qualitative	AcciMap factors coded by time; strength of causal links
Salmon et al. (2010)	Led outdoor recreation; Lyme Bay, Dorset, UK	DCC official inquiry report; 1993	6	Students canoeing, separation at sea, capsize; 4 fatalities	1	42 (1, 2, 8, 14, 14, 3)	Qualitative	–
(Salmon et al. (2012)	Led outdoor recreation; New Zealand	Official organisation report; 2009	6	Mangatepopo tragedy, student group drownings; 7 fatalities	1	61 (1, 3, 13, 12, 18, 14)	Qualitative	No distinction made between direct & indirect causes
Salmon et al. (2013)	Transport (rail); Victoria, Australia	OCI rail safety investigation report, V/line trains; 2007	6	RLC collision, passenger train & semi-tuck; 23 injuries, 11 fatalities	1	36 (2, 9, 3, 2, 11, 9)	Qualitative	–
Salmon et al. (2014a)	Led outdoor recreation; New Zealand	OER NID; 2007 to 2011	6	Near-miss incidents; errors; injuries, illnesses & fatalities	1014	38 (2, 7, 6, 8, 7, 8)	No	Aggregation indicated in parentheses
Salmon et al. (2014b)	Emergency response; Victoria, Australia	VRBC report; 2010	6	Black Saturday bushfires; 73 injuries & 40 fatalities	1	71 (12, 2, 8, 12, 14, 23)	Qualitative	–
Underwood and Waterson (2014)	Transport (rail); Cumbria, UK	RAIB investigation report; 2011	6	Grayrigg train derailment; damage, 30 injuries, single fatality	1	56 (0, 1, 15, 7, 31, 2)	Qualitative	Colour coding applied to AcciMap factors
Akyuz (2015)	Maritime	MAIB official investigation report; 2014	6	Bulk carrier ship grounding	1	31 (3, 4, 8, 6, 6, 4)	Qualitative	ANP integrated into AcciMap to analytically weight factors
Fan et al. (2015)	Civil engineering; Harbin City, China	Varied data sources, e.g., official report, media; ~2012	6	Bridge collapse; structural damages, 5 injuries & 3 fatalities	1	19 (3, 2, 3, 4, 2, 4)	Qualitative	–
Newnam and Goode (2015)	Transport (road); USA	NTSB investigation reports' 1996–2013	6	Heavy road freight vehicle crashes; injuries & fatalities	27	62 (6, 4, 3, 13, 21, 15)	Quantitative	Aggregate AcciMap indicating report numbers for each factor
Nayak and Waterson (2016)*,†	Public health; South Wales, UK	Official investigative report; 2009	5	Food supply chain contamination *e coli*; sickness & fatalities	1	34 (hierarchy structure changed)	Qualitative	Factors coded as precondition, (in) direct or complex
Stevens and Salmon (2016)†	Transport (off-road); Fraser Coast, Australia	Queensland state coroner inquest report; 2010	6	Off-road vehicle rollover; 7 injuries, single fatality	1	20 (0, 0, 1, 3, 10, 6)	Qualitative	–
Kee et al. (2017)*,‡	Maritime; South Korea	Official BAI Korea report, media sources; 2014	5	Sewol passenger ferry capsize; injuries & 304 fatalities	1	29 (factors spread over 5 levels)	Qualitative	AcciMap levels modified & factors thematically 'grouped'
Lee et al. (2017)*	Maritime; South Korea	KMST official report, media	5	Sewol passenger ferry capsize; injuries & 304 fatalities	1	28 (factors spread over 5 levels)	Qualitative	AcciMap levels modified to include an 'outcome' level
Salmon et al. (2017b)	Led outdoor recreation; Australia	UPLOADS data from 43 organisations over 3 months	6	Near-miss incidents; errors; injuries, illnesses & fatalities	226	56 (0, 1, 9, 6, 30, 10)	Quantitative	RMF theory translated into a practical online data system

* Indicates the four studies excluded from Fig. 6 (further information can be found in Section 3.3).
† Indicates that data were extracted only for the second of two accidents.
‡ Indicates that data were extracted only for the first of two AcciMaps given that the second model was concerned with the post-incident recovery effort only; **ANP**, Analytical Network Process; **BAI**, Board of Audit & Inspection; **BSE**, Bovine Spongiform Encephalopathy; **CDM**, Critical Decision Method; **DCC**, Devon County Council; **EEA**, European Environmental Agency; **HTA**, Hierarchical Task Analysis; **IPCC**, Independent Police Complaints Commission; **KMST**, Korea Maritime Safety Tribunal; **KSC**, Kennedy Space Centre; **MAIB**, Maritime Accident Investigation Branch; **NASA**, National Aeronautics and Space Administration; **NHS**, National Health Service; **NTSB**, National Transportation Safety Board; **OCI**, Official Commissioners Inquiry; **OER NID**, Outdoor Education Recreation National Incident Database; **RAIB**, Rail Accident Investigation Branch; **RLC**, Rail Level Crossing; **SMS**, Sociometric Status; **UK**, United Kingdom; **UPLOADS**, Understanding & Preventing Led Outdoor Accidents Data System; **USA**, United States of America; **VRBC**, Victorian Royal Bushfires Commission.

Table 3
Overview of extracted information associated with 43 HFACS studies ordered by ascending publication date. The column titled 'version' refers to the specific HFACS framework used, including the number of levels and categories. 'Errors' indicates the total number of causal/contributory factors identified, whereas 'categories' refers to the cumulative total HFACS levels/categories/causal codes for a given study. The column titled 'relationships' refers to whether or not a given study modelled the interactions across errors and/or HFACS categories, and if so, specifies the approaches and techniques to do so. Hyphenated fields indicate that information was not provided or relevant.

Study	Context	Source/data	Version	Outcome/severity	Accidents	Errors	Categories	Relationships
Wiegmann and Shappell (2001)[*,†,‡]	Aviation (civil); USA	NTSB & FAA database records; 1990 to 1996	HFACS; 4 levels, 17 categories	Varied incidents & severity	119	319	245	–
Gaur (2005)[*,†,‡]	Aviation (civil); India	DGCA summary reports; 1990 to 1999	HFACS; 4 levels, 17 categories	Varied incidents & severity	48	153	329	–
Dambier and Hinkelbein (2006)[†]	Aviation (civil); Germany & international	Jan to Dec 2004; BFU internet reports	HFACS; 4 levels, 17 categories	Varied incidents & severity	239	581	–	–
Li and Harris (2006)[*‡]	Aviation (military); China	ASU narratives; ROC air force; 1978 to 2002	HFACS; 4 levels, 18 categories	Varied incidents & severity	523	–	1762	χ^2, λ
Reinach and Viale (2006)[†]	Transport (rail); USA & Canada	FRA RCL operations, interviews & reports; 2004	HFACS-RR; 5 levels, 23 categories	Railroad yard collisions, derailments; injuries	6	36	–	–
Tvaryanas et al. (2006)	Aviation (military); USA	RPA mishap database & records; 1994 to 2003	HFACS; 4 levels, 17 categories	Varied incidents	221	–	–	χ^2, Cramer's V, logistic regression
Shappell et al. (2007)[*,‡]	Aviation (civil); USA	NTSB & FAAs NASDAC databases; 1990 to 2002	HFACS; 4 levels, 19 categories	Varied incidents & severity	1020		2210	–
Baysari et al. (2008)[*,†,‡]	Transport (rail); Australia	ATSB, OTSI, Victorian DOI & QT reports;1998 to 2006	HFACS; 4 levels, 19 categories	Collision, derailment, shunting, irregularity	23	215	164	–
Gibb and Olson (2008)	Aviation (military); USA	Air force SID reports & summaries; 1992 to 2005	HFACS; 4 levels, 19 categories	CFIT, mid-air collision, LoC, taxi, take-off, landing	124	–	–	–
Lenne et al. (2008)[*,‡]	Aviation (general); Australia	278 insurance claims; 2002 to 2004	HFACS; 4 levels, 18 categories	Varied incidents, e.g., take-off, landing, wire strike, collisions	169	–	414	χ2, Fisher's exact test, logistic regression
Li et al. (2008)[*,‡]	Aviation (civil); China	ROC ASC reports; 1999 to 2006	HFACS; 4 levels, 18 categories	Varied incidents & severity	41	–	330	χ^2, λ, visual causal modelling
Tvaryanas and Thompson (2008)	Aviation (military); USA	AFSC RPA mishap database reports; 1996 to 2005	–	Varied incidents	48	–	–	PCA, probability modelling
Baysari et al. (2009)[*,†,‡]	Transport (rail); Australia	ATSB, OTSI, Victorian DOI & QT reports; 1998 to 2006	HFACS; 4 levels, 19 categories	Varied incidents, e.g., collisions	19	162	119	–
Celik (2009)	Maritime; Australia	ATSB report; 2007	HFACS; 4 levels, 19 categories	Boiler explosion onboard shipping vessel	1	–	–	FAHP, priority weights indicate factor clustering
Patterson and Shappell (2010)[*,‡]	Mining; Australia	DME reports; 2004 to 2008	HFACS-MI; 5 levels, 20 categories	Varied incidents & severity	508	–	2686	–
Wang et al. (2011)[†]	Maritime; UK	MAIB reports	HFACS; 4 levels	Hazardous vapour release, shipping industry; injury, toxic inhalation	2	24	–	BN, CPT, FAHP
Hale et al. (2012)[†]	Construction; UK	HSEs database, interviews; 2006 to 2008	HFACS modified; 3 levels, multiple 4th order categories	Varied incidents, e.g., FFH, vehicle & object impact, electrocution; fatalities	26	44	–	–
Lenne et al. (2012)[*,†,‡]	Mining; Australia	Company ICAM, mixed data sources; 2007 to 2008	HFACS; 4 levels, 17 categories	Varied incidents & severity	263	2868	1323	Fisher exact test
Chauvin et al. (2013)[*,‡]	Maritime; Canada & UK	TSB & MAIB reports; 1998 to 2012	HFACS-Coll; 5 levels, 22 categories	Shipping/fishing vessel collision	27	–	230	χ^2, MCA, HC, CTA
Chen et al. (2013)[†]	Maritime; Belgium	DOT report via MAIB	HFACS-MA; 5 levels (SHEL integrated), 21 categories	Zeebrugge passenger ferry capsize; 193 fatalities	1	23	–	WBA, visual causal modelling
Hooper and O'Hare (2013)[*,‡]	Aviation (military); Australia	ICAO database; incident accounts; 2001 to 2008	HFACS; 4 levels, 19 categories	Non-grounded incidents; damage &/or injury	288	–	787	χ^2, λ, logistic regression
Li and Harris (2013)[*,‡]	Aviation (military); China	See Li & Harris (2006)	HFACS; 4 levels, 18 categories	Varied incidents & severity	523	–	1762	–
Wang et al. (2013)[†]	Maritime; Cherbourg peninsula	MAIB report; 2010	HFACS; 4 levels	Shipping/fishing vessel collision	1	15	–	BN, CPT, FAHP
Akhtar and Utne (2014)[†]	Maritime; Norway, Sweden, Canada, UK, Australia	AIBN, SHK, TSB, MAIB, ATSB; 1997 to 2012	–	Shipping vessel groundings	93	63	–	BN, CPT
Akyuz and Celik (2014)[†]	Maritime; UK	MAIB report; 2012	HFACS-CM; 4 levels	Personnel overboard; injuries	1	40	–	CM matrix, GCV, NCV
Batalden and Sydnes (2014)[†]	Maritime; UK	MAIB reports; 2002 to 2010	HFACS modified; 4 levels, 28 categories	Varied incidents & severity, shipping industry, e.g., collisions, explosions	94	478	–	–
Daramola (2014)[*]	Aviation (civil & military); Nigeria	AIB (of the NCAA) & ASN databases; 1985 to 2010	HFACS; 4 levels, 18 categories	Varied incidents & severity	42	–	–	χ^2

(continued on next page)

Table 3 (*continued*)

Study	Context	Source/data	Version	Outcome/severity	Accidents	Errors	Categories	Relationships
Gong et al. (2014)	Aviation	NTSB; 2007 & 2009	HFACS; 4 levels, 19 categories	RPA crashes	2	–	–	Qualitative, AcciTree, visual causal modelling
Kim et al. (2014)[*,†,‡]	Nuclear; Korea	NSIC reports; 2000 to 2011	HFACS modified; 4 levels, 13 categories (failure' subcategory)	NPP Reactor trip events	38	317	55	χ^2
Yunxiao and Yangke (2014)[*,‡]	Mining; China	Work safety web of Chinese coal mines; reports & forms; 2007 to 2012	HFACS; 4 levels, 19	Coal industry; 'high potential incidents' & fatalities	107	–	319	–
Madigan et al. (2016)[*,†,‡]	Transport (rail); UK	7 TOCs; reports from 2012 to 2014	HFACS; 4 levels, 19 categories	Minor incidents, e.g., signals passed at danger, stop failure	74	228	219	χ^2, ASR
Wong et al. (2016)[*]	Construction; China	Audio transcripts, inquest summaries, expert reports; 1999 to 2011	HFACS modified: 4 levels, 20 categories	FFH; fatalities	52	–	–	Fisher exact test, LCA
Akyuz (2017)[†]	Maritime	MAIB report	HFACS; 4 levels, 19 categories	Liquified propane leak onboard shipping vessel; injury	1	20	–	ANP
Al-Wardi (2017)[*,‡]	Aviation (civil & military); Oman, Taiwan, USA	Reports; 1980 to 2002	HFACS; 4 levels, 18 categories	Varied incidents & severity	40	–	129	–
Fu et al. (2017)	Mining; China	SAWS	HFACS; 4 levels, 19 categories	Coal & gas outburst; 10 fatalities	1	–	–	–
Theophilus et al. (2017)[*,‡]	Industrial (oil & gas); USA	US CSB reports; 1998 to 2012	HFACS-OGI; 5 levels, 25 categories	Offshore/onshore oil & gas facilities; total loss/repairs, fatalities	11	–	54	χ2, Fisher exact test, Spearman's correlation
Verma and Chaudhari (2017)[*,‡]	Mining; India	Data reports, summary sheets, narratives; 1985 to 2015	HFACS modified; 5 levels, 20 categories	Varied incidents & severity	102	–	276	Fuzzy reasoning
Yıldırım et al. (2017)[†]	Maritime	MAIB & ATSB reports; 1991 to 2014	HFACS-MA; 5 levels, 24 categories	68 collisions & 189 groundings	257	1310	–	χ^2, correspondence analysis
Yoon et al. (2017)	Nuclear; Korea	KINS database, interviews; 2014	HFACS; 4 levels, 19 categories	Reactor trip event	1	–	–	–
Zhan et al. (2017)[†]	Transport (rail); China	SAWS report; 2011	HFACS-RA; 4 levels, 20 categories	High-speed train collision; 172 injuries, 40 fatalities	1	22	–	F-DEMATEL, ANP, supermatrix
Zhou and Lei (2017)[*,‡]	Transport (rail); China	MRSSD, BRB & SAWS reports; 2003 to 2014	HFACS; 4 levels, 16 categories	Varied incidents, e.g., derailment, breakdowns, overhead contact, fire hazards	407	–	2281	χ^2, λ
Mirzaei Aliabadi et al. (2018)	Mining; Iran	Organisation data, 5 sites; 2001 to 2015	–	Varied incidents & severity	295	–	–	BN, CPT
Zhang et al. (2018)	Mining; China	4 organisational reports; 1997 to 2011 (e.g., SAWS)	HFACS modified; 5 levels, 14 categories	"Extraordinary" accidents, gas, fire, flood blasting, collapse etc; varied severity	94	–	–	Fisher exact test, visual causal modelling

* Indicates the 22 studies eligible for a quantitative HFACS categorisation summary as visualised in Figs. 8 and 9 (further information can be found in Section 3.5).

† Indicates the 19 studies included in Table 4.

‡ Indicates the 20 studies included in Table 4; χ^2, Chi-squared; λ, Goodman & Kruskal's lambda; **AFSC**, Air Force Safety Centre; **AIB**, Accident Investigation Bureau; **AIBN**, Accident Investigation Board Norway; **ANP**, Analytical Network Process; **ASC**, Aviation Safety Council; **ASN**; Aviation Safety Network; **ASR**, Adjusted Standardised Residuals; **ASU**, Aviation Safety Unit; **ATSB**, Australian Transport Safety Bureau; **BFU**, Bundesstelle fuer Flugunfalluntersuchung; **BN**, Bayesian Network; **CFT**, Controlled Flight into Terrain; **CM**, Cognitive Mapping; **CPT**, Conditional Probability Table; **CSB**, Chemical Safety Board; **CTA**, Classification Tree Analysis; **DGCA**, Directorate General Civil of Aviation; **DME**, Department of Mines & Energy; **DOI**, Department of Infrastructure; **DOT**, Department of Transport; **FAA**, Federal Aviation Administration; **FAHP**, Fuzzy Analytical Hierarchy Process; **F-DEMATEL**, Fuzzy Decision Making Trail & Evaluation Laboratory; **FFH**, Fall From Height; **FRA**, Federal Railroad Administration; **GCV**, Global Centrality Value; **HC**, Hierarchical Clustering; **HFACS-CM**, Human Analysis & Classification System Cognitive Mapping; **HFACS-Coll**, Human Factors Analysis & Classification System Collision; **HFACS-MA**, Human Analysis & Classification System Maritime Accidents; **HFACS-MI**, Human Factors Analysis & Classification System-Mining Industry; **HFACS-OGI**, Human Analysis & Classification System Oil & Gas Industry; HFACS-RA, Human Factors Analysis & Classification System Rail Accidents; **HFACS-RR**, Human Factors Analysis & Classification System Railroad; **ICAM**, Incident Case Analysis Method; **ICAO**, International Civil Aviation Organisation; **KINS**, Korean Institute of Nuclear Safety; **LCA**, Latent Class Analysis; **LoC**, Loss of Control; **MAIB**, Maritime Accident Investigation Branch; **MCA**, Multiple Correspondence Analysis; **MRSSD**, Ministry of Railways Safety Supervision Division; **NASDAC**, National Aviation Safety Data Analysis Centre; **NCAA**, Nigerian Civil Aviation Network; **NCV**, Normal Centrality Value; **NPP**, Nuclear Power Plant; **NSIC**, Nuclear Safety Information Centre; **NTSB**, National Transportation Safety Board; **OTSI**, Office of Transport Safety Investigations; **PCA**, Principal Component Analysis; **QT**, Queensland Transport; **RCL**, Remote Control Locomotive; **ROC**, Republic of China; **RPA**, Remotely Piloted Aircraft; **SAWS**, State Administration of Work Safety; **SHEL**, Software Hardware Environment Liveware; **SHK**, Swedish Accident Investigation Authority; **SIB**, Safety Investigation Board; **TSB**, Transport Safety Board; **UK**, United Kingdom; **USA**, United States of America; **WBA**, Why-Because Analysis.

Table 4
Overview of accidents, errors, and HFACS category frequencies across studies. 'Errors' indicates the total number of causal/contributory factors identified, whereas 'categories' refers to the total HFACS levels/categories/causal codes for a given study.

	Studies	Total	Range	Median	Mean (SD)
Accidents	43	5965	1–1020	48	139 (203)
Errors	19[†]	6938	15–2868	153	365 (681)
Categories	20[‡]	15,720	55–2686	324	786 (868)

[†] Includes only those studies indicated in Table 3.
[‡] Includes only those studies indicated in Table 3.

et al., 2017), aerospace (Johnson and de Almeida, 2008), bushfire emergency response (Salmon et al., 2014b), and civil engineering (Fan et al., 2015).

A majority of AcciMap studies used six hierarchical levels consistent with Rasmussen's (1997) RMF. Exceptions to this were few, with three studies depicting five levels (Nayak and Waterson, 2016; Kee et al., 2017; Lee et al., 2017). One study included an 'outcomes' level containing the factors most proximal to a bacterial foodborne outbreak (Nayak and Waterson, 2016). Two studies analysing the systemic cause (s) of a passenger ferry disaster replaced the equipment and surroundings level (i.e., the sixth level) with a similar outcomes level (Kee et al., 2017; Lee et al., 2017). Other unique AcciMap features and changes included the incorporation of logic gates or decision trees that visualised a sequence of branching causality (Woo and Vicente, 2003). One study drew attention to a critical event, or the point at which the accident and its consequences on population health was unavoidable (Cassano-Piche et al., 2009). Other studies coded contributory factors to provide contextual insight into the occurrence of certain events. For instance, the shading of AcciMap factors indicated the time and physical location of when and where decisions and actions took place (Jenkins et al., 2010). Equally, factors were coded based on whether they were preconditions (i.e., latent and distal to the accident), direct, or complex (i.e., factors that had multiple aetiologic roles) (Nayak and Waterson, 2016). Three studies used a quantitative approach when modelling contributory factors and their relationships (Newnam and Goode, 2015; Akyuz, 2017; Salmon et al., 2017b). For example, the weighting of factors in terms of their contributory significance to the accident was based on the use of Analytical Network process (ANP) methods (Akyuz, 2017). Two studies descriptively quantified relationships according to the frequency with which those relationships across incidents were reported (Newnam and Goode, 2015; Salmon et al., 2017b).

3.3. AcciMap contributory factor characteristics

Sixteen (80.0%) of 20 studies were eligible for quantitative summary regarding the mean number of AcciMap factors identified across six levels of the RMF (Fig. 6). The four studies excluded did not follow the traditional AcciMap format in terms of the labelling or number of system levels (Waterson, 2009; Nayak and Waterson, 2016; Kee et al., 2017; Lee et al., 2017). Regarding Fig. 6, the highest factor frequency was found for the physical process and actor activities level, with a mean of 13.4 (SD = 8.0) factors identified. The lowest factor frequency was found for the government policy and budgeting level, with a mean of 3.2 (SD = 3.1) factors identified.

Twenty studies were eligible for a quantitative summary regarding the total number of AcciMap factors (Fig. 7). The mean and median number of AcciMap factors identified was 40.0 and 37.0 (SD = 16.5), respectively. The highest total number of AcciMap factors was 71 (Salmon et al., 2014b). The lowest was seven (Waterson, 2009).

Table 5
Overview of extracted information associated with six STAMP-CAST studies ordered by ascending publication date. The column titled 'focus' refers to whether the study included system development, system operation, or both. A written summary of findings can be found in Section 3.6. Hyphenated fields indicate that information was not provided.

Study	Context	Source/data	Outcome/severity	Focus	Unique features
Ouyang et al. (2010)	Transport (rail); China	Internet, user-edited webpage	Zibo train collision; 416 injuries & 72 fatalities	System operation	Application of Leveson's classification framework of control flaws to each actor & organisation. The categories of 'context', 'mental model flaws' & 'coordination' were included
Kontogiannis and Malakis (2012)	Aviation (rotary wing); Greece	AAISB official report; 2002–2004	HEMS crash into sea; 5 fatalities	System operation	Application of Leveson's classification framework of control flaws supplemented with the VSM to reveal the organisational breakdowns underlying the flaws of control algorithms identified with STAMP
Altabbakh et al. (2014)	Industry (oil & gas)	–	Structural damage; 20 injuries & 2 fatalities	System operation	Application of Leveson's classification framework of control flaws to each actor & organisation. The category 'feedback' was missing, whereas 'context' & 'mental model flaws' were included
Rong and Tian (2015)	Military; USA	Official AIB USAF report; 2008	Minuteman III silo fire; structural damages	System operation	Application of Leveson's classification framework of control flaws to each actor & organisation. The use of a CLD of the Minuteman III operation system modelled the causal relationships among human-related errors
Kim et al. (2016)	Maritime; South Korea	KMST & MOF official reports; 2014	Sewol passenger ferry capsize; injuries & 304 fatalities	System operation (development visualised in model)	Application of Leveson's classification framework of control flaws to each actor & organisation. The categories of 'context' & 'mental model flaws' were included
Canham et al. (2018)	Public health; UK	NPSA official report; 2008	Medication error incident (unknown severity)	System operation (development visualised in model)	Apply both RCA & STAMP to the same accident & compare results & associated recommendations aimed to reduce the risk of future errors

AIB, Accident Investigation Safety Board; **AAISB**, Air Accident Investigation Safety Board; **CLD**, Causal Loop Diagram; **HEMS**, Helicopter Emergency Medical Services; **KMST**, Korean Maritime Safety Tribunal; **MOF**, Ministry of Oceans and Fisheries; **NPSA**, National Patient Safety Agency; **RCA**, Root Cause Analysis; **STAMP**, Systems Theoretic Accident Model and Processes; **UK**, United Kingdom; **VSM**, Viable Systems Model.

Table 6
Overview of select CAST characteristics among six studies ordered by ascending publication date. The 'constraints', 'controls', and 'feedback' columns correspond to the inadequate enforcement of constraints (control actions), the inadequate execution of control actions, and inadequate or missing feedback, respectively. Hyphenated fields indicate that information was not provided.

Study	Constraints	Controls	Feedback	Context	Mental model flaws	Coordination	Total
Ouyang et al. (2010)*	20	17	2	20	11	1	71
Kontogiannis and Malakis (2012)†	–	8	3	12	7	3	33
Altabbakh et al. (2014)‡	17	17	–	20	11	–	65
Rong and Tian (2015)§	17	32	–	7	–	–	56
Kim et al. (2016)**	25	11	2	9	5	–	52
Canham et al. (2018)††	–	6	4	–	4	–	14

* Data were based on Fig. 5 through to Fig. 8.
† Data were based on Figs. 3 and 4.
‡ Data were based on a qualitative description of the hierarchical control structure (i.e., the model itself was a drawing/picture of the oil and gas system, i.e., Fig. 6).
§ Data were based on Table 4 and Fig. 4 (i.e., Table 4 included, 'controlled component failures', 'dysfunctional interactions', 'delayed or missing control actions', and 'incorrect process models' at the operating processes level of STAMP and had to be manually defined under the appropriate category of the control flaws classifications taxonomy).
** Data were based on Fig. 3 through to Fig. 5 (the CAST category 'constraints' includes 'the subcategory process model flaws').
†† Data were based on Table 3.

3.4. Overview of HFACS studies

A total of 43 HFACS studies were included (Table 3). There were 14 studies published between the years 2000 and 2009, and 29 studies published between the years 2010 and 31 July 2018, inclusive. Most studies aimed to understand the human and organisational factors underpinning aviation (n = 15) and maritime (n = 10) accidents. Studies in the mining (n = 7), rail (n = 6), construction (n = 2), nuclear power (n = 2), and industrial (n = 1) work domains were identified. The sources of accident data as well as the type and severity of accidents varied across studies.

In terms of HFACS framework modifications, eight studies incorporated an additional fifth level above the organisational level (Reinach and Viale, 2006; Patterson and Shappell, 2010; Chauvin et al., 2013; Chen et al., 2013; Theophilus et al., 2017; Verma and Chaudhari, 2017; Yıldırım et al., 2017; Zhang et al., 2018). Thirty-four studies used a traditional four level HFACS framework that included between 17 and 20 individual categories. One study modified the HFACS framework to include 28 categories across the traditional four levels (Batalden and Sydnes, 2014). Twenty-six (60.5%) studies modelled interactions across errors and/or HFACS categories. The approaches and techniques to model relationships included traditional statistical modelling (e.g., chi-squared, Fisher's exact test, logistic regression analyses), hierarchical decision-making process methods (e.g., ANP, Fuzzy Analytic Hierarchy Process (FAHP)), and quantitative probability modelling (e.g., Bayesian networks (BN)). Table 4 provides a summary of the total accident, error, and HFACS category frequencies, as well as measures of central tendency applicable only to studies reporting the necessary information.

3.5. HFACS classifications

A total of 22 (51.2%) studies reported the frequency of the presence of a HFACS category (Fig. 8). The weighted mean proportions and standard deviations of 18 HFACS categories are based on 4456 accidents (i.e., 74.7% of the total accidents analysed). Details of the 22 studies can be found in the nomenclature directly below Table 3 and Fig. 8.

Skill-based error, decision error, perceptual error, inadequate supervision, planned inappropriate operation, and supervisory violation were the HFACS categories featuring in all 22 studies. The remaining mean proportions computed were limited to those studies (parentheses) that reported HFACS category frequencies: violation (n = 20), physical environment (n = 20), technical environment (n = 20), adverse mental state (n = 19), adverse physiological state (n = 20), physical and mental limitation (n = 19), crew resource management (n = 21), personal readiness (n = 21), failed to correct a known problem (n = 21), organisational resource management (n = 20), organisational climate (n = 19), and organisational process (n = 20). HFACS category frequencies in one study were estimated from a histogram (Daramola, 2014). In another study, the human failure investigations rather than the equipment failure investigations were examined (Baysari et al., 2008). The variation around the classification of HFACS categories was generally less pronounced when studies were weighted according to the number of accidents analysed.

In terms of the weighted mean proportions, skill-based error (53.5%), decision error (36.5%), physical environment (30.6%), violation (27.2%), and inadequate supervision (25.5%) were the most frequently coded HFACS categories. The lowest proportions were found for physiological state (3.4%), supervisory violation (4.9%), failed to correct a known problem (5.6%), organisational climate (8.9%), and physical and mental limitation (9.3%).

A total of 10 (23.3%) studies in the civil and/or military aviation context reported the frequency of the presence of a HFACS category (Wiegmann and Shappell, 2001; Gaur, 2005; Li and Harris, 2006; Shappell et al., 2007; Lenne et al., 2008; Li et al., 2008; Hooper and O'Hare, 2013; Li and Harris, 2013; Daramola, 2014; Al-Wardi, 2017) (Fig. 9). The weighted mean proportions and standard deviations of 18 HFACS categories are based on 2813 accidents (i.e., 47.2% of the total accidents analysed). The HFACS category frequencies for the 10 aviation studies were compared with the remaining 12 studies (Fig. 8) that included 1643 accidents (i.e., 27.5% of the total accidents analysed). Three of 10 aviation studies did not report the HFACS category frequencies for physical environment and technological environment (Wiegmann and Shappell, 2001; Gaur, 2005), or adverse mental state and physical and mental limitations (Daramola, 2014).

Notable differences between the 10 aviation and 12 varied studies in terms of classifying errors were found for the HFACS categories of organisational process (diff. 24.4%), technological environment (diff. 21.4%), organisational climate (diff. 19.4%), inadequate supervision (diff. 17.4%), and planned inappropriate operation (diff. 14.3%).

3.6. Overview of STAMP-CAST studies

A total of six STAMP-CAST studies were included (Table 5). Further information pertaining to the STAMP control structure model and Leveson's (2004) classification taxonomy of control flaws can be viewed in Section 1.2.3.

The use of the CAST method was similar across studies in terms of the approach taken to develop models and analyse control flaws. For

Table 7
Overview of extracted information associated with four FRAM studies ordered by ascending publication date. The column titled 'functions' refers to the frequency of functions identified. Frequencies in parentheses indicate the number of functions per FRAM diagram, or alternatively, number of functions per level of a work system. A written summary of findings can be found in Section 3.8.

Study	Context	Source/data	Outcome/severity	Functions	Unique features
Herrera and Woltjer (2009)	Aviation; Norway	AIBN, 2004	Instrument landing system glide path failure; reapproach required	9 (limited time interval: 14:42:37–14:43:27 only)	Compare the STEP method with FRAM & compare results/outputs
De Carvalho (2011)*	Aviation; Brazil	Official government reports, CENIPA, NTSB	Mid-air collision between commercial aircraft & private jet; 154 fatalities	11 (2, 5, 4)	Three FRAM diagrams. Discussion of specific ATM system resilience features (i.e., buffering capacity, flexibility, margin, tolerance, cross-scale interactions) in context of the study results
Patriarca et al. (2017)†	Transport (rail); UK	RAIB; 2005	SPAD; impact on rail traffic operations (defined serious with catastrophic potential)	95 (6, 20, 69)	Contextualise the FRAM functions with Rasmussen's AH theory, using the abstraction/decomposition framework to facilitate a within & across systems levels analysis
Patriarca et al. (2018)	Aviation; Los Angeles	Official NTSB report, personal testimonies,	Runway collision; 29 injuries, 35 fatalities	57	FRAM diagram colour coded based on actor type. The addition of the RAM – a FRAM support tool – helped to structure the analysis and highlight which functions exhibited/contributed the greatest level of potential variability.

* Indicates that the frequency of the FRAM functions identified correspond to each FRAM diagram.
† Indicates that the frequency of the FRAM functions identified correspond to the top three of levels of a five tiered abstraction hierarchy (i.e., the vertical axis); **AH**, Abstraction Hierarchy; **AIBN**, Accident Investigation Board; **ATM**, Air Traffic Management; **CENIPA**, Centro de Investigação e Prevenção de Acidentes Aeronáuticos (Aeronautical Accidents Investigation & Prevention Centre); **FRAM**, Functional Resonance Analysis Method; **NTSB**, National Transportation Safety Board; **RAIB**, Rail Accident Investigation Branch; **RAM**, Resonance Analysis Matrix; **SPAD**, Signal passed at Danger; **STEP**, Sequential Timed Events Plotting; **UK**, United Kingdom.

example, missing or deficient control mechanisms were examined by applying or extending Leveson's (2004) classification taxonomy of control flaws (Ouyang et al., 2010; Kontogiannis and Malakis, 2012; Altabbakh et al., 2014; Rong and Tian, 2015; Kim et al., 2016; Canham et al., 2018), and/or were supplemented via the use of additional theories, methods, and models (Kontogiannis and Malakis, 2012; Rong and Tian, 2015). Common to all but two studies (Kim et al., 2016; Canham et al., 2018) was a focus on system operations rather than system development. To be precise, the studies by Kim et al. (2016) and Canham et al. (2018) briefly described the role of engineering safety into the design of systems from the 'ground-up' prior to their analyses, however each application of STAMP-CAST was focussed on system constraints and flawed control mechanisms from the perspective of working operations either before or at the time of an accident. The studies did not elaborate on the importance of engineering safety and resilience into systems, nor did they formally analyse or evaluate the properties of existing work structure(s) from a design-based safety standpoint.

3.7. STAMP control structure and CAST characteristics

The number of control structure levels and controllers (e.g., equipment, physical components, technologies, environments, weather conditions, people, organisations) included in six CAST analyses can be visualised in Fig. 10. Also included in Fig. 10 is the number of system levels and controllers that were described in each study prior to a CAST analysis. The number of system levels was determined based on Leveson's (2004) control structure model as many studies provided their own description of a system that did not adhere to the traditional hierarchy.

In relation to Fig. 10, notable differences between the levels and controllers described and analysed is not a reflection of the relative quality of a given study. Firstly, the analysis of an accident using CAST is reliant on the availability of the data sources and information used. Secondly, the research purpose could be to identify control flaws among human operators and physical/technical components only, despite a reduction in analytical scope. Thirdly, the studies by Altabbakh et al. (2014) and Rong & Tian (2015) are not necessarily more comprehensive in terms of the congruence between a system description and the subsequent analysis. Rather, those studies offered an initial description of the system that was applicable only to the analysis itself.

The total number of control flaws in six CAST analyses can be viewed in Table 6. The mean (SD) number of constraints, control and feedback-based errors and deficiencies was 49 (21.3).

3.8. Overview of FRAM studies

A total of four FRAM studies were included (Table 7). Information pertaining to the process of identifying different FRAM functions, including their six aspects (i.e., input, output, preconditions, resources, time, control), can be viewed in Section 1.2.4. It was not possible to identify the number of couplings (i.e., relationships) among FRAM functions for each study given the complex nature of the diagrams presented. One study did report a total of n = 245 couplings, however such information was the exception (Patriarca et al., 2018).

In the study by Herrera and Woltjer (2009), a total of 19 FRAM functions were identified. The analysis itself included nine functions and focussed only on a specific time interval during the incident. No reasons for this were specified. De Carvalho (2011) presented three different FRAM diagrams relating to: (i) the Air Traffic management (ATM) system; (ii) take-off; and, (iii) in-flight activities. Both applications involved a more traditional application of FRAM and used official accident reports to extract the necessary data and information.

Patriarca et al. (2017) combined FRAM with Rasmussen's (1985) abstraction-decomposition framework to develop a systemic, multi-layered description of a rail incident. The FRAM diagram was overlaid onto the abstraction-decomposition framework which contained two

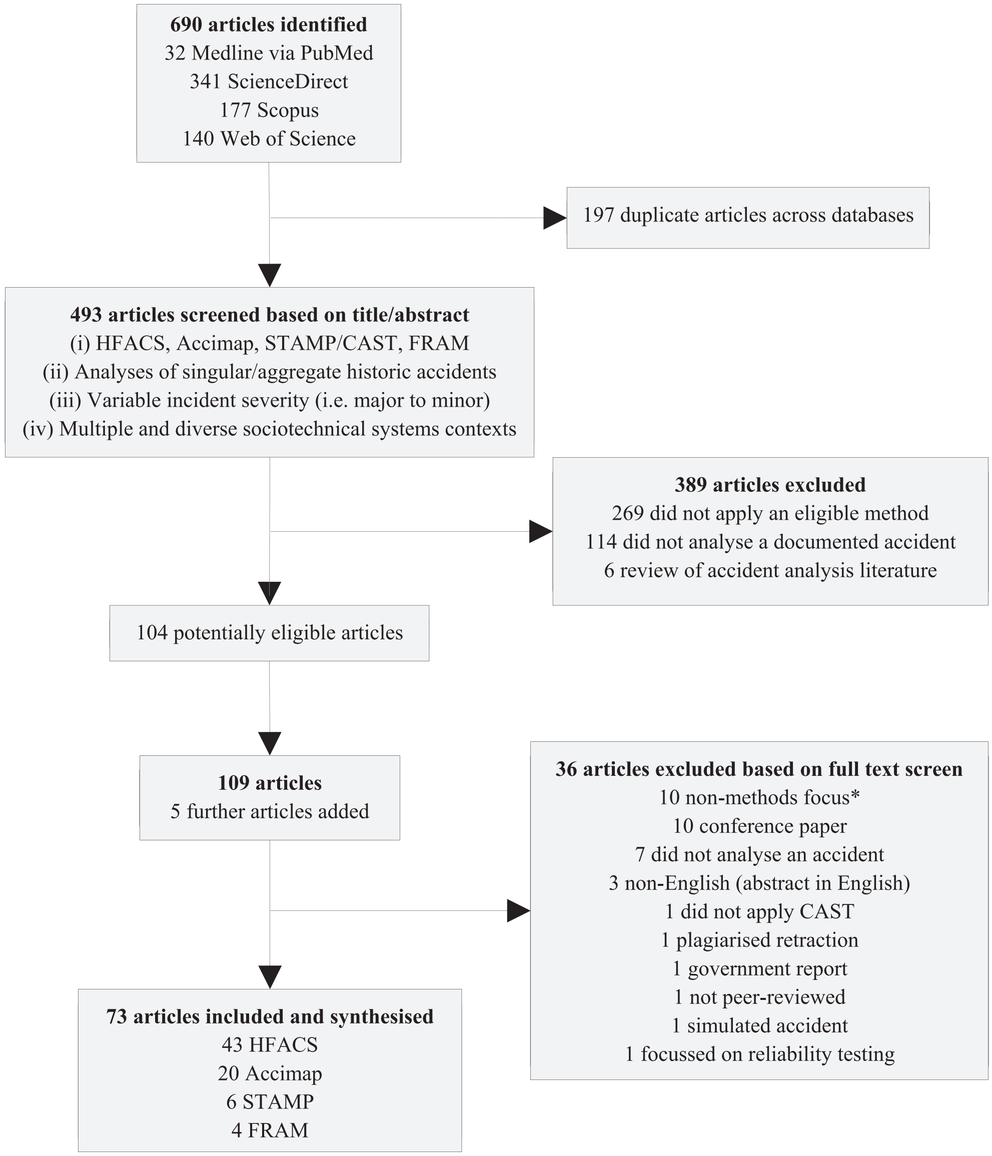

Fig. 5. A visualisation of the systematic searching process (*‘non-methods focus’ refers to studies that aimed to enhance or expand an existing approach via the use of certain principles or aspects associated with another method resulting in an incomplete application of one of the primary methods to be included, or did not actually use an eligible method).

mutually inclusive dimensions: (i) a description of the rail system based on five functional and generalised purposes (i.e., a vertical axis); and, (ii) an overview of the agents in the rail system (e.g., infrastructure company, signaller, train company, driver) who played a role at the time of the accident (i.e., the horizontal axis). A cross-examination of the interactions between different agents at a single functional level of abstraction with the interactions among agents across different levels of the rail system provided a deeper level of analysis that could not be achieved with a more traditional FRAM application. Patriarca et al.’s (2017) investigation was focussed on contextualising the identified FRAM functions and did not discuss the results of the analysis in terms of dampening unwanted performance variability in the rail system to inform the implementation of future accident prevention interventions.

The second study by Patriarca et al. (2018) used the Resonance Analysis Matrix (RAM), a FRAM support tool, to visualise and structure the couplings among functions. The RAM was used because a traditional application of FRAM can include multiple functions and potentially hundreds of couplings resulting a highly complex model that is difficult to understand. Indeed, each function in a FRAM analysis is unique in terms of its effect on performance variability across the system as a whole. Consequently, the RAM provided the means to systematically examine the number and type of couplings among different functions, including the functions that are highly connected and have a critical role to play in accident causation.

3.9. Accident contexts

Fig. 11 shows the most popular accident contexts to feature across the four methods categories. Aviation is the most popular context given the relatively high number of HFACS studies included.

4. Discussion

The aim of this systematic literature review was to examine and report on peer reviewed studies that have applied AcciMap, HFACS, STAMP-CAST, and FRAM to analyse and understand the cause of accidents in a diverse range of sociotechnical systems contexts. Based on the eligibility criteria and scope of article inclusion, HFACS (n = 43) was the most widely used method between 1990 and 2018, followed by AcciMap (n = 20), STAMP-CAST (n = 6), and FRAM (n = 4). Despite

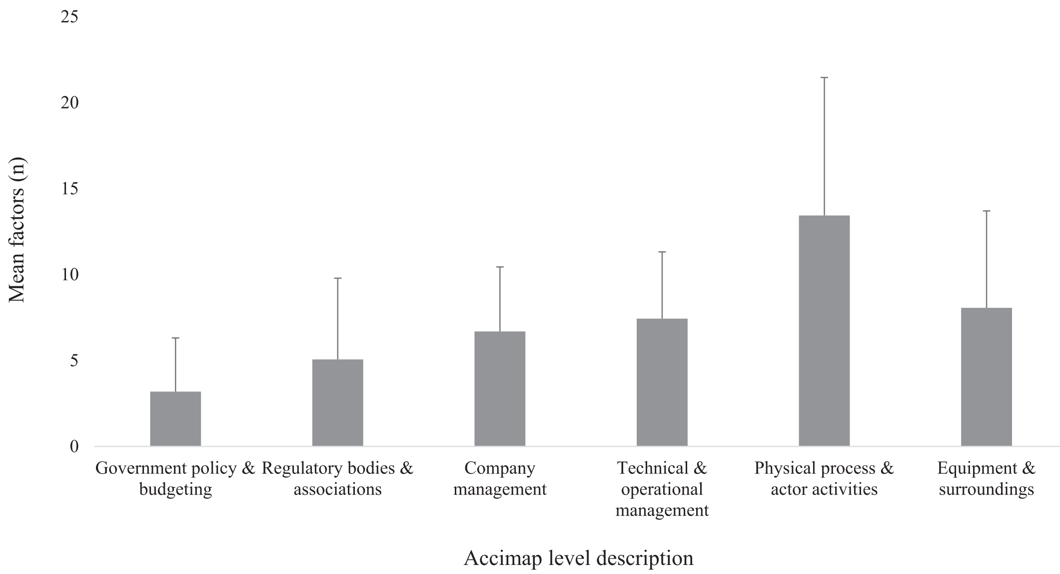

Fig. 6. Mean and standard deviation for the number of AcciMap factors included on each level of Rasmussen's (1997) RMF across 16 studies. Studies analysed both single and multiple accidents. Further information can be found in the nomenclature below Table 2.

being the older of the four methods, AcciMap continues to be applied to analyse and understand accident causation in modern day sociotechnical systems. Although each method is underpinned by its own set of theories and philosophes (i.e., Rasmussen's (1997) RMF, Reason's (1990) Swiss Cheese Model, systems and control theory (Leveson, 2004; Leveson et al., 2009), functional resonance (Hollnagel, 2004, 2012)), there are a number of key findings across the applications reviewed in terms of the general approach taken to identify casual factors and elucidate accident mechanisms.

4.1. Key findings from the studies reviewed

The first finding is the identification of a greater number of contributory factors at the sharp-end of a sociotechnical system relative to the number of factors identified at higher levels (e.g., congressional, governmental, regulatory). For example, most of the contributory factors in the AcciMap studies were located at the 'physical process and actor activities' and 'equipment and environment' levels. Likewise, many contributory factors in the HFACS studies were identified at the

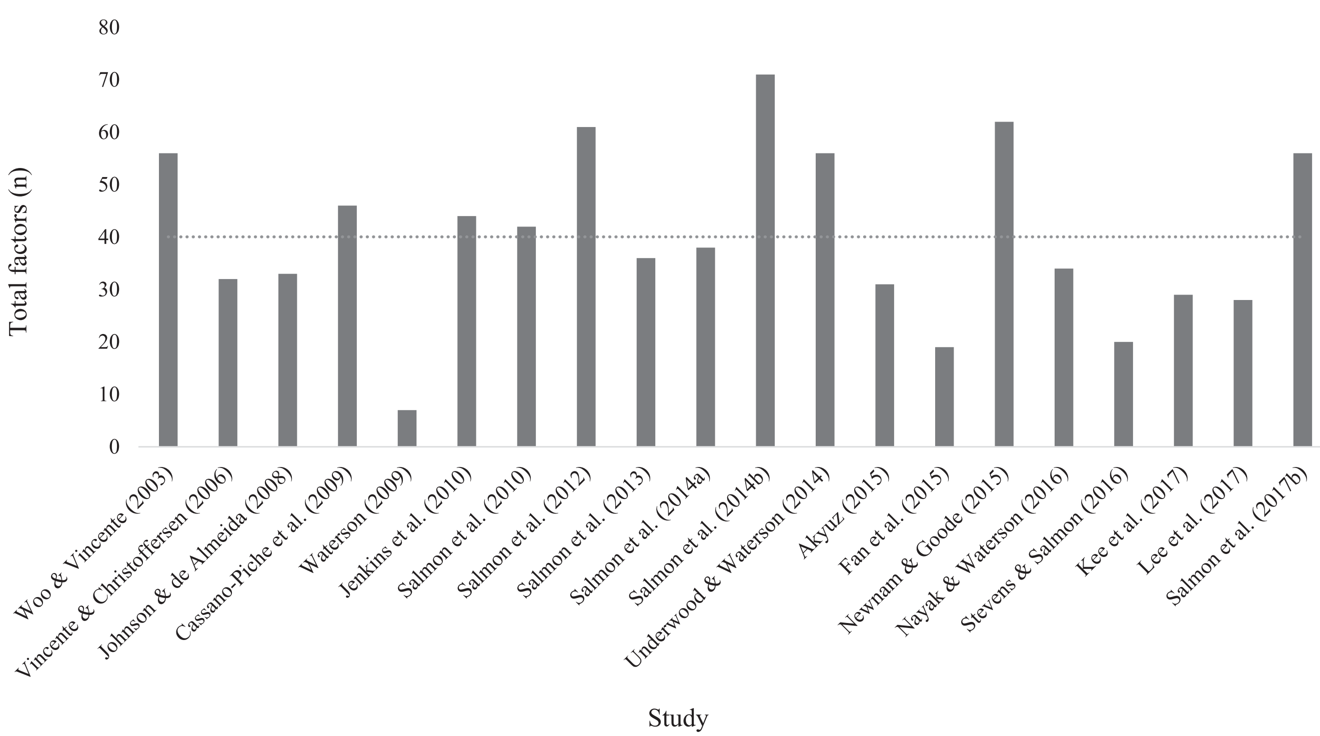

Fig. 7. Total number of AcciMap factors identified in 20 studies including mean trendline overlay. Studies mapped factors across six system levels and are ordered by ascending publication date.

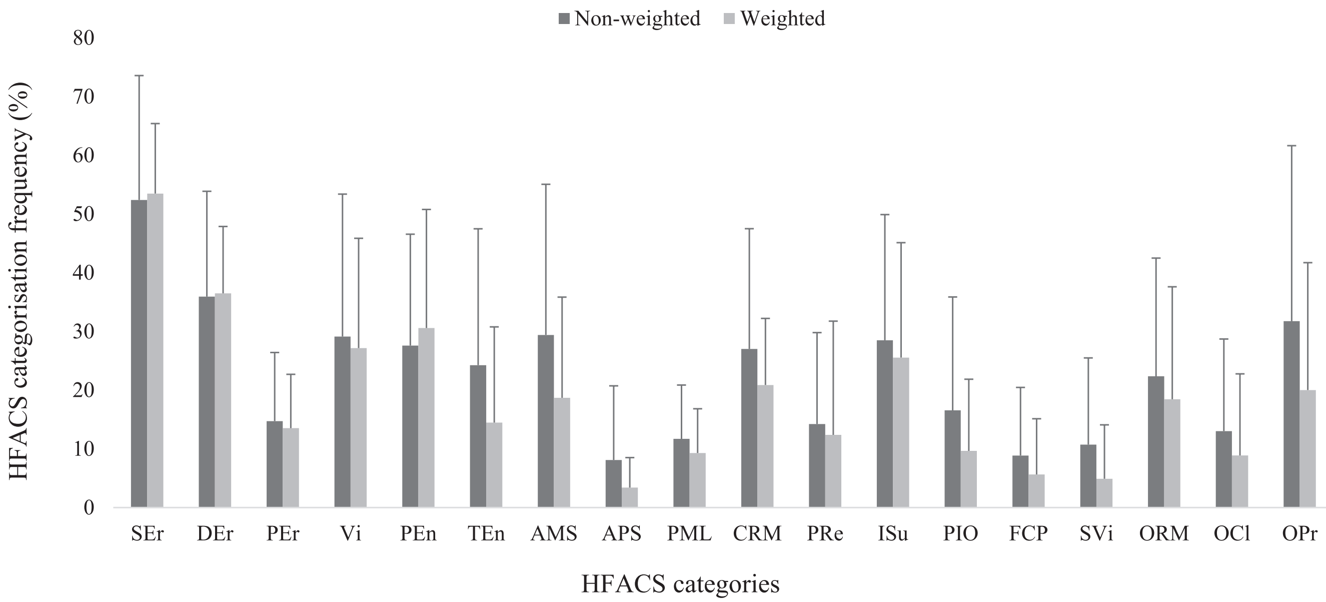

Fig. 8. Non-weighted and weighted mean proportions of 18 HFACS categories across 22 studies (aviation n = 10, rail n = 4, mining n = 4, maritime n = 1, construction n = 1, nuclear power n = 1, industrial n = 1). **AMS**, Adverse Mental State; **APS**, Adverse Physiological State; **CRM**, Crew Resource Management; **DEr**, Decision Error; **FCP**, Failed to Correct a Known Problem; **ISu**, Inadequate Supervision; **OCl**, Organisational Climate; **OPr**, Organisational Process; **ORM**, Organisational Resource Management; **PEn**, Physical Environment; **PEr**, Perceptual Error; **PIO**, Planned Inappropriate Operation; **PML**, Physical-Mental Limitation; **PRe**, Personal Readiness; **SEr**, Skill-based Error; **SVi**, Supervisory Violation; **TEn**, Technological Environment; **Vi**, Violation.

'unsafe acts' and 'preconditions for unsafe acts' levels, including skill-based errors, decision errors, violations, and factors related to the physical environment. The CAST analyses demonstrate a similar pattern, with studies typically identifying control flaws among controllers at the 'operating process', 'operational management', and 'company' levels. A focus on including contributory factors at lower system levels may be a function of the information and data available to analysts rather than a consistent feature of accident causation. Nevertheless, the limited number of factors identified at higher system levels suggests that interventions and strategies designed to prevent accidents could be ignoring the potential benefit of going upstream where arguably some of the greatest differences could be made. A disproportionate focus on human and technical factors is not necessarily consistent with a systems theoretic accident causation philosophy which draws attention to the role of governmental, regulatory, and organisational factors.

A second finding is the fact that all of the studies reviewed, regardless of the method adopted, identified multiple contributory factors, functions, and relationships. For example, although AcciMap studies generally identified fewer factors at higher system levels, there were instances whereby > 50 contributory factors were described

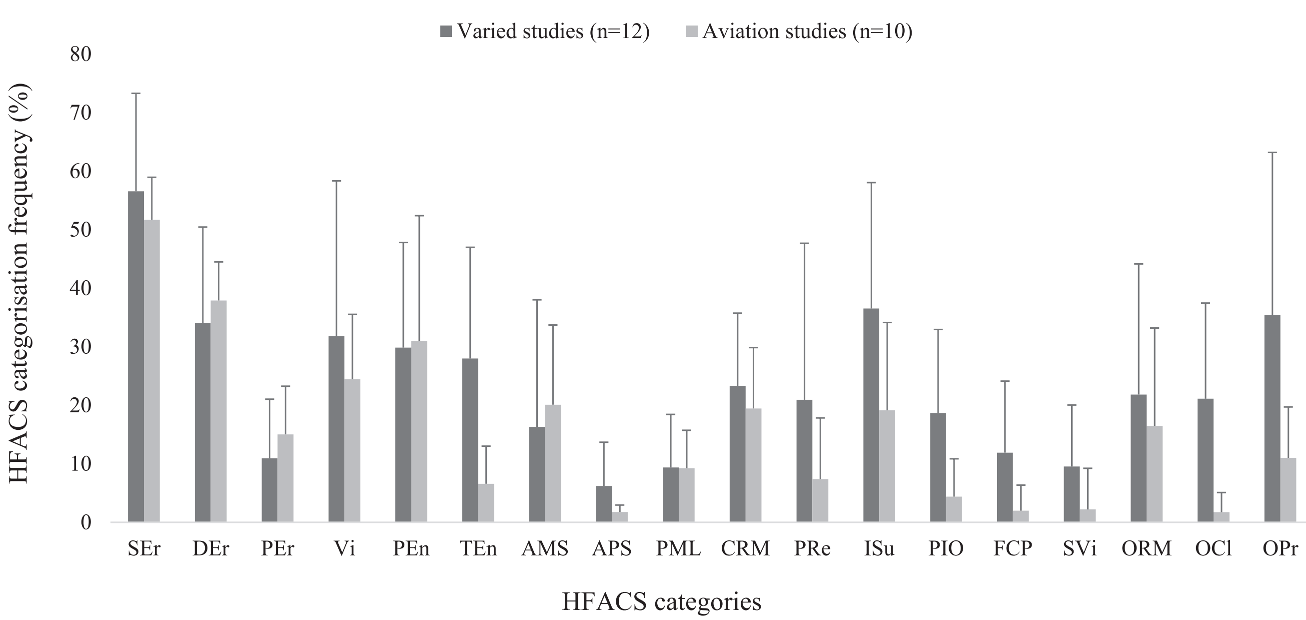

Fig. 9. Comparison of the weighted mean proportions of 18 HFACS categories between 12 varied and 10 aviation studies. **AMS**, Adverse Mental State; **APS**, Adverse Physiological State; **CRM**, Crew Resource Management; **DEr**, Decision Error; **FCP**, Failed to Correct a Known Problem; **ISu**, Inadequate Supervision; **OCl**, Organisational Climate; **OPr**, Organisational Process; **ORM**, Organisational Resource Management; **PEn**, Physical Environment; **PEr**, Perceptual Error; **PIO**, Planned Inappropriate Operation; **PML**, Physical-Mental Limitation; **PRe**, Personal Readiness; **SEr**, Skill-based Error; **SVi**, Supervisory Violation; **TEn**, Technological Environment; **Vi**, Violation.

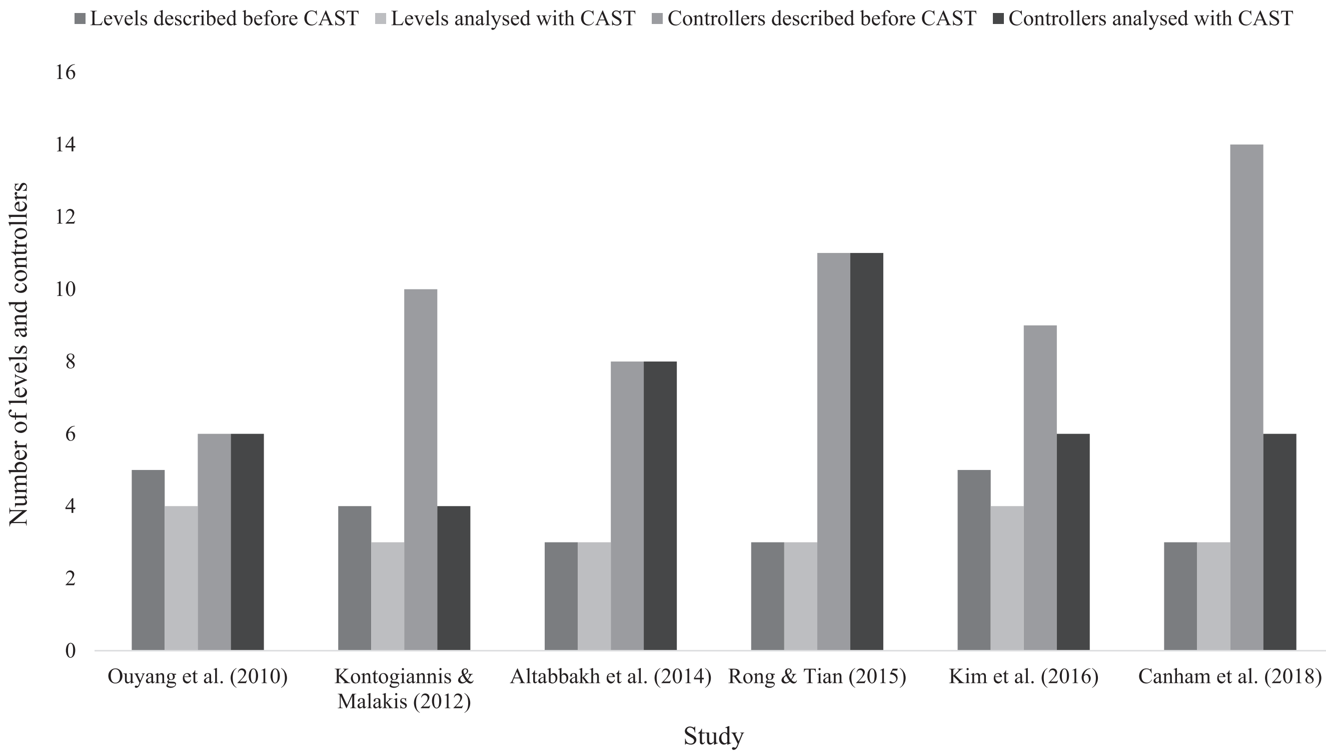

Fig. 10. Number of control structure levels and controllers described and analysed in six STAMP/CAST studies ordered by ascending publication date. The number of system levels was determined based on Leveson's (2004) model.

(Woo and Vicente, 2003; Salmon et al., 2012; Salmon et al., 2014b; Underwood and Waterson, 2014; Newnam and Goode, 2015; Salmon et al., 2017b). Similarly, there was an average of 49 control flaws across the STAMP-CAST applications based on Leveson's (2004) classifications taxonomy. In the FRAM category, one study identified a total of 95 functions across three analyses (Patriarca et al., 2017). Not only does this finding emphasise the complex and multifactorial nature of accident causation (Rasmussen, 1997), but it also has implications for data collection and analysis. Incident reporting systems and accident analysis methods require the capacity to collect and analyse data on multiple factors from across an overall sociotechnical system. Such information may be external to the organisation and could even relate to

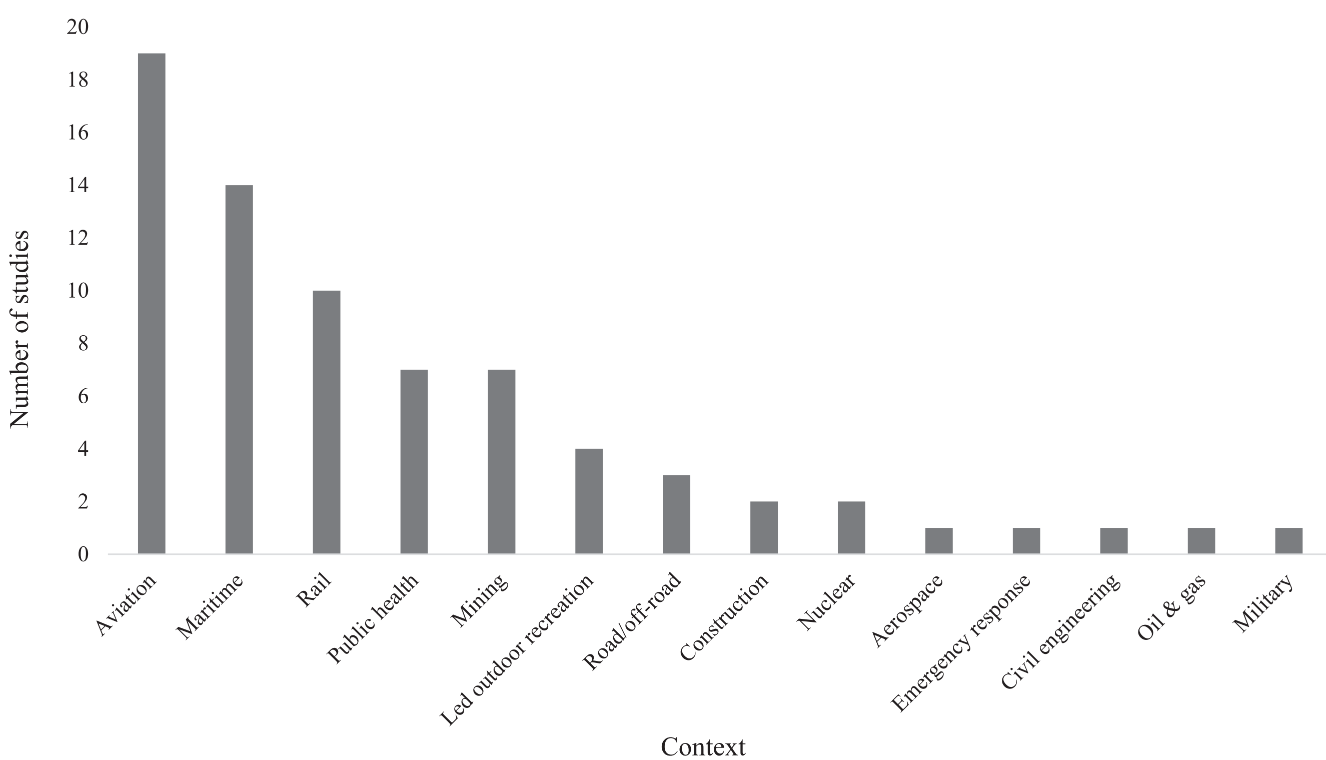

Fig. 11. The frequency of the different accident contexts that were studied across the four methods categories.

certain decisions and actions that occurred months or years prior to an accident. Unfortunately, many of the incident reporting and accident data collection systems currently used in practice are deemed inadequate (Salmon et al., 2017a; Goode et al., 2018), suggesting that accident analysis in practice may not be providing a complete understanding of how and why accidents occur. An important area of future research is to explore the context-dependent feasibility of introducing or upgrading incident reporting systems to account for big data and the complexities of accident causation (Goode et al., 2018). The Understanding and Preventing Led Outdoor Accidents Data System (UPLOADS) is a good example of a nationwide incident reporting system that was developed to address a lack of quality data on injuries and incidents in various led outdoor Australian contexts (UPLOADS, 2018). This novel database has gained considerable traction in Australia and affords led outdoor recreation organisations the ability to benchmark performances and compare incident data with other, similar providers.

A third finding relates to the way that studies have attempted to enhance or extend the analytical scope of a method to better meet the needs of a given problem or sociotechnical systems context. For example, across the methods categories, it was relatively common for studies to modify the total number of system levels, change the traditional labelling of system levels and categories, and/or extend the utility of analyses with additional theories, approaches, or statistical techniques. Notably, in the HFACS methods category, 60% of studies applied some form of quantitative or statistical approach to better understand the degree (or strength) to which higher level organisational determinants influenced factors at the lower end of a system. Examining the statistical dependency between factors in this way is congruent with the underlying unidirectional causal theory of HFACS. Also interesting is the evolution of the analytical approaches across HFACS studies. For instance, Li and Harris (2006) used relatively basic asymmetric measures of association to quantify the relationships between latent and active failures. Since then, the use of more sophisticated forms of statistical and probability modelling (e.g., regression analyses, FAHP algorithms including priority weighting procedures, BN modelling) have become more common (e.g., Tvaryanas et al., 2006; Lenne et al., 2008; Celik and Cebi, 2009; Wang et al., 2011; Akhtar and Utne, 2014; Zhan et al., 2017; Aliabadi et al., 2018). In short, one reason for wanting to improve HFACS is the need for a quantitative dimension that is better able to objectively pinpoint the most significant factors and causal ‘routes to failure’ (Li et al., 2008). It could be argued that the methods in their current form are being stretched beyond their capabilities and are not necessarily congruent with sociotechnical systems thinking or approaches (Leveson, 2011; Stanton and Harvey, 2017; Salmon et al., 2017; Walker et al., 2017).

A fourth finding relates to the disconnect between the different theories and tenets of accident causation with the models and outputs that are produced in practice. For example, a recent review has identified a set of 15 integrated systems thinking tenets across accident causation models as found in the original texts describing the use of AcciMap, STAMP, and FRAM (Grant et al., 2018). These tenets include vertical integration, functional dependency, emergence, normal performance, non-linear interactions, modularity, feedback loops, and performance variability (Table 8). The intention of Grant et al.’s (2018) work was to synthesise the core features of contemporary accident causation models as a basis to develop a formal methodology for predicting accident occurrence. The authors’ (Grant et al., 2018) analysis determined that despite considerable variation in the different philosophies of accident causation, the tenets were universally supported in the source literature. Accordingly, the question that remains is to what extent do state-of-the-art methods, including the studies in this review, take into consideration the key systems thinking tenets of accident causation? Unfortunately, the answer to this question is that not every study, model, or accident description has (or can) account for the tenets in their current form. To illustrate this point, a predominant focus on errors, failures, malfunctions, and deficiencies was noted across the AcciMap, HFACS, and STAMP-CAST applications. This is contradictory to the tenet of normal performance which is thought to play a key role in accident causation (Perrow, 1984; Hollnagel, 2004; Dekker, 2011; Hollnagel et al., 2013; Dekker and Pruchnicki, 2014; Salmon et al., 2015; Salmon et al., 2017a). Although FRAM is designed to account for normal performance variability, its outputs can be highly complex and difficult to interpret. This has forced researchers to come up with new and innovative ways of contextualising the results of FRAM so that meaningful insights from the analysis can be used to inform practice (e.g., Patriarca et al., 2017; Patriarca et al., 2018). Similar limitations of accident causation methods and models have been noted (Salmon et al., 2015, 2017a), suggesting that further work is required to understand exactly how normal performance, as well as other systems thinking tenets, contribute to accident causation. Overall, there appears to be a requirement to ensure that Grant et al.’s (2018) tenets are considered during accident analysis efforts.

4.2. Implications for accident analysis research moving forwards

Based on the key findings described, there is an opportunity for future research to examine whether the proposed interventions to prevent accidents are consistent with the results of each study identified. For example, factors related to equipment and the technical environment, as well as human error and failure, were emphasised across studies relative to those factors that would typically be found at higher levels of a sociotechnical system (e.g., legislative decision-making, policy formation, organisational regulation, guidelines around company management practices). Such a detailed critique of the practical implications as described in each study would provide further evidence to support whether current systems thinking methods and models are capable of producing results that can be translated into effective interventions. However, with current interest levels around the safety-II paradigm mounting (Hollnagel et al., 2013; Braithwaite et al., 2015; Patterson and Deutsch, 2015; Hollnagel, 2018), as well as a recognised need for theoretical and methodological advancement (Salmon et al., 2017a), the focus of future research could also be positioned around the development of novel approaches that can account for the key systems thinking tenets of accident causation (Grant et al., 2018). Lastly, and in relation to the scientific approach adopted in this review, we encourage other practitioners in the field of safety science and human factors research to follow a systematic process and document clearly the steps leading to article inclusion and evidence synthesis. In doing so, the science is more likely to be objective and fair, especially as it can be tempting to select and include only those articles that might be known to the research team and/or that tend to support a preconceived hypothesis or argument.

4.3. Limitations and research-based considerations

This review has limitations that should be noted. During the process of screening for potentially eligible articles, there is a possibility that studies were not included. In anticipation of a considerably large number of accident analysis investigations in the safety science literature, the initial screening of studies was based on the title and abstracts of peer reviewed journal articles only (i.e., books, conference proceedings and articles, and official reports were excluded). It was expected that a majority, if not all studies, would also make explicit reference to the primary method used in the abstract. In addition, the eligibility criteria were narrowly defined to emphasise the use of the main four methods to be included. For example, Section 2.2.2 specified that studies were excluded if they attempted to enhance the theoretical and/or analytical capability of another accident analysis approach by integrating certain aspects of AcciMap, HFACS, STAMP-CAST, or FRAM. This is despite the value and utility of studies that take the better aspects of one or more methods to form a new accident analysis approach. Although this review has included HFACS studies utilising BN

Table 8
The systems thinking tenets of accident causation adapted from Grant et al. (2018). The term 'elements' refers to both the living and non-living interacting parts of a sociotechnical system, including for example, people, artefacts, technologies, services, procedures, and policies.

Tenet	Description
Vertical integration	Interaction between elements across levels of the system hierarchy
Constraints	System elements that impose limits on, or influence, the behaviour of other system elements to ensure safe operation
Normal performance	The way that activities are actually performed within a system, regardless of formal rules and procedures
Performance variability	System elements change performance and behaviour to meet the conditions in the world and environment in which the system operates
Emergence	Outcomes that result from the interactions between elements in the system that cannot be fully explained by examining the elements alone
Functional dependencies	Necessary relationships and path dependence between tightly coupled system elements (i.e., components that serve a functional purpose)
Coupling	The degree or 'tightness' and interconnectivity of the interactions that exist between system elements
Non-linear interactions	Complex interactions that produce dynamic unpredictable sequences and outcomes
Linear interactions	Direct and predictable cause and effect relationships between system elements and production sequences
Feedback loops	Communication structure and information flow to evaluate control requirements of hazardous processes
Modularity	Sub-systems and elements that interact but are designed and operate independently of each other
Sensitive dependence on initial conditions	Characteristics of the original state of the system that are amplified throughout and alters the way the system operates at a later point in time
Decrementalism	Minor modifications to system elements and/or normal performances that gradually create a significant change with safety risks
Unruly technologies	Unforeseen and unpredictable behaviours of new technologies that are introduced into the system
Contribution of the protective structure	The formal and organised structure that is intended to protect and optimise system safety but instead competes for resources with negative effects

and ANP modelling, those studies did so after retaining the underlying layers of defence theory whilst equally considering supplementary techniques as methodological additions. We also alert the reader to the fact that many studies were not included despite a complete application of one or more of the eligible methods. For example, we initially identified a total of 62 studies that referred to the use of STAMP following the initial systematic search. However, a majority of these investigations were concerned with optimising sociotechnical systems and applying methods for the purposes of undertaking a hazard analysis to generate potential list of causal (or other) scenarios that could inform future accident prevention interventions (e.g., Pawlicki et al. 2016). Other studies did not undertake a complete application of CAST. Similarly, FRAM analyses depicting work-as-done variability as a basis to understand the emergent nature of risk or hazards were excluded, particularly as these studies also do not require an accident to have occurred (e.g., Rosa et al., 2015; Patriarca et al., 2017).

5. Conclusion

This systematic review has examined and reported on systems thinking accident analysis methods in the peer reviewed safety science literature. A total of 73 studies were included across four methods categories: AcciMap, HFACS, STAMP-CAST, and FRAM. These methods have been popular for close to two decades and have been applied in a diverse range of sociotechnical systems contexts. In consideration of the main results, the following take-home messages are provided. First, there has been a focus on identifying and recording or classifying contributory factors at the sharp-end of the sociotechnical systems analysed. Given the widely accepted belief that accidents are a systems problem and require a whole systems approach to elucidate complex aetiologies, there is little evidence that this is occurring in practice among the applications reviewed. This is most likely a result of the information and data available to support analyses rather than a common feature of accident causation more broadly. The implication of this finding leads to a second point; namely, the recognised need for more sophisticated incident reporting systems that have the potential to collect data from across all levels of a sociotechnical system. Doing so will provide a more complete understanding of how and why accidents occur whilst considering the influence of legislative, regulatory, and organisational factors. Third, many of the applications modified or extended the analytical scope of a method in an attempt to better reflect the nuances of a particular context. Methodological innovation has generally occurred out of necessity, whether to enhance the applicability of a method to a new context, model multi-factor relationships, or overcome the potentially complex nature of certain accident analysis outputs. Fourth, and based on the inherent properties of the methods themselves, there appears to be a disconnect between the theories and tenets of accident causation with the models that are produced in practice. There is a need to further explore research opportunities around the development of novel approaches that consider the key systems thinking tenets of accident causation.

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