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ABSTRACT

The International Civil Aviation Organization (ICAO) Annex 13 framework for aviation investigation is long-standing and well developed but does not require or audit use of methodologies for investigation analysis, including research literature safety/accident models (SAMs). Government Safety Investigation Authority (SIA) websites rarely mention methodologies. Limited published research engages directly with SIAs. A research/practice gap has been suggested.

To address ICAO, SIA and research gaps, this qualitative multi-case study examines SIA use and documentation of methodologies for accident analysis. Nine of seventeen SIA members of the International Transportation Safety Association (ITSA) that investigate aviation accidents agreed to participate and provided written answers to our research questions, relevant internal documentation, and exemplar investigation reports.

Our key findings are that participant SIAs have augmented ICAO requirements internally by their use of methodologies but that this usage was generally not obvious in published investigation reports and other SIA website material. It also varied significantly among the participants. All participant SIAs reported use of multiple methodologies, sometimes in the same investigation. Explicitly reported SIA methodology usage included: six Reason-based, six Rasmussen-based, three 'recent systemic', five 'BowTie', five 'bespoke', and seven using various other methodologies like 'SHELL'.

The industry impact of this qualitative research is hoped to be significant by being shared with participant SIAs unaware of each other's practice, enabling consideration of different options. It can inform additional aviation SIAs, ICAO, air safety investigators, and other high-risk industry regulators and investigators. Safety researchers may be better placed to develop SAMs with greater practical industry relevance.

1. Introduction: Background, research gaps, rationale and scope

Major civil aviation accidents can lead to multiple deaths and injuries, environmental and financial damage, and serious family, media and political impacts and concerns. Antecedents and 'causes' of such accidents are typically multi-factorial, and complexity in socio-technical systems can increase the risk and unpredictability of such outcomes (Dekker, 2004a, 2011b; Leplat 1984, 1997; Perrow, 1984; Rasmussen, 1990, 1997; Reason, 1990a, 1997; Turner, 1978, 1994; Turner and Pidgeon, 1997). This challenges both the design and maintenance of safer and more resilient systems with robust controls (Leveson, 2011a,b; Hudson, 2014, 2020) and finding better ways to understand, investigate and prevent major accidents (Benner, 2003, 2020; Dekker, 2004b; Hollnagel and Speziali, 2008; Hopkins, 2003, 2009; Stoop, 2014, 2020).

Commercial passenger aviation has a long and well-developed international framework for safety through the International Civil Aviation Organization (ICAO), including with mandatory independent investigation. But national arrangements vary, and major accidents still occur. Worldwide, in each year between 2008 and 2019 (pre Covid-19), ICAO reported 75–139 accidents of commercial aviation aircraft over 5.7 tonnes involving a total of 50–911 fatalities and an accident rate per million departures of 4.7 in 2008, falling to 2.79 in 2019 (ICAO, 2019c, 2020c). Despite improving technology and regulation, it is a challenge to further improve 'ultra-safe' operations (Amalberti, 2001, 2013; Dekker and Pitzer, 2016; Lofquist, 2010; Lundberg et al., 2022). Public critics sometimes consider all major accidents to be preventable and are intolerant of failure and lack of transparency. Intolerance is exacerbated by the ubiquitous spread of smart devices, a '24/7' news cycle and social media that may amplify ignorance. Maximising benefits from timely and professional investigation of major accidents and incidents and

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associated safety recommendations published by aviation Safety Investigation Authorities (SIAs) therefore remains an important priority (Bills, 2007; Braithwaite, 2010; Burin, 2018; Farrier, 2018; Stoop, 2020). This complements safety management system elements such as proactive data analysis (Stoop and Dekker, 2012; Stroeve et al., 2022).

Lundberg et al. have argued that 'what you look for is what you find' (Lundberg et al., 2009; see also Vaughan, 1992) although 'what you find is not always what you fix' (Lundberg et al., 2010; see also Hollnagel, 2004, 2008, 2020). Investigation methodologies, including Safety/Accident Models (SAMs) and theories of causation for understanding contributing factors to accidents and the role of complex systems, can inform, constrain or broaden approaches to accident investigation data collection, analysis and recommended safety action. In this paper 'methodologies' are considered broadly with a focus on the models and theories underpinning accident investigation analysis derived from both the research literature and developed or modified by SIAs internally as 'bespoke' methodologies.

Utilising the Netherlands Aerospace Centre NLR database, by 2016 there were reportedly 161 SAMs in the academic and industry literature of varying provenance and type (Karanikas, 2022) that may directly or indirectly inform investigation methodologies. This may be an underestimate as some models, discussed later in the current paper, such as by the ATSB, BEA, JST, Rasmussen, and Dekker are not listed in the 2016 or 2020 updates of this NLR database (Everdij and Blom, 2020). Listed models include: the James Reason-based 'Swiss Cheese Model (SCM)', 'Tripod', 'HFACS', 'ICAM' and 'GEMS'; the Jens Rasmussen-based 'Accimap'; 'BowTie' analysis; more recent systemic approaches such as Nancy Leveson's 'STAMP/CAST', Erik Hollnagel's 'FRAM' and some by Paul Salmon et al; various other models such as 'SHELL'; and the bespoke TSB 'ISIM' model (Everdij and Blom, 2020).[1]

ICAO's Annex 13 safety investigation framework does not specify use of such methodologies for accident investigation and analysis, or audit such methodology use under its Universal Safety Oversight Audit Programme (USOAP) (ICAO, 2020a, 2020e). The Annex 13 definition of 'investigation' assumes investigation evidence analysis to determine and report conclusions and causes and/or contributing factors and any safety recommendations. ICAO discusses some methodologies in guidance and non-binding documentation such as in its Safety Management Manual (ICAO, 2018a). ICAO's safety role and relevant publications are summarised in the Appendix A.

Research and analysis that compares and evaluates accident investigation methodologies used by government bodies rarely involves an aviation SIA. Much government investigation methodology research has involved regulatory bodies in various non-aviation high-risk industries. However, some researchers have analysed aviation accident investigation reports (e.g., Burggraaf and Groeneweg, 2016; Johnson and Holloway, 2004, 2005, 2006, 2007; Johnson et al., 2012; Pimble and O'Toole, 1982; Rashid et al., 2013; Snowdon and Johnson, 1999; Thoroman et al., 2019, 2020). Some researchers have analysed data obtained from individual aviation safety investigators (e.g., Dodshon and Hassall, 2017; Macrae, 2014; Nixon and Braithwaite, 2018; Rollenhagen et al., 2010; Underwood and Waterson, 2013a; Underwood et al., 2016).[2] Recent papers by Karanikas and colleagues are notable in both aviation categories (Chionis et al., 2022; Karanikas, 2022; Karanikas and Nederend, 2018; Karanikas and Passenier, 2019; Karanikas et al., 2019, 2020). Some researchers have highlighted a research/practice gap in relation to industry/SIA knowledge, understanding and use of more complex systemic researcher-based methodologies, and a gap also seems evident in the opposite direction.[3] However, directly obtaining information from multiple aviation SIAs about their use of researcher-based and bespoke methodologies has yet to be reported.

Karanikas has argued that because all SAMs have strengths and weaknesses, dogmatism in choice should be avoided, but safety investigations could be better supported by use of various simple or more detailed SAMs depending on context (Karanikas, 2022). Salmon and colleagues (Salmon and Read, 2019; Salmon et al., 2023: 3-4, 14-17) have suggested that use of multiple methodologies may have benefits in complex investigations.

Because ICAO does not require use of methodologies in investigation analysis and there are research gaps regarding SIA methodology use in practice, a key initial research issue is to establish what, if any, methodologies SIAs use. Exploratory research questions in relation to this 'what' element that are addressed in the current paper are:

(1) have SIAs utilised researcher-based or bespoke methodologies in investigation analysis? and if so,
(2) what methodologies have been used?
(3) have multiple methodologies been utilised by individual SIAs? and
(4) how and where has SIA methodology usage been documented?

These four questions are addressed to provide a significant step towards better understanding SIA practice. Establishing the practice of important aviation SIAs and sharing and publishing the results will inform research participant and non-participant SIAs, ICAO, researchers, and investigators in high-risk industries. This has the potential to improve options for major investigations and associated safety action even before 'why' questions regarding methodology choice, use and non-use are addressed in a subsequent phase of this research project.

[1] Linear models of accident causality were pioneered by H.W. Heinrich in his books and articles including the 'domino model' from 1934 (Heinrich, 1941: 12-15; Busch, 2018, 2021). Popular contemporary methods include Root Cause Analysis (Hollnagel, 2004: 51-52; Hollnagel and Speziali, 2008: 28), Fault Trees (Smith et al., 2017), the 'Five Whys' (Serrat, 2017), 'TapRoot' (n.d.; Paradies, 2019; Paradies and Unger, 2015); and forms of 'BowTie' analysis (Ale et al., 2006; Bellamy et al., 2007; Bice and Hayes, 2009; Ferjencik et al., 2023; Hudson, 2010; Hudson and Hudson, 2015). A '6M' organisational accident model incorporates Mission, Man, Machine, Medium, Management and Money (ICAO, 2011a: III-3–2). The software, hardware, environment, liveware and liveware-liveware 'SHELL' model was originally introduced by Edwards (1972) as 'SHEL' and extended by Hawkins from 1975 to include a diagram emphasising the human liveware-liveware interactions (Metso et al., 2016: 64, 66). It is variously referred to as the 'SHELL-L', 'SHELL', 'SHEL(L)' or 'SHEL' model (Hawkins, 1993; ICAO, 2006, 2009, 2011a, 2012b, 2018a; Skybrary, n.d.3) that we standardise as 'SHELL'. Some more recent, complex and systemic models are mentioned later in the paper and summarised in footnote [4] but comparative analysis of such models is not within the scope of this initial research paper.

[2] Other relevant research on government high-risk investigations and methodologies includes that by Benner (1975, 1980, 1985, 2013), Cedergren and Petersen (2011), Harvey (1984, 1985), Henderson et al. (2001), Hovden et al. (2010), Hulme et al. (2019), Katsakiori et al. (2009), Logan and Post (2013), Sklet (2002, 2004), Stanton (2019) and Ziedelis and Noel (2011). Additional EU investigation material has been documented by Colavita (2019), Dechy et al. (2012), ENCASIA (2020, 2022), ESReDA (2009, 2015a, 2015b, 2015c, 2020), EC (2022), Roed-Larsen et al. (2004, 2005), and Roed-Larsen and Stoop (2012).

[3] Underwood and Waterson (2013a) interviewed accident investigators and found that a decade ago they were mostly unaware of methodologies like FRAM, STAMP and Accimap. Underwood et al. (2016) noted that a systems approach "has been used as the conceptual foundation for various accident analysis techniques, of which STAMP (Leveson, 2004, 2011a), FRAM (Hollnagel, 2004, 2012, 2018) and AcciMap (Rasmussen, 1997) are the most popular within the research community" (Underwood et al., 2016, 129). But they found that "methods and tools employing a systemic perspective are not being adopted in practice. … (and) a research-practice gap exists" (Underwood et al., 2016, 129) including because they may be difficult to use (see also, Meeuwis et al., 2020). Underwood and Waterson (2012, 2013a, 2013b, 2014) among others (Chung and Shorrock, 2011; Farooqi et al., 2022; Roth et al., 2014; Saleh et al., 2010; Salmon, 2016; Shorrock, 2020; Shorrock and Williams, 2016) provide further background in relation to a gap between research and practice.

2. Material and methods

This paper uses a qualitative multi-case study research strategy where the cases are the SIAs and the research focus is their use of investigation analysis 'methodologies' - a terminology used by SIAs. A range of case study research strategies incorporate varying contexts and paradigms (e.g., Cresswell and Poth, 2017; Miles et al., 2014; Patton, 2015; Schwandt and Gates, 2017; Yin, 2018). We primarily draw on methodologist Robert Stake's work in relation to qualitative multi-case studies (Stake, 1995, 2005, 2006, 2010). Stake recommends using 4–10 cases with both similarities and diversity to understand a research focus or target in which the cases provide an 'instrumental' means to an end (Stake, 2006: vi, 1, 6–8, 14, 22–23). Our focus is establishing methodology use by SIA participants but not at this stage assessing used SAM characteristics in terms of paradigms such as systems thinking. Stake notes a dilemma and dialectic in balancing the cases with research questions associated with the focus (Stake, 2006: 7, 39, 308). He recommends that cases be considered in terms of their own situational issues, contexts and backgrounds when interpreting the focus data. However, analysing cross-case data is not simply a comparison of cases but also has a target focus (Stake, 2006: 9-12, 83). Stake considers that the study of case situations requires experiential researcher knowledge, and that multi-case complexity favours research and analysis being largely undertaken by one person (Stake, 2006: 12, 18). In this project, a multi-case strategy is appropriate for exploratory and descriptive qualitative research into SIA methodology use through documentary data provided in response to our questions. Relevant context, as summarised in the Introduction and Appendix A, was provided through a literature review and analysis by the primary researcher/author. This included the ICAO framework for aviation safety and investigation, researcher-based SAMs and other methodologies available to underpin investigation and analysis, and past research on government accident investigation methodology use in high-risk industries.

Members of the International Transportation Safety Association (ITSA) include 'important' SIAs that have met criteria for high quality independent investigations of major accidents (ITSA, 2020; Van Vollenhoven, 2001). Arguably the most important aviation SIAs are those with a long and meritorious history, responsibilities linked to the size of their own State-registered commercial aircraft fleet and/or airspace, and host State of Design and/or Manufacture of aircraft. The largest manufacturers are Airbus that is based in France and the UK, and the US-based Boeing. Canada hosts ICAO and former Bombardier aircraft are manufactured in Canada by Airbus and Mitsubishi CRJ. The Moscow-based SIA is important because it investigates commercial aircraft made in the former USSR and subsequently in the Russian Federation, has a vast airspace, and investigates on behalf of some post-Soviet States.

To establish whether the gaps summarised in the Introduction were reflected in investigation and analysis overviews on aviation SIA websites, a web search was undertaken in May 2020 by the primary researcher/author. This found mostly high-level and generic ICAO Annex 13 process material on ITSA aviation member websites including: the UK (AAIB, 2020), South Korea (ARAIB, 2020), France (BEA, 2020), Japan (JTSB, 2020), the US (NTSB, 2002, 2020a, 2020b), Sweden (SHK, 2020), Finland (SIAF, 2020), New Zealand (TAIC, 2020c), Canada (TSB, 2020a), Singapore (TSIB, 2020), Chinese Taipei (TTSB, 2020) and the Interstate Aviation Committee (IAC/MAK) led by Russia (IAC, 2020). A similar result was found for newer ITSA members from Argentina (JST, 2022) and Papua New Guinea (AIC, 2022). Only Norway, which changed its SIA name acronym from AIBN to NSIA after its website was first accessed (AIBN, 2017, NSIA, 2021, 2022), and to a lesser extent Australia (ATSB, 2019a; Walker and Bills, 2008) and the Netherlands (DSB, 2020a), included some details of investigation analysis methodology. There was a potential gap in knowledge and use of investigation methodologies and/or documentation among this diverse group comprising all 17 ITSA aviation SIA members. At this stage, any methodology usage documentation in the hundreds and thousands of past aviation investigation reports on individual SIA websites and/or within any SIA internal non-public material was unknown.

Reiman and Viitanen (2020) have suggested a strategy of collaborative applied research, while Rae et al. (2020) proposed a safety science research 'manifesto' to address the gap between researchers and practitioners by focusing on research into work-in-practice and incorporating collaborative industry case studies. Collaborating with ITSA SIAs to establish, document, and understand their use of major aviation investigation analysis methodologies is consistent with such guidance.

To progress the research, university ethics approval was obtained and all 17 of the ITSA members that investigate aviation accidents were invited to participate in the research, respond to research questions, and provide links to exemplar investigation reports and any other documentary support about their methodology use. By December 2022, nine had formally agreed and provided the sought data - a diverse sample of over half the ITSA membership including well-recognised and important independent government SIAs drawn from the UK and Europe, North and South America, Asia and Australasia. In alphabetical order, the nine SIAs are the Air Accidents Investigation Branch (AAIB) of the United Kingdom, Australian Transport Safety Bureau (ATSB), Bureau d'Enquêtes et d'Analyses pour la sécurité de l'aviation civile (BEA) of France, Dutch Safety Board (DSB), Japan Transport Safety Board (JTSB), Junta de Seguridad en el Transporte of Argentina (JST), Safety Investigation Authority of Finland (SIAF), Transport Accident Investigation Commission (TAIC) of New Zealand, and the Transportation Safety Board (TSB) of Canada.

The research approach initially involved establishing primary researcher credibility, ethics and trust in order to recruit ITSA participants that were required to sign a participation form and provide the sought documentary material noted in the previous paragraph. This was not a straightforward process because ITSA aviation SIAs had not previously agreed to such research and could face potential public embarrassment depending on the content of any research publications. It could also present ethical issues in relation to delegated SIA individuals who had provided the data. The primary researcher was able to satisfy the then ITSA Chair that these issues would be appropriately addressed.

In October 2020 the ITSA Chair sent all ITSA SIA heads a covering email supportive of the primary researcher's project, noting his past SIA and ITSA background, to which was attached a copy of the research participation letter and agreement. Seven SIAs signed the agreement expeditiously and supplied the documentary data. In order to increase participation by ITSA SIAs, the primary researcher attended the August 2022 International Society of Air Safety Investigators (ISASI) Annual Seminar (not held face-to-face in 2021 because of Covid-19) and informally encouraged some senior SIA investigators and board members present to reconsider the research project invitation. This led to the UK AAIB and Japan's JTSB also becoming participants and the NTSB actively reviewing participation. As a result, more than half of the 17 ITSA SIAs that investigate aviation accidents were able to be included.

The primary researcher carefully reviewed and summarised the data and material that was obtained from the nine ITSA SIA participants. This included their written responses to research questions together with links to exemplar investigation reports and any other documentary support about methodology use. This provided a basis for a draft of the current qualitative exploratory and descriptive article. The draft included some individual SIA context, addressed four research questions, and indicated each SIA's most recent ICAO USOAP audit result. No significant material provided by the SIAs that related to the focus and questions in the draft article was omitted (other material provided by the SIAs will be used in future publications). The draft paper was sent to participant SIAs in January 2023 as part of the agreed collaborative approach. This enabled them to propose 'member checking' corrections to increase trustworthiness and address any errors, omissions, unconscious bias or misrepresentation (Birt et al., 2016; Stake, 2006: 37), and to avoid any unintended public or political SIA embarrassment. A few SIAs suggested small changes or updates that were included. The two other authors periodically reviewed the draft article and proposed changes to ensure clarity and improve the paper's structure.

3. Results from the ITSA SIA participants

Individual SIA backgrounds and research data on use of methodologies is documented below with key results, similarities and differences tabulated in Section 3.10 and discussed in Section 4.

3.1. AAIB

The UK Air Accidents Investigation Branch (AAIB) and its predecessors have a long and distinguished history of aviation safety investigation since 1915 at the start of commercial aviation (Matthews, 2014). AAIB's ITSA membership is through the Accident Investigation Chiefs' Council that also includes marine and rail accident investigation branches (AICC, 2019). The AAIB advised that beyond the ICAO framework the AAIB "don't have a mandated or even preferred analysis methodology. Rather investigation teams draw on a variety of methodologies and in a variety of levels of formality depending on the needs of the particular investigation" (AAIB, 2022a). The AAIB response to our research questions (AAIB, 2022b) included reference to three reports illustrating the use of various investigation methodologies (AAIB, 2010, 2016, 2017). AAIB stated that while it does not promote any single methodology, its Operations Manual section on Analysis Methods has "links to several sites which we consider have suitable methods" (AAIB, 2022b) including: the Norwegian AIBN (2017), ATSB (Walker and Bills, 2008), UK Health and Safety Executive (HSE, 2004), STAMP and CAST (Leveson, 2004, 2017b), and the UK Energy Institute (2008). Human factors methodologies and processes used, as required, included: "Accimap, Boeing Maintenance Error Decision Aid (META), CIEHF White Paper on Human Factors in Barrier Management, Human Factors Analysis and Classification System (HFACS), SESAR human performance repository (GEMS, HEART, HERA, ATM-TRACEr), SHELL model, Fatigue Investigation data collection guidance, Startle and Surprise guidance, Guidance on investigating organisational factors" (AAIB, 2022b). Further, AAIB stated that "Where the investigation is very heavy on the technical side, we tend to run with the manufacturer's methodology", so with the Boeing 777 fuel icing investigation (AAIB, 2010), the focus was on "Technical investigation reliant on Apollo (Boeing) and DRED (Rolls Royce). …" (AAIB, 2022b). Methodology preference by the Investigator in Charge (IIC) and suggestions by Accredited Representatives were also relevant in various investigations (AAIB, 2022b). Overall, "The methodologies all have advantages and limitations; inspectors [investigators] all think differently. A methodology needs to encourage creativity to allow thinking outside the box, while having the discipline to pull the multiple threads together" (AAIB, 2022b).

Great care is taken in selection of investigators (Smart, 2004), with AAIB reports renowned for technical excellence, independence and collaboration (Braithwaite, 2010; Vickery, 2016). Initial training includes use of BowtieXP (AAIB, 2022b). The most recent ICAO audit of effective implementation of applicable standards for Accident Investigation was in 2009 with a score of 70 % compared with the global average of most recent USOAP mission year audits of 54 % (ICAO, 2023). The USOAP is focused on a State (such as the United Kingdom of Great Britain and Northern Ireland) but in some cases, such as the UK and the Netherlands, overseas territories may be included by ICAO (BEA, 2023b). While the AAIB investigates aviation accidents and serious incidents, the UK Airprox Board investigates airspace proximity occurrences, and broader reporting of UK occurrences is to the UK Civil Aviation Authority (CAA, 2022a, 2022b).

3.2. ATSB

The Australian Transport Safety Bureau (ATSB) has been Australia's independent no-blame multi-modal accident investigator since 1 July 1999 (ATSB, 2019c, 2020a, 2020b). It incorporated modal predecessors including the Bureau of Air Safety Investigation (BASI) that had a prior history from 1927 (ATSB, 2009: 1; Matthews, 2014). From 1991, BASI pioneered use of an early version of the Reason model (ATSB, 2009: 23; BASI, 1994; Reason 1990a, 1990b, 1991a, 1991b). BASI noted that Reason's accident causation model was becoming an industry standard that ICAO encouraged for use in investigating the role of management policies and procedures in aircraft accidents and incidents (BASI, 1994: 45-58). BASI Director, Dr Rob Lee, also worked with Professor James Reason, Neil Johnston and ICAO's Captain Dan Maurino to help develop the ICAO Safety Management System (SMS) approach (Maurino et al., 1995; Lee, 2017). Since 2002, major ATSB investigations have been based on a system safety investigation methodology (Walker and Bills, 2008; Walker 2019). Beyond its roots in models by Reason (1990a, 1990b, 1991a, 1991b, 1995, 1997, 2000, 2003, 2008), Reason and Hobbs (2003), Reason et al. (2006), Walker (2003) it has been modified to incorporate insights from other theorists, BowTies, and to require contributing factor evidence tables, and make language more neutral (ATSB, 2020e, 2023b; ATSB and NTSC, 2018; ICAO, 2018b; Underwood and Waterson, 2013a; Walker and Bills, 2008). From 2004, the ATSB drew from the Canadian TSB's pioneering Integrated Safety Investigation Methodology (ISIM) IT-based system and process (see Section 3.9 below) to develop a bespoke ATSB version termed the Safety Investigation Information Management System (SIIMS) that included analysis (ATSB, 2007b: 67; 2009: 19, 25). The ATSB adapted Reason's model to include risk recovery controls (see Diagram 1) and included key aspects from Jens Rasmussen's Socio-technical hierarchy system model and 'Accimap' presentation (ATSB, 2023b; Hopkins, 2000, 2009; Rasmussen, 1990, 1997; Rasmussen and Svedung, 2000; Svedung and Rasmussen, 2002; Walker and Bills, 2008) (see Diagram 2) where the focus is on the five levels of hierarchy on the left reading from the bottom up.

ATSB investigations assess contributing factors on a whole-of-system basis rather than just seeking a proximal or probable cause or causes (Hopkins, 2014: 11; Walker and Bills, 2008). Safety action is recommended if safety issues are found during an investigation regardless of their linkage to accident causality, and directed to the body or bodies most relevant to addressing the safety issue (ATSB, 2019b, 2020c, 2020d, 2020e, 2021a). ATSB investigation analysis does not use a simple linear sequential or 'epidemiological' model but is systemic and uses a 'link-to-link' approach to assess evidence and ascribe a probability between links in a hierarchy progressively more remote from the accident event. The methodology and associated processes were designed to suit a professional safety investigation and safety improvement context (Stoop, 2014; Stoop and Dekker, 2012) rather than a narrower focus on probable cause or concepts of legal causality that may be used to ascribe blame or liability (Benner, 2003; Walker and Bills, 2008). At the invitation of the ATSB, methodology and processes were peer reviewed by the TSB after a controversial and problematic ATSB report into a non-fatal Norfolk Island air ambulance fuel exhaustion ditching accident. In summary, the ATSB's methodology and systems were found to represent best practice provided its processes were consistently applied and checked in a timely manner, which had not always occurred (TSB, 2014b). The re-released report is now one of three nominated methodology exemplar reports (ATSB, 2017, 2021b, 2022a, 2023a). The ATSB investigation model was revised slightly in 2013 and again at the end of 2019 when new documentation was prepared as part of a formal investigation teaching collaboration with RMIT University (ATSB, 2022c; RMIT, 2019, 2022). For the purposes of this research, the ATSB provided copies of its extremely detailed bespoke internal manuals with, for example, much more material on the use of causal charts and influence diagrams involving hypothesis testing (ATSB, 2019b, 2020c, 2020d, 2020e). A new ATSB Investigation Management System (AIMS) has recently been launched with a new software platform and taking a project management approach (ATSB, 2021c, 2022b). The most recent ICAO audit of effective implementation of applicable standards for accident investigation in Australia was in 2022 with a score of 96 %

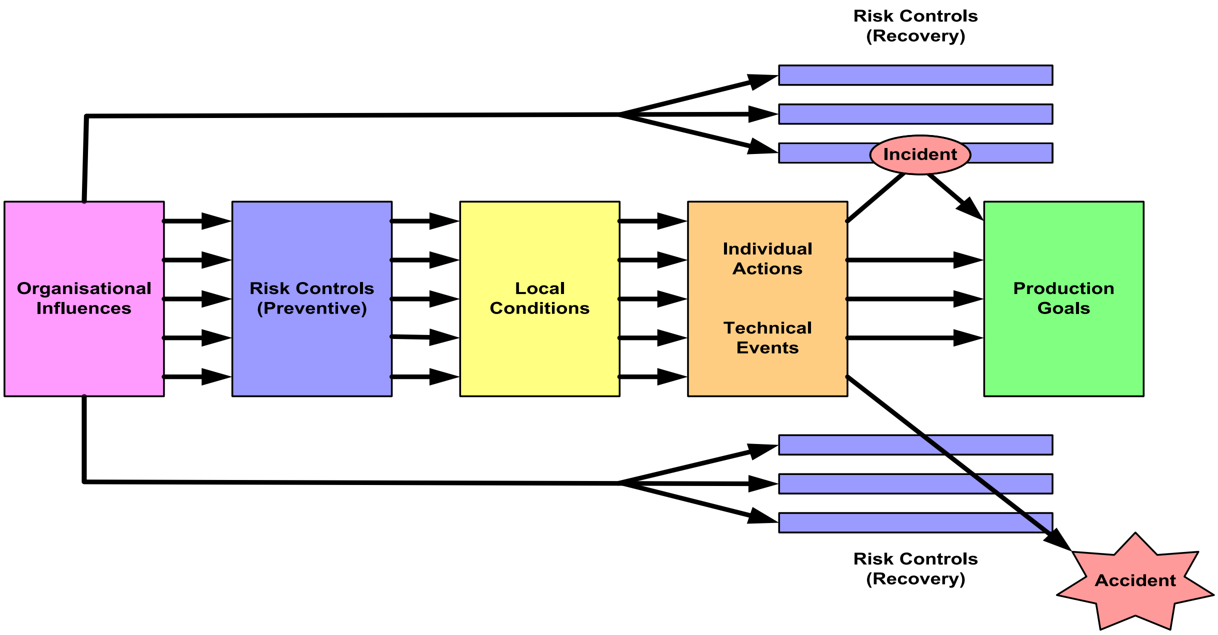

Diagram 1. ATSB adaption of Reason model (Walker and Bills, 2008: 36).

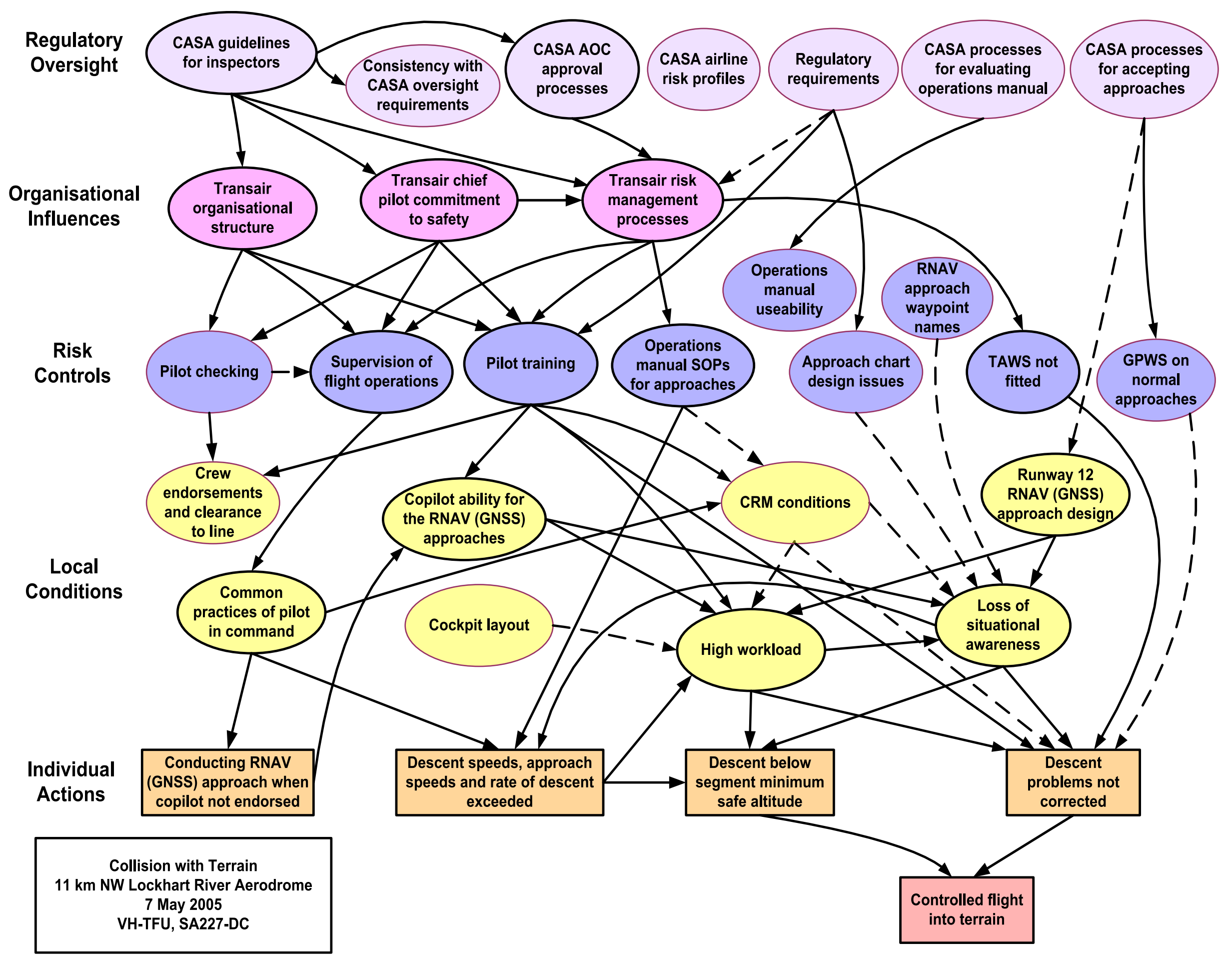

Diagram 2. ATSB systemic investigation and analysis example using a 15-fatality scheduled commercial passenger aviation accident incorporating Rasmussen's hierarchy and 'Accimap' (ATSB, 2007a; Walker and Bills, 2008: 46).

compared with the global average of the most recent USOAP mission audits of 54 % (ICAO, 2023).

3.3. BEA

The Bureau d'Enquêtes et d'Analyses pour la sécurité de l'aviation civile (BEA) of France has a distinguished history in aviation accident investigation since 1946 (Matthews, 2014). Extensive BEA State of Design and Manufacture responsibilities include Airbus, ATR, Dassault Aviation, Daher, CFMI (a GE and Safran joint venture), and Airbus Helicopters (BEA, 2023a). The BEA has an investigation role in French territories around the world. The BEA (2021) provided public links to two major investigation reports to illustrate its use of analysis methodology (BEA, 2012, 2016b). An ISASI paper (Choudet and David, 2017) provided 'presents BEA analysis methodology' (BEA, 2021). The methodology's background is from the Dédale SAS company (BEA, 2023a; Gilbert et al., 2007; Pariès, 1999; Steele and Pariès, 2007, 2008). Presentations at ICAO in 2015 provided useful developmental detail (Desjardin, 2015a, 2015b, 2015c). The BEA methodology was further outlined at other meetings of ICAO and ISASI (BEA, 2018; Rome, 2018).

The BEA emphasised the use of a structured analysis methodology looking at both explanatory factors and similar occurrences and actual practices more broadly, and communicating lessons persuasively.

This process is iterative and has increased in complexity when looking at systemic and organisational issues. … As an accident or incident can be considered as a failure of actual control risk measures (not only regulatory and documented ones), the analysis methodology must also study actual practices and similar occurrences. The analysis methodology adopted by the BEA is adapted from MINOS© [developed by Dedale company as a pragmatic step-by step guide for safety investigators]. With this approach safety is considered as the ability to manage perturbations rather than its conformity to a predetermined behaviour considered as safe. An accident or an incident is therefore considered as an escape from a controlled environment. The BEA analysis methodology consists in four iterative steps (Choudet and David, 2017).

The first step, based on the theory of joint cognitive systems (Hollnagel and Woods, 2005), defines the sociotechnical system, the operational situation and the occurrence category. The analysis framework includes operators and the operational situation before and during the occurrence, and seeks to limit hindsight bias. This enables selection of relevant similar events. The second step determines the safety principles in the operational situation and considers system safety in relation to implicit and explicit safety expectations, provisions and assumptions in the way safety is normally assured. The third step describes the performance of 'safety principles' during the occurrence and considers what actually happened that led some to fail and others to lead to positive success. The fourth step analyses and explains both failure and success in terms of performance variability (Hollnagel and Goteman, 2004) and determines the robustness of controls utilising three possible means: classic explanatory causal analysis, comparison with similar occurrences, and analysis of everyday operations and actual practices (BEA, 2018; Choudet and David, 2017; Rome, 2018). The third of these possible means establishes how errors can occur such that:

if similar failures are not observed, the variability may be an exception to usual practices. If not, the reliability of the safety expectations and provisions can be considered as insufficient with risks that will be addressed in lessons learnt and safety recommendations. Data science significantly increases the accuracy of this analysis. The use of these analyses is crucial to … [be] convincing and persuasive to the aviation community. (Choudet and David, 2017).

The BEA uses a 'gutter' pictorial metaphor model of an accident. This illustrates that a non-linear system accident is the result of an unrecovered loss of control of the system's (disturbed) dynamics (Rome, 2018). In Diagram 3, the green ball accelerates down a curved incline gutter. It normally stays under control within the gutter edges. Occasionally environmental and other vagaries, and disruptions of normal

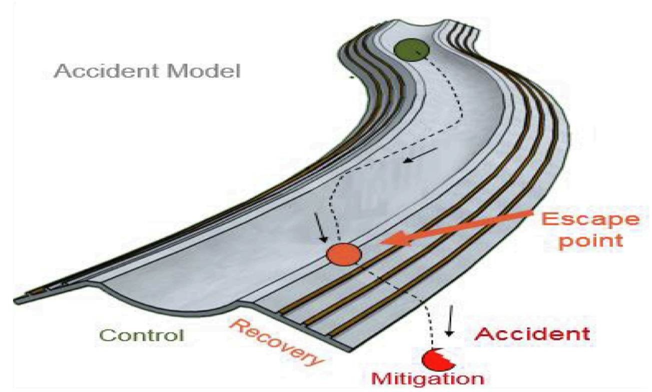

Diagram 3. BEA 'gutter' accident model adaption of Dédale MINOS (BEA, 2018, 2023a; Rome, 2018).

work and activity, may be strong enough to allow the ball to escape out of the gutter. Without successful recovery mitigation, the ball's loss of control leads to an accident:

The escape point is the state of the sociotechnical system after which an accident occurs if no recovery actions are taken (the ball is forced out of the gutter). Escape points such as 'a visual approach towards an inappropriate runway' or 'undetected conflicting flight paths' are examples that illustrate the concept (BEA, 2018: 3).

The BEA cited Dekker (2004c) in support of the point that:

*The aim of safety analysis is to understand why there are occurrences and draw up recommendations to prevent their re-occurrence. These two objectives are complementary but not alike. Indeed, predictions (and thus recommendations) are possible only because "we have created some kind of 'model' for the situation we wish to gain control over, not because we can exhaustively foresee every contextual factor, influence and data point" (*Dekker, 2004*).* (BEA, 2018: 2).

BEA analysis methodology allows for determination of contributing factors by listing the functions and mechanisms that failed to ensure flight safety (BEA, 2023a). The BEA has drawn from Rasmussen's (1997) work on migration or drift towards unsafe boundaries in relation to general aviation accidents and helicopter firefighting (BEA, 2016a; Boudou and Ferrante, 2002; Rome, 2019).

A final report into a serious incident on 11 March 2017 of an Airbus A340 with 268 passengers and 13 crew found that an abnormally long take-off towards the end of the runway led to the aircraft flying over the opposite runway threshold at a height of 6 feet and clearing ILS antennas by only 12 feet. The pilot flying's nose-up input was insufficient to reach the rotation rate of 3 degrees per second assumed in the A340's certified performance model. This theoretical performance model was found to be inconsistent with data from 2,300 actual A340 take-offs from Bogotà which had averaged 1.8 degrees per second. In part, this was because the runway safety margin had been eroded by an airline emphasis on the risk of tailstrikes that can occur if nose-up input is excessive during the takeoff. Underpinning the report, but not stated explicitly, is the BEA's systemic model and the influence of risk trade-offs as suggested by Rasmussen (BEA, 2019; Ecalle, 2020).

The BEA has emphasised the need for technical competence and collaboration as well as independence in investigation (David and Romat, 2017; Jouty, 2016). The most recent ICAO audit of effective implementation of applicable standards for accident investigation in France was in 2020 with a result of 100 % compared with the global average of most recent USOAP mission audits of 54 % (ICAO, 2023).

3.4. DSB

The Dutch Safety Board (DSB) website included the following brief overview of methodology under 'Analysis' in relation to DSB investigators: "In order to do so in a structured way, they use investigative techniques such as the timeline analysis, the Tripod model, the BowTie method and STAMP" (DSB, 2020a). The DSB provided answers to the research questions and links to two example reports on a serious taxiway incident and on air traffic safety at Schiphol airport that demonstrated use of analysis methodology (DSB, 2011, 2017). DSB included material on use of Tripod (STP, 2007) and STAMP/CAST models (Helferich, 2012; Leveson and Stringfellow, 2009), and a report in Dutch (DSB, n.d.) describing a bespoke tool used "to collect and analyse data about power and influence" (DSB, 2020b).

The DSB stated that for more complex safety investigations it:

*uses several methods to analyse (aviation) accidents/occurrences and the system in which they occur. For the analysis of accidents/occurrences we use Sequentially Timed Events Plotting (STEP → reconstruction of the accidents and emergency and rescue part) and Tripod Beta to identify barriers that failed or were missing. In the investigation into air traffic safety at Amsterdam Airport Schiphol we analysed all occurrences that took place on and around the airport using Tripod Beta [*DSB, 2011*]. For the take-off from the taxiway we used Tripod Beta as a method to analyse a single occurrence [*DSB, 2017*]. For the safety study of Schiphol, the results of the separate Tripod analyses were compared using cross-case analyses (comparing failed barriers and preconditions across the occurrences). The common factors that were found in this cross-case analyses created the point of departure for the analysis of the hierarchical structure that should control the identified hazards. Furthermore, we used a method to analyse the balance of forces/fields of influence at the airport (civilians living near Schiphol, e.g. noise nuisance, pollution; parties with financial-economic interests) in relation to the safety deficiencies that were identified. For the analysis of the system in which an accident or several accidents took place we sometimes use CAST (Causal Analysis using STAMP).* (DSB, 2020b).

The most recent ICAO audit of effective implementation of applicable standards for accident investigation in the Netherlands was in 2008 with a score of 73 % compared with the global average of the most recent USOAP mission audits of 57 % (ICAO, 2022g).

3.5. JST

The Junta de Seguridad en el Transporte (JST) was created as Argentina's multimodal Transport Safety Board in 2020 and incorporates the former JIAAC Civil Aviation Accident Investigation Board. The JST became a member of ITSA in 2020 and provided the sought research data later that year (JST, 2020). It reported that since 2014 its approach included "all the organizational factors and safety deficiencies contributing to the accident". In 2017 the 'cause' of the accident was replaced by conclusions in relation to factors related to the accident and related to other safety risk factors not directly related to the accident but identified in the investigation (JST, 2020). The JST advised that since becoming multimodal in 2020:

the need of using an investigation methodology ensuring the implementation of the 'systemic approach' model in all the investigations arose. In this regard, the JST has been exploring different methodologies implemented by other AIAs (Accident Investigation Authorities), such as Accimap, bow tie and a combination of both. Currently, these methodologies are being assessed and implemented in some accidents in order to evaluate their applicability according to our model. … both individually and combined, in complex investigations. Besides, some investigators use a methodology developed by one of them as a tool to organize the information and investigation ensuring the systemic approach. This methodology can be easily implemented to any type of event and is called Vortex (see attachment). … We can … say our preliminary use of them (Accimap, bow tie) is that both methodologies do not overlap but they are complementary. We consider that an investigation methodology must be a universal and easy tool (to use in an incident as well as in a major accident) that can assist investigators to organize the investigation and collect the necessary information to conduct a systemic investigation and helps avoid not considering aspects in the early stage of the investigation (JST, 2020).

In addition to two aviation accident report examples, JST provided a '5.16 Methodological Guide for Human and Organizational Factors'. This used an adapted 'Swiss Cheese' model of Reason and stated that "the JST adopts a systemic/epidemiological approach for the analysis of accidents, serious incidents and incidents, making some necessary adjustments for the Argentine aeronautical context" (JST, 2020). A further attachment entitled 'Vortex Method of Investigation' was authored by Daniel Barafani as National Director Aviation Investigations from 2016 to 2019 (JST, 2023). As well as Reason (1997), this listed Heinrich's 1930s Domino Model (Heinrich, 1941: 13–18) as 'the most relevant approaches to investigation' leading towards a Vortex systemic approach. The three models are seen to be applicable individually or in combination depending on the accident or incident to improve safety and move beyond human error and technical failure. Barafani's 'Vortex' Investigation Method examined three levels of system context – micro-operational, operational, and macro-operational. In each level, operational errors, technical failures, real or potential deficiencies, and defences/barriers should be considered in a cyclical way. In Vortex, defences and barriers are classified as Standard or procedures, or Training, or Technological (STT). Further summarising Vortex:

In accidents or complex incidents, there may be as many vortexes as elements involved in the occurrence interacting among each other … according to how they connect, we will be able to identify the interaction that was decisive … This methodology is a practical guide allowing investigators to be organized to be able to analyze each element involved from an operational staff, an aeronautical component, infrastructure, an organization, to the aeronautical authority itself from a systemic point of view. Through the STT analysis of each of them and the performance of the different defences of each turn of the vortex, we can identify the real or potential safety deficiencies, directly or indirectly related to the accident/incident, which were not effective to prevent the error or failure. (JST, 2020).

JST training includes "techniques and procedures for the investigation of accidents and incidents with an interdisciplinary and systemic approach" (JST, 2022). Utilising its 2020 Protocol Questions, ICAO conducted a first Argentina USOAP audit "in June 2022 in order to determine the level of effective implementation (EI) of the SARPs set out in Annex 13 and related documents" (JST, 2023). The JST had a 2022 USOAP audit score of 89 % compared with the global average of the most recent USOAP mission audits of 54 % (ICAO, 2023).

3.6. JTSB

The Japan Transport Safety Board (JTSB) responded to the research questions with supporting extracts from the JTSB 'Accident and Serious Incident Investigation Manual' (JTSB, 2022b, 2022c, 2023), and two example investigation reports (JTSB, 2013, 2014). JTSB's senior aviation investigators and the highly qualified Chairperson and five specialist aviation subcommittee board members use a range of methodologies supported by ICAO such as the human factors 'SHELL' model and '6M' organisational model, combined with a Reason model and other ICAO material on organisational issues (JTSB, 2022b, 2022c). The final investigation report into a Boeing 737–700 serious incident involving an upset event and nosedive on 6 September 2011 included an Appendix 4 Factor Classification Table and four pages of analysis based on the SHELL model comprising Software, Hardware, Environment, and Liveware with other Liveware factors linked to the first four. This helped the JTSB to establish how and why human and ergonomics factors led to the First Officer's 'erroneous' operation of rudder trim (JTSB, 2014).

The JTSB emphasised that use of methodologies depended on the stage of investigation and analysis, stating that:

"[In] the information-gathering stage, the fish bone model, SHEL[L] model … and 6 M model are often used in order to fully understand the circumstances leading up to the accident and to prevent omissions" (JTSB, 2023).

Analysis may begin with Variation Tree Analysis (VTA) to establish "chronological order according to the parties involved (actors)" and conclude with a cascading 'why' process [similar to the Five Whys] to help logically structure the report and a Fishbone model". The ATSB model is 'often used' for a 'complex accident' that requires "deeper analysis of technology, individual behaviour, site conditions, and operator risk management, organizational impact, and laws and regulations" (JTSB, 2023). The example reports used NTSB-type 'probable cause/s' language and other safety-related matters or findings and referenced 'erroneous' actions (JTSB, 2013, 2014). Investigator training included human factors and may include Cranfield University and the NTSB Academy (JTSB, 2011, 2022a, 2022b, 2022c). A digest of safety-related lessons from multiple themed cases is published annually or biannually in Japanese (JTSB, 2023). The latest ICAO audit of effective implementation of applicable SARPs for accident investigation in Japan was in 2010 with a score of 96 % compared with a global average of the most recent USOAP mission audits of 57 % (ICAO, 2022g).

3.7. SIAF

The Safety Investigation Authority, Finland (SIAF) provided its research response (SIAF, 2020b), a link to an overview of Accimap (Rasmussen and Svedung, 2000), a full exemplar accident report in English (SIAF, 2019) and key elements of a report on two serious incidents on successive days (SIAF, 2018). The two serious incidents involving incorrectly entering active runways, were each analysed using chain of events plus Engeström's 'developmental work research method' that includes a diagrammatic model with four triangles nested in a larger triangle that consider, for each relevant actor, Rules, Subject, Tool, Target and Division of Duties (SIAF, 2020b; see also Blunden, 2015). SIAF responded to the research questions that:

*We have systematically developed investigation methodology. We use a chosen analysis method in every investigation. Mostly we use AcciMap … a systems-based technique for accident analysis, specifically for analyzing the causes of accidents and incidents that occur in complex sociotechnical systems. … Accimap was originally meant for analyzing and managing risks [*Rasmussen and Svedung, 2000*], but its primary application has been as an accident analysis tool…. We have developed the original technique a little further for our specific needs. We also use rarely other methods such as the Bowtie method, the Grounded Theory or the Activity Theory of Yrjö Engeström. ….*

We like to use AcciMap because it provides a systematic tool for describing the sequence of events leading to the accident and then finding and linking factors that created circumstances for the accident development. Factors contributing to the accident can be found at different levels of analysis. The AcciMap technique encourages [investigators] to search for work practices, organizational factors, industry level factors and problems in legislation. … AcciMap is not so useful in theme investigations where several accidents are investigated at the same time. In these investigations of multiple cases, we have for instance used the Grounded Theory method. The two serious incidents at Helsinki-Vantaa aerodrome we analysed by first describing the chain of events similarly as in AcciMap and then analysed each phase in the chain of events by using the Activity Theory of Yrjö Engeström. … The used analysis method depends on the special characteristics and circumstances of the analyzed accident. It is important that we manage to analyze that case deeper than just focusing on the traditional human factors (HF). The traditional HF analysis focuses too much on pilots and neglects work practices, systemic factors and organizational safety management activities. … the AcciMap method has proven to be more complete than many other methods. … [however] the demonstration of the incubation period depends on the expertise of the AcciMap user. The method itself does not encourage such thinking. (SIAF, 2020b).

The latest ICAO audit of effective implementation of applicable SARPs for accident investigation in Finland in 2018 scored 98 % compared with the global average of the most recent USOAP mission audits of 57 % (ICAO, 2022g).

3.8. TAIC

New Zealand's Transport Accident Investigation Commission (TAIC) includes some broad material on evidence analysis and process on its website (TAIC, 2020c). TAIC's initial response to research questions (TAIC, 2020a) included copies of TAIC Investigation Guidelines covering Analysis, a list of recent aviation occurrence reports, and a link to an example final report involving a non-fatal helicopter forced landing during firefighting operations in 2019 (TAIC, 2020b). TAIC's then CEO explained in 2007 that for TAIC:

Systems behaviours and system learnings are key concepts in the Commission's current thinking. … Applying systems thinking brings the quality of interactions between system agents (parts) into sharp relief. Considerations brought to bear on the inquiry go to: i. the events leading up, during, and immediately after the occurrence, ii. Patterns that emerge out of the interactions of the system agents, or the system's interaction with other systems, iii. The influence of systemic structures, iv. The influence of peoples mental models on their interactions with the system(s). The systems of interest to the Commission influence the scope and scale of its inquiries. … Delving into operator or sector systems may require human and organisational factors, financial auditing, business consulting, and economic analysis skills on top of the specialist accident investigation skill sets already engaged. (Hutchinson, 2007).

In answering the specific research questions, TAIC responded that its investigation "analysis methodology is based on the ATSB investigation analysis model which is based on the Reason model. TAIC also uses other analysis techniques such as mind-maps, timelines and Human factors analysis" (TAIC, 2020a).

Using a bespoke systemic approach, the Civil Aviation Authority of New Zealand (CAA) aviation regulator also undertakes a large number of aviation investigations when TAIC does not assert its primacy (Foley and Harris, 2020). The most recent ICAO audit of effective implementation of applicable SARPs for accident investigation in New Zealand was in 2016 with a score of 78 % compared with the global average of the most recent USOAP audits of 57 % (ICAO, 2022g). This result includes the relevant roles of TAIC and the CAA.

3.9. TSB

The Transportation Safety Board of Canada (TSB) provided responses to the initial research questions together with in-house methodology documentation and two exemplar investigation reports (TSB, 2020b). The responses and in-house documents provided were all marked 'Confidential – Not for Distribution' and included detail of the TSB's Integrated Safety Investigation Methodology (ISIM) updated from its origins in 1999, with a Reference Manual, User's Manual, Lexicon, chart of major ISIM components and sub-components, and an overview of methodology (TSB, 2020b). This material provided very helpful background to ensure that methodological references in public TSB investigation reports and in presentations by TSB leaders and investigators were properly understood and characterised by the primary researcher/author without breaching confidence.

The previous TSB Chair highlighted how the newer investigation view considers accidents broadly "in the context of an organization's overall policies and priorities … [and does] not talk about pilot error anymore" (Tadros, 2013; TSB, 2014a). The current Chair reinforced these points and argued that "To keep improving we need to expand our scope and take a more in-depth look at the organizational factors that contribute to accidents, as well as the regulatory environment … [noting that regulators] have moved away from a traditional 'inspect and fix' approach to a systems-level approach" (Fox, 2017). Chair Fox's 2021 ISASI keynote speech referred to older 'linear' models of accident causation by Reason but now found Rasmussen's 'safe operating envelope' particularly relevant. She stated that:

Safety investigators, of course, don't rely on just two models any more than they rely on any two tools" and "it helps our safety investigators to

Table 1
ITSA SIA reported use of accident investigation analysis methodologies.

ITSA SIA	Reason*	Rasmussen**	Recent***systemic	BowTie	Bespoke	Other
AAIB	✔	✔	✔	✔		Multiple various including SHELL & ATSB
ATSB	✔	✔		✔	SIIMS/AIMS	Multiple various including SHELL
BEA		✔	✔		Gutter model (via Dédale MINOS)	
DSB	✔		✔	✔	Power and influence analysis	STEP, timeline analysis
JST	✔	✔		✔	Vortex model	Heinrich Domino model
JTSB	✔					SHELL, 6 M, 5 Whys, VTA, ATSB, Fishbone
SIAF		✔		✔		Engeström's activity theory & developmental work research method, power analysis, chain of events, grounded theory
TAIC						ATSB, mindmaps, timelines, human factors analysis
TSB	✔	✔			ISIM	

*Including Tripod, HFACS, GEMS, Swiss Cheese Model and Reason's more complex systemic variants.
**Including Accimap, socio-technical Hierarchy, and Migration to safety boundaries.
***Including Leveson's STAMP/CAST, Hollnagel's FRAM, and other models by Hollnagel and by Dekker.
Note that columns are only ticked when explicit SIA mention is made in written responses or publications[4].

follow a rigorous methodology … [ISIM] is the backbone of every TSB investigation, an eight-step process. (Fox, 2021).

Fox's paper included a TSB diagram listing eight steps: 1. Occurrence assessment process, 2. Data collection process, 3. Occurrence sequence of events identification and diagram, 4. Integrated investigation process, 5. Risk assessment process, 6. Defence analysis, 7. Risk control option analysis, 8. Safety communication process (Fox, 2021).

Previously, TSB human performance investigators had highlighted the influence of Reason's work including in a second edition of the TSB *Guide to Investigating for Organizational and Management Factors* (c2013) first produced in 2002 as underpinning the TSB ISIM methodology (Morley and Stuart, 2013, 2014). Morley subsequently argued that to maximise safety benefit from investigations required:

five critical success factors 1. Follow a method [an investigation methodology based on good safety science such as ISIM], 2. Back up your method with tools and frameworks [complementary frameworks such a version of Reason's Generic Error Modelling System used by the TSB], 3. Use a team, 4. Iterate, 5. Consider the whole system (Mumaw et al., 2018: 8–9).

The TSB stated that it planned in 2022–23 to "implement new tools and procedures to improve the management of investigation activities and enhance the safety analysis by providing updated guidance that supports the iterative approach of the Integrated Safety Investigation Methodology (ISIM)" (TSB, 2022). The most recent ICAO audit of effective implementation of applicable SARPs for accident investigation in Canada was in 2005 with a score of 91 % compared with the global average of the most recent USOAP mission audits of 54 % (ICAO, 2023).

3.10. Summary of results

Investigation methodologies used by the nine ITSA SIAs outlined earlier in this section are summarised in Table 1 below. A mixture of commonality and difference is evident and the use by all SIAs of multiple methodologies is noteworthy. This material is discussed in Section 4.

4. Discussion

4.1. Discussion of results

Investigation methodologies used by the nine ITSA participant SIAs were reported in Section 3 and summarised above in Table 1. Such methodologies complement specialist insights by individual SIA investigators based on their technical disciplines and past generalist investigative experience including as pilots, air traffic controllers, maintenance engineers, cabin safety, human and organisational factors, metallurgists and recorder specialists.

Most SIAs would be aware of the SHELL model and the Reason model discussed for decades by ICAO (outside of Annex 13 and other ICAO requirements), and some were explicit about using them in systemic investigations, including Reason's Swiss Cheese Model and underpinning of Tripod, HFACS and GEMS. Six SIAs cited Reason's models and six SIAs cited Rasmussen's models such as Hierarchy, Migration, and Accimap. Three SIAs documented use of 'recent' systemic models such as by Leveson, Hollnagel and Dekker. Five SIAs documented use of BowTie analysis. Documentation by three SIAs (AAIB, ATSB and JTSB) explicitly mentioned SHELL and in total seven SIAs reported use of at

[4] James Reason's 'Swiss Cheese Model' (SCM) accident causality metaphor (Reason, 1995, 1997, 2008, 2016; Reason et al., 2006) is based on work by Barry Turner (1978) in relation to the incubation of latent conditions and confluence with active failures via a trigger event (Bills et al., 2023). Reason's work is well known and has long been supported by ICAO for investigation practice (BASI, 1994; ICAO, 2006, 2009, 2011a, 2012b, 2018a; Maurino et al., 1995). It underpins methodologies such as: Tripod (Energy Institute, 2015; Groeneweg, 2002; Groeneweg et al., 2010; Hudson et al., 1994; STP, 2007; Verhoeve et al., 2004; Wagenaar and van der Schrier, 1997); ICAM (Dam, 2016; Hopkins, 2003; SIA, 2012); HFACS (Ergai et al., 2016; Lenné et al., 2012; Shappell et al., 2007; Shappell and Wiegmann, 2001; Skybrary, n.d.4; Wiegmann and Shappell, 2001,2003); and GEMS (Eurocontrol, 2012; SKYbrary, n.d.7) as well as some forms of BowTie analysis. The ATSB version of the Reason model is illustrated in Diagram 1 in Section 3.2. There is ongoing debate as to how 'systemic' rather than 'epidemiological' the Reason model is. Undoubtably, early versions of the model were less advanced and less dynamic than those from 1997 and Reason himself has not been uncritical of SCM as a model (Reason et al., 2006). Jens Rasmussen's important safety/accident models include those focused on multi-disciplinarity and socio-technical Hierarchy, and Migration or drift towards safety boundaries (Rasmussen, 1990, 1994, 1997; see also Dekker, 2011a). The 'Accimap' developed by Rasmussen (1997) provides a 'map' or diagrammatic overview of an accident incorporating hierarchical levels from the 'sharp end' to regulators and government, and potentially society (Branford, 2011; Branford et al., 2009; Goode et al., 2019; Hopkins, 2000, 2003; Rasmussen and Svedung, 2000; Read et al., 2022; Svedung and Rasmussen, 2002, 2008; Vicente and Christoffersen, 2006; Waterson et al., 2017). The ATSB version of Accimap is illustrated in Section 3.2. More recent advocates of system safety include Leveson's STAMP/CAST that builds on Rasmussen and has a focus on system control (Leveson, 2004, 2011a, 2011b, 2017a, 2017b, 2019; Leveson et al., 2003, 2009, 2019; Leveson and Stringfellow, 2009; Leveson and Thomas, 2020; Leveson and Willeboordse, 2016; Lower et al., 2018; Patriarca et al., 2022; Stoop and Benner, 2015; Vacher et al., 2018; Zhang et al., 2022), Erik Hollnagel's FRAM (Hollnagel, 2012, 2018; Hollnagel and Goteman, 2004; Masys, 2004, 2005; Tian and Caponecchia, 2020), and contributions by Paul Salmon and colleagues (Goode et al., 2016, 2017; Grant et al., 2018; Hulme et al 2019, 2021a, 2021b; Read et al., 2021, 2022; Salmon, 2021; Salmon et al., 2012, 2015, 2017, 2020a, 2020b, 2023; Salmon and Read, 2019; Trotter et al., 2014; Walker et al., 2017).

least one 'other' methodology.

The TSB's bespoke 'ISIM' investigation methodology was integrated with IT systems to manage investigations, analysis based on data collected, and potential safety recommendations. The ATSB had built upon this with its bespoke 'SIIMS' system (recently revised and relabelled as 'AIMS') with detailed documentation and training related to analysis and testing of causality and significance. Other SIAs such as TAIC, JTSB and to an extent AAIB, reported use of ATSB methodology that dated from Walker and Bills (2008). Argentina's JST employed an in-house bespoke 'Vortex' model that had drawn upon Reason. The BEA used a bespoke 'gutter' model adapted from MINOS by the Dédale company to help understand systemic variability an nonlinear complexity and indeterminacy and the circumstances in which this provides insightful systemic analysis. The DSB used a bespoke form of power and influence analysis.

Some SIAs highlighted various other methodology use. The DSB used 'STEP' and timeline analysis. The JTSB used a '6M' model, a '5 Whys' type process, 'VTA', and 'Fishbone' diagrams. The JST sometimes used a variant of Heinrich's linear Domino model. The SIAF had used activity theory and a developmental work research method by Engeström, a form of power analysis, and grounded theory. TAIC used mindmaps, timelines and human factors analysis. The AAIB and ATSB reported use of various additional investigation methodology methods, models and theories.

4.2. Research questions

Based on the research data summarised in Section 3, the answers to the four research questions are as follows.

(1) have SIAs utilised researcher-based or bespoke methodologies in investigation analysis? Notwithstanding the lack of requirements (SARPs) in ICAO Annex 13 and its USOAP audit, methodologies were found to have been used by all participant SIAs in their investigation and analysis processes for major aviation investigations.
(2) what methodologies have been used? The most commonly used methodologies were based on early systemic models by Professors James Reason and Jens Rasmussen. More recent systemic models such as by Professors Nancy Leveson, Erik Hollnagel and Sidney Dekker were stated to have been used by three SIAs. Bespoke systemic methodologies had been developed and used by the ATSB (SIIMS/AIMS), BEA (Gutter model), JST (Vortex model) and TSB (ISIM), while the DSB sometimes used a bespoke power and influence analysis model. A range of various other methodologies, including BowTie and SHELL, was used by individual SIAs, sometimes depending on the type of investigation or stage of investigation as the JTSB emphasised.
(3) have multiple methodologies been utilised by individual SIAs? Yes, all SIAs used multiple methodologies and in some cases several of them in the same investigation, depending on the investigation issues and context. This is consistent with findings and recommendations by Salmon and colleagues (Salmon and Read, 2019; Salmon et al., 2023) and Karanikas (2022). SIAF stated that "The used analysis method depends on the special characteristics and circumstances of the analyzed accident. (SIAF, 2020b). The AAIB considered that the various available: "methodologies all have advantages and limitations; inspectors [investigators} all think differently. A methodology needs to encourage creativity to allow thinking outside the box, while having the discipline to pull the multiple threads together" (AAIB, 2022b).
(4) how and where has SIA methodology usage been documented? Our research has established that among participating ITSA SIAs, only the ATSB and DSB made some reference to methodology usage beyond Annex 13 process material in general areas of their websites. A number of SIAs made some reference to methodology use in particular accident investigation reports but this lacked detail and was likely to be difficult for researchers to find because of the hundreds or thousands of reports on each SIA's website. We were able to find such references in some of the exemplar reports provided by participants. There was also some methodology documentation in ICAO and ISASI investigator seminars around the world and associated publications (e.g., by ATSB, BEA and TSB) but this was not widely known or cited by academic researchers. Most participant SIA methodology was documented internally and used in the background for analysis. The type and extent of methodology usage has only now been made available, with SIAs' collaboration, through this research project.

4.3. Limitations

In Section 2 we noted Stake's encouragement of single researcher experiential knowledge and multi-case analysis (Stake, 2006: 12, 18). The primary researcher/author was once an 'insider' having led a SIA, been a chair of ITSA, and actively participated at ICAO in Montréal to revise Annex 13. Although these roles were completed more than a decade ago and there was credibility and less risk of misunderstanding as a result of this background, there is a risk of unconscious bias. Potential limitations and pitfalls of insider case study research (Arber, 2017; Breen, 2007; Chenail, 2011; Emmel, 2013; Greene, 2014; Hellawell, 2006; Hockey, 1993; Hodkinson, 2005; Merton, 1972; Unluer, 2012) were carefully considered and will be further reviewed as the next phase of research progresses.

There is a potentially interesting gap between investigation methodologies espoused and stated to be used by ITSA SIAs and the understanding and practice of individual SIA investigators but that is not a focus of this research. There is a substantial and important literature on mechanisms of learning from accident investigations that is mostly not within the scope of this paper. Why SIAs do or do not choose and use particular methodologies is largely not addressed in this initial paper. Each investigation of a major aviation accident by an SIA can be considered a form of 'case study' (Zotov, 2000) but that is not the usage in this paper where the focus is on SIA methodology use.

Some important ITSA members such as the US NTSB, Moscow-based IAC and Sweden's SHK had not, at the time of writing, chosen to participate in the research and provide data. A few well-resourced and experienced SIAs such as the German BFU (2022) are not ITSA members and some other ICAO State SIAs with an increasingly large manufacturing base, aircraft fleet and airspace are not ITSA members (e.g., China's Office of Aviation Safety and Brazil's CENIPA). However, the participant base obtained is diverse, includes important SIAs, and the nine cases obtained is close to Stake's suggested qualitative study maximum.

Exposition and analysis of bespoke SIA methodologies and other SAMs is an important and major undertaking that is not included in this paper and will take place in the next phase of research. This will consider their operational characteristics and adequacy for the purposes they are used in SIA investigation analysis, including the desirability or otherwise of using complex non-linear systemic models and/or multiple models.

5. Conclusions

Research into major aviation accident investigation methodologies used by the independent government safety investigation authorities that comprise ITSA had not been undertaken until this study. The initial research responses of nine ITSA participant SIAs in relation to the four research questions outlined in the Introduction has been documented and discussed. Context for the responses was provided by reference to the international ICAO framework, an overview of safety/accident models that can underpin major accident causality and investigation analysis, previous research on government accident investigation methodologies, and some background on each participant SIA.

We established that there are gaps (and lack of detail) within Annex 13 and its USOAP audit process concerning SIA use of methodologies for investigation analysis, gaps regarding SIA knowledge/use of research literature SAMs and peer bespoke methodologies, and gaps in participant SIA's external publications detailing their use of methodologies. Our research established that methodologies were used by all participant SIAs in their investigation analysis processes for major aviation investigations. As summarised in Table 1, these included methodologies based on Reason, Rasmussen and more recent systemic models, BowTie, bespoke methodologies developed by individual SIAs, and various other models including SHELL. All SIAs used multiple methodologies and some SIAs reported using several of them in the same investigation, depending on the accident context and stage of investigation. Most of this methodology usage was not publicly visible or was difficult to find until provided through this project and paper.

Despite being primarily exploratory and descriptive, the 'industry impact' of this initial qualitative research is hoped to be significant. Sharing the research with participant SIAs that were unaware of each other's practice provides additional options for them to consider. This paper may also be read by the remaining eight ITSA aviation SIAs and some non-ITSA SIAs, ICAO staff, professional air safety investigator members of ISASI, as well as by various researchers who may be better placed to develop or refine safety/accident models with greater practical industry relevance. Industry impact should increase as the research progresses and may include regulators and investigators in other high-risk industries such as offshore oil and gas (Bills, 2012; Hudson and Hudson, 2010, 2015), mining (Bills, 2020: 46-8, 56-8, 67-8), and chemicals (Vuorio et al., 2017) that, unlike aviation, do not have international investigation regulatory frameworks and dedicated independent government safety investigation bodies.

Further ethics approval has been obtained for an additional research phase. This will include the primary researcher interviewing staff designated by ITSA participant SIA heads. It will delve deeper into why the SIAs use particular investigation methodologies and not others and whether, in light of this first phase, they intend to consider other options. More extensive analysis and contextualisation of participant data, and more detailed exposition and assessment of relevant SAMs and methodologies, ICAO documentation and past research is being undertaken. This should enable better understanding of investigation analysis methodology options and choice and the desirability of bridging any research/practice gap. It should also assist with improving the content and impact of safety action and recommendations and other learning from investigation reports. Our multi-case study will then be instrumental in understanding investigation methodologies used in government aviation safety practice and future improvement.

CRediT authorship contribution statement

Kym Bills: Conceptualization, Data curation, Writing - original draft, Writing - review & editing, Investigation, Formal analysis, Methodology, Supervision. **Leesa Costello:** Writing- review & editing, Supervision. **Marcus Cattan**: Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: There are no declarations of interest in relation to this draft manuscript by any of the three authors. The only financial support was a PhD student fee remission scholarship provided to the primary researcher under the Australian Government Research Training Program. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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Appendix A. The ICAO international investigation and safety framework

The Convention on International Civil Aviation was signed in Chicago on 7 December 1944 by 52 States (i.e., countries). Following ratification of this 'Chicago Convention' in 1947 by the required minimum 26 States, the International Civil Aviation Organization (ICAO) was formally established as a specialised agency of the United Nations based in Montréal, Canada (ICAO, 2022e). In 1951 the first edition of the framework for civil aviation investigation was provided through the approval of Annex 13 to the Chicago Convention, and the current 12th edition of Annex 13 was published in 2020 (ICAO, 2020a).

Under Annex 13, the State of Occurrence has the primary responsibility to investigate an accident or serious incident (which can be delegated) with the State/s of Operator, Design, and Manufacture able to be involved in such an investigation through Accredited Representatives who may be supported by relevant industry and other advisers (ICAO, 2020a).

ICAO regulates civil aviation as a form of 'system of systems' (Albers et al., 2018; Bennett, 2016; Nielsen et al., 2015; Stanton et al., 2012, 2013; Woltjer et al., 2022) that includes large and complex subordinate systems including airports, aircraft, maintenance, flight and cabin crew, and air traffic control. ICAO seeks to maximise standardisation, better practice and overall system safety. As Stoop summarises: "ICAO chose a strategy with technology as the flywheel for progress, keeping organisational and institutional standardization and harmonization" (Stoop, 2020, 45).

In particular, Annex 13 provides for independent 'no-blame' safety investigation by a SIA (in the Annex termed an accident investigation authority or AIA):

The accident investigation authority shall have independence in the conduct of the investigation and have unrestricted authority over its conduct, consistent with the provisions of this Annex.

The investigation shall normally include

a) the gathering, recording and analysis of all relevant information on that accident or incident;
b) the protection of certain accident and incident investigation records in accordance with 5.12;
c) if appropriate, the issuance of safety recommendations;
d) if possible, the determination of the causes and/or contributing factors; and
e) the completion of the Final Report.

Where feasible, the scene of the accident shall be visited, the wreckage examined and statements taken from witnesses. The extent of the investigation and the procedure to be followed in carrying out such an investigation shall be determined by the accident investigation authority, depending on the lessons it expects to draw from the investigation for the improvement of safety. Any investigation conducted in accordance with the provisions of this

Annex shall be separate from any judicial or administrative proceedings to apportion blame or liability (ICAO, 2020a: 5.4 & 5.4.1).

Key definitions in Annex 13 include:

(1) ***Causes.*** *Actions, omissions, events, conditions, or a combination thereof, which led to the accident or incident. The identification of causes does not imply the assignment of fault or the determination of administrative, civil or criminal liability.*
(2) ***Contributing factors.*** *Actions, omissions, events, conditions, or a combination thereof, which, if eliminated, avoided or absent, would have reduced the probability of the accident or incident occurring, or mitigated the severity of the consequences of the accident or incident. The identification of contributing factors does not imply the assignment of fault or the determination of administrative, civil or criminal liability.*
(3) ***Investigation.*** *A process conducted for the purpose of accident prevention which includes the gathering and analysis of information, the drawing of conclusions, including the determination of causes and/or contributing factors and, when appropriate, the making of safety recommendations.*
(4) ***Safety recommendation.*** *A proposal of an accident investigation authority based on information derived from an investigation, made with the intention of preventing accidents or incidents and which in no case has the purpose of creating a presumption of blame or liability for an accident or incident. In addition to safety recommendations arising from accident and incident investigations, safety recommendations may result from diverse sources, including safety studies.*
(5) ***Safety recommendation of global concern (SRGC).*** *A safety recommendation regarding a systemic deficiency having a probability of recurrence, with significant consequences at a global level, and requiring timely action to improve safety* (ICAO, 2020a: 1-2 & 1–3).

Annex 13 is reviewed regularly (ICAO, 2016a, 2020a). Since 2017 this has occurred through an Accident Investigation Group expert Panel (AIGP) reporting to, and tasked by, ICAO's Air Navigation Commission (BEA, 2023a). Occurrence reporting uses data exchange (ECCAIRS) and a taxonomy (ADREP, 2000) with the 'SHELL' model (ICAO, 2020f).

ICAO's suite of safety-related material (ICAO, 1998, 2003, 2006, 2009, 2011a, 2011b, 2012a, 2012b, 2013, 2014, 2015, 2016c, 2017, 2019a, 2019b, 2020b, 2020d, 2022a, 2022b, 2022d) includes a Global Aviation Safety Plan and Global Aviation Safety Roadmap (Creamer, 2022; ICAO, 2022f). ICAO also publishes detail on the proactive elements of safety management systems in Annex 19 and an associated manual (ICAO, 2016b, 2018a) and requires the reporting of statistics, technical, audit and other safety data (ICAO, 2019c, 2020c, 2022c, 2022f, 2022g, 2023; see also SKYbrary, n.d.6; SMICG, 2019).

While investigation of accidents to consider causality is a reactive post-event process, investigating serious incidents and safety recommendations and other safety actions as a result of investigations can be proactive. For example, there may be safety issues found during an investigation that were not necessarily linked to an accident sequence but if unaddressed could lead to a different accident in the future. In addition, major aviation accident and serious incident investigations provide the opportunity for new understanding and learning based upon the depth and systemic manner with which they are undertaken (Braithwaite, 2010; Stoop and Dekker, 2012).

In ICAO's Universal Safety Oversight Audit Programme (USOAP) the aviation arrangements of each ICAO State are audited against key standards and recommended practices (SARPs). Annex 13 is among the elements audited from time to time as part of 'Accident Investigation'. The percentage of compliance with the SARPs is published by ICAO enabling public comparison, including with respect to a global average (ICAO, 2022g, 2023). A State without a competent AIA or where AIA functions are shared with a regulator and not fully independent in areas where this is required in the SARPs, all else being equal, is likely to have a reduced USOAP score for Accident Investigation. The 2020 edition of the USOAP has 84 Accident Investigation protocol questions but they do not include an evaluation of the use of a documented investigation analysis methodology or of its effectiveness (BEA, 2023a; ICAO, 2020e).

In the course of this research, the primary researcher discovered some significant inconsistencies under 'Accident Investigation' within the ICAO online USOAP database. Five participant SIAs were impacted, three seriously. On 3 September 2022, the 2010 result for Japan was 96 % but on 15 April 2023 87 %. On 3 September 2022, the 2008 result for the Netherlands was 73 % but on 15 April 2023 was 7 %. On 3 September 2022, the 2018 UK result was 83 % but on 15 March 2023 a 2009 result was showing as the latest with a result of 70 %. The issues were initially raised with the five SIAs and other participants and then followed-up on 12 May via an email to the ICAO USOAP area and a later reminder email. While USOAP uses a dynamic/continuous database, and as new audit results are added the global average will change slightly, this should not change State results when there is no updated audit result. Additional information is being obtained on these issues pending further analysis.

Investigation of major accidents under Annex 13 provisions remains important but faces challenges (Farrier, 2018; Nagy, 2019; Roed-Larsen and Stoop, 2012; Vincent et al., 2017; Walsh, 2008). Like the Manual of Aircraft Accident and Incident Investigation (ICAO, 2011a) and the earlier related Circulars 240 (1993a) and 247 (1993b), all four editions of the ICAO Safety Management Manual (SMM) include support for the Reason and SHELL accident causality models (ICAO, 2006, 2009, 2012b, 2018a). The latest SMM takes a detailed approach to system safety (ICAO, 2018a).

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