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Review Article

Learning from Incidents in Aircraft Maintenance and Continuing Airworthiness Management: A Systematic Review

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The purpose of this systematic review is to highlight the salient elements of learning from incidents in the aircraft maintenance and continuing airworthiness management area. This involved the review of more than 1,000 publications reflecting practice in different domains. The cache was eventually distilled to 18 publications of relevance to learning from incidents. The systematic review of the literature was not intended to be exhaustive, but it was deliberately bound by the parameters of predefined search terms. A robust analysis was performed on the 18 distilled publications with the use of the NVivo software. A critical and systematic examination of this body of literature further supported the development of the five codification themes. The analysis of the literature revealed the benefits of a just culture as an enabler of reporting and learning from incidents. Moreover, it identified limitations inherent in the current body of knowledge. The most evident being a paucity of literature relevant to the featured industry segment. Some impediments to learning from incidents are also highlighted. Central to this is the prevalence of lack of effective focus and practice on satisfactory causation of events. Currently, the efforts applied across many featured domains appear to be based upon ineffective legacy linear practices. However, emerging investigative philosophies that look beyond direct cause and effect contain opportunities for practitioners to consider causation through dawning axioms. This systematic review could be used in the European aviation regulatory activities associated with improving learning from incident in aircraft maintenance and continuing airworthiness management.

1. Introduction

Freeman Dyson, the notable theoretical physicist and mathematician, once said, “aviation is a branch of engineering that is least forgiving of mistakes” [1]. It is true that such high reliability domains can pose a great degree of risk that may in turn contribute to mistakes being made. However, a guiding principle of continuously improving aviation safety is our ability to learn from events such as incidents. In the world of aviation safety, standards and recommended practices tend to be biased towards translating the experiences from such events into tangible outcomes aimed at preventing similar reoccurrences.

A review of safety in aviation from the perspective of maintenance and continuing airworthiness management staff is the key to understanding the relationship between safety and the concept of learning from incidents [2]. Despite the efforts of fallible humans and the ever-increasing complex systems they moderate, achieving a utopian reality where there are no risks or hazards present is clearly an unreasonable expectation [3]. Safety in aviation has evolved along a continuum from the early 1900s where aircraft mechanical and design issues were the primary contributors to aircraft accidents, according to the International Civil Aviation Organisation (ICAO) [4]. Improvements in these technical factors reached a plateau in the 1970s and the challenges realised then were centred around human performance and limitations [5]. Notwithstanding efforts and investment in human factor initiatives, accidents and incidents continued to occur. In the 1990s, there was a clear recognition that, as the aviation industry continued to develop, there were a number of factors outside the human at play with a potential to affect safety behaviour [6]. This paradigm-shift informed today's systematic approach to safety and, in particular, the approach to learning from incidents [7].

Most people relate safety to freedom from risk and danger [8]. Unfortunately, risk and danger are often ubiquitous in the presence of high reliability activities. Managing sources of risk and danger are a tall order for some organisations. The ICAO Doc 9859 [4] recognises that "aviation systems cannot be completely free of hazards and associated risks." However, the guidance does acknowledge that, as long as the appropriate measures are in place to control these risks, a satisfactory balance between "production and protection" can be achieved. Perrow [3] acknowledges that "we load our complex systems with safety devices in the form of buffers, redundancies, circuit breakers, alarms, bells, and whistles" because no system is perfect.

When one thinks of the word "incident," it conjures up the notion of an action that may have grave consequences. Similarly, the word "accident" is often used in the context of an unplanned event or a particular circumstance. In many industrial sectors and business domains, these descriptors are used with a degree of interchangeability when the words are applied to describe events. In the world of aviation, there are clear high-level definitions for both event categories, and these are based on potential for harm. Throughout aviation, learning from incidents is often considered to be one means of augmenting what Perrow [3] terms "safety devices." "Experience is the best teacher" according to Kleiner and Roth [9] as they claim that the causes of the mistakes are often not featured and continue to be present in the absence of learning. In general terms, Nonaka [10] suggests that creating new knowledge extends past a mechanistic approach and is strongly related to employees' insights. An effective enabler of learning in this area is the collation of information on incidents. Details of the related processes, environment, procedures, competencies, and implementing timely corrective actions all have a positive impact on learning and help prevent recurrence in the future. Learning from incidents is therefore mainly associated with post-incident learning.

Detecting and identifying hazards highlighted through incident reporting systems is recommended by International Civil Aviation Organisation (ICAO) standards and recommended practices as an effective means of achieving practicable levels of safe operations. Therefore, objective data mined from a reporting system offers the potential to enlighten aviation stakeholders and to illuminate weakness that may be present. Such information can assist with a better understanding of events and augment mitigating measures against the potential effects of these hazards. When incidents occur, this can be an indication of a failure in an organisation's process and/or practice. Due to continuous challenges faced by the organisations in the aviation industry there is potential to learn from resulting incidents and precursors. The learning is based on the potential new knowledge available from the associated collection, analysis, and interventions of these events. Effective learning can be considered as a successful translation of safety information into knowledge that actively improves the operating environment and helps prevent recurrence of events we can potentially learn from. Learning in this context can often be experienced as modifying or implementing new knowledge where cultural, technical, or procedural elements are integrated. Therefore, when learning in this context is transformed into measures to prevent reoccurrence, an organisation often has a reasonable means of mitigating future similar events.

The objective of this systematic review is to examine how learning from incidents occurs in aircraft maintenance and continuing airworthiness management and other sectors and what issues impact learning in those areas. It also intends to identify the contributing and constraining factors to learning from incidents. A qualitative review approach was selected as it has the advantage of providing a deeper contextual understanding of the literature and can assist with better research integration. Applying a degree of rigour and comprehensiveness can assist with advancing knowledge and identifying research gaps and aspects for further research in this particular area.

The publication's systematic literature review covered primary publications up until 2017. As the subject of learning from incidents is a valid topic with potential to augment safety, a brief review of a cross-section of the latest publications was performed to see if a "delta" in the knowledge exists. Insley and Turkoglu [11] reaffirm aircraft maintenance is still a key point of concern within many areas of aviation. Their work highlights frequently recorded maintenance related consequences, naming runway excursions and air turn-backs in the highest percentile. The study identified factors relating directly to these events naming inadequate and incorrect procedures, poorly executed inspection tasks, and incorrect installation as common causal factors ascribed to the event categories named. These issues are not unique to Europe. Habib and Turkoglu [12] review a dataset of maintenance-related incidents originating outside of Europe (Nigeria). Their analysis revealed causal factors such as poor aircraft husbandry, deficiencies in inspection and testing, and inadequate safety oversight (organisation and regulator). Habib and Turkoglu [12] also consider the consequential impact of errors as causal elements in subsequent events. They also highlight the increase in incidents recorded and attribute this to a recent increase in air movements. Batuwangala et al. [13] present the idea that forecasted growth in air traffic requires a strong effort to ensure aviation incidents continue to be progressively reduced. They recognise a novel approach to safety improvements will need to be propagated in support of this. Although the authors point out some of the benefits of implementing a safety management system (SMS), they reaffirm the notion that not all areas of aviation operations are mandated to comply with SMS requirements. Some of the implementing constraints recorded by Batuwangala et al. [13] include protection of safety data/reporters, lack of just culture and reporting, and reporting system deficiencies, to name a few.

The review of the sample examining a cross-section of current research in the area of aircraft maintenance and continuing airworthiness does not identify any significant new knowledge in support of this publication. The additional exercise reaffirms the concept that some organisations are continuing to ineffectively embrace a desire to learn from incidents.

2. Materials and Methods

In order to conduct an efficient and effective review, a structured approach was deemed necessary. Okoli and Schabram [14] state that "a dedicated methodological approach is necessary in any kind of literature review." An initial search of literature highlighted a scarcity of best-practice guidelines for conducting systematic literature reviews in the subject domain. This situation is also experienced in other sectors as Levy and Ellis [15] and Webster and Watson [16] confirm. Qualitative research involves handling considerable volumes of data and a degree of discipline is required so that search results and decisions regarding subject inclusions and exclusions are recorded and references are well managed. Endnote was used in support of the literature review during this research. An electronic database is useful for supporting a search strategy, arranging publications, and storing references [17]. The qualitative data analysis software NVivo [18] was used to augment the data management, storage, and analysis associated with the literature review. NVivo possesses many functions that are capable of facilitating the synthesis of a review [19]. However, the software does not have the capability of understanding text and the analytical skills of a researcher cannot be replaced in this respect.

2.1. Search with Predefined Terms. Bandara et al. [19] suggest two main criteria to consider before a search to identify papers for extraction and review begins: the source and search strategy. The source considers which outlets and databases to target, and the search strategy refers to the search terms and discipline to be exercised during the manuscript extraction process. A systematic search of the literature was performed in the following databases:

(i) Web of Science [20]
(ii) Scopus [21]
(iii) IEEE Xplore [22]
(iv) ProQuest [23]
(v) EBSCO [24]

The following set of predefined terms associated with the thematic of the systematic review was selected to search in these sources:

(i) "learning from incidents"
(ii) "learning from experience"
(iii) "aircraft maintenance"
(iv) "aircraft management"
(v) "safety management systems"

This step concluded with the creation of an initial set of publications, which would further be filtered in next steps.

2.2. Practical Screen of Title and Abstract. In this step, each title and each abstract were reviewed (practical screen). This part of the process not only had to be broad enough to create a sufficient number of applicable publications but also had to be practically manageable. The following criteria were laid down for the practical screen of the source bibliographic details, title, and abstract:

(i) Subject: related to learning from incidents and past experiences
(ii) Setting: any high reliability industry or sector where learning from incidents is critical.
(iii) Publication: journal or peer reviewed conference proceedings
(iv) Date range: published post 1992

The output of the practical screen step produces a list of publications denoted as the screened set of publications. An Endnote library was created to store and manage the full text of the retrieved publications.

2.3. Classification to Primary and Secondary Publications. This step involved the filtering (classification) of publications in the following two categories:

(i) Primary publications: any research publication based on original data collected by the publications' author(s)
(ii) Secondary publications: those publications based on data generated by somebody other than the author(s), e.g., a review and use of existing literature/data developed by another party

Effectively, the screened set of publications was split over to a subset of primary publications and subset of secondary publications. Of those, in the next step, only the subset of primary publications was used.

2.4. Application of Inclusion and Exclusion Criteria. Brunton et al. [25] suggest there needs to be explicit inclusion and exclusion criteria in order for the reviewer to screen titles and abstracts for topical, population, temporal, and methodological relevance. Having a set of criteria helps to reduce any researcher bias in the screening system. A set of inclusion and exclusion criteria was developed considering the below objectives and in accordance with the guidelines included in [26, 27]:

(i) To review current literature and to identify factors related to learning from incidents
(ii) To identify obstacles and to learn from incidents
(iii) To make recommendations how learning from incidents might be improved in the aircraft maintenance and continuing airworthiness management sector

In this context, the inclusion and exclusion criteria presented in Table 1 were used for the filtering of the subset of primary publications. The output of this step leads to the creation of the final set of publications.

2.5. NVivo Analysis and Codification with Themes. In this step, the Endnote library containing the final set of publications is imported to NVivo for further analysis. The following approaches, previously suggested by Bandara et al. [19], were used for the selection of the codification themes:

(i) Deductive: themes reported on are predetermined to some extent. In this case, these predetermined themes were the output of a focus group process. The present review paper does not report details on the focus group, as this is within the scope of a future research paper of the authors.

(ii) Inductive: themes reported are derived from analysis of the literature.

In addition to the three inductive themes (learning from incidents, just culture, and precursors) arising during the literature review, two additional themes (root cause and reporting) were deduced from conducting focus group activities concurrently with the review. The aggregate of both of these efforts resulted in five themes being developed. According to Kitzinger [29], "focus groups are group discussions organised to explore a specific set of issues such as people's views and experiences." The idea of conducting group interviews is not a new one. Bogardus [30] is an early example of a reference to utilizing the group interview. Frey and Fontana [31] say that group interviews can be formally structured for a specific purpose or can be performed in a more informal setting where a researcher can "stimulate a group discussion." A total framework of five nodes eventually representing the themes was constructed in the NVivo database and used in support of completing the systematic literature review. These five nodes were also later used as the main framework for the semistructured interview template.

The description and origin (focus group or literature analysis) of the themes identified are described in Table 2.

Using the codification themes, the final set of publication was searched using the NVivo software to extract and code the passages identified to any of the coding categories. NVivo only provides thematic classifications of data based on the occurrence of key words. This merely assisted in identifying common prescribed keywords in publications, enabling classification into categories or clusters of words and examination of relationships within these publications. As NVivo does not perform analysis, the researcher must search the outputs and extract meaning for themselves. Thus, each of the publications were physically reviewed inductively by the researchers. Effectively, the final set of publications was searched and coded to Table 2 which has five themes. The coding process consisted of selecting relevant passages of text that were captured in one or several of the framework nodes. The overall document screening process and associated steps described in the previous sections are illustrated in the flowchart of Figure 1.

Maykut and Morehouse [32] define a propositional statement as "a statement of fact the researcher tentatively proposes, based on the data." Memos were used to draft these summary statements which form part of Section 3 of this paper.

3. Results and Discussion

In the first step of the process described in Section 2 of this paper, the search with predefined returned in excess of 1,000 publications (initial set of publications). From this tranche, a total of 239 publications were retrieved in the practical screen phase (constituting the screen set of publications), which were then classified to a subset of 53 primary publications and a subset of 186 secondary publications. The final set of publications was derived by applying the inclusion and exclusion criteria of Table 1, leading to a total of 18 publications. The progressive filtering process is presented in the flowchart of Figure 2.

The 18 publications are summarised in Table 3, where the utilised methodology (qualitative and quantitative of mixed) and the application domain (different industries) are also provided.

In the next step, this final set of 18 publications was analysed and codified with NVivo, using the five codification themes described in Table 2. This has led to the distribution of publications per codification theme shown in the flowchart of Figure 3.

One can observe from this distribution that publications share some common codification themes. This is presented in Table 4, which provides the results of the mapping exercise of the 18 publication against each of the five codification themes.

Memos were used to draft the literature summary statements, which formed the final narrative for the synthesis. NVivo facilitated collation of the summary statements and enabled a transparent audit trail in support of the literature review exercise presented separately in sections under the five codification themes.

3.1. Root Cause. An overview of the Jacobsson et al.'s [43] study findings that relate to poor causation identification can be consolidated as follows: fewer event aspects recorded, often only operator error and technical failure recorded, and shallow root causation. It was found that when limited analysis of underlying event causes is performed, only limited effective actions are possible. This is evident when poor root cause analysis only contributes to minor procedural, and cosmetic changes are aimed at preventing recurrence. Such deficiencies were considered to have a limited impact upon the potential lessons available as a result of ineffective root cause establishment.

Pickthall [44] considers root cause through the lens of an individual's competence when a technical and human factors-related impediment is present. The research examined the prevalence of these factors when aircraft maintenance staffs perform fault diagnosis on complex aircraft systems. The researcher found that often maintenance staffs are

Table 1: Inclusion and exclusion criteria used for the filtering of the subset of primary publications (table adopted from Clare and Kourousis [28]).

Included	Excluded
Research studies	Literature reviews
Qualitative and mixed methods	Quantitative methods
Perceptions and experiences	Focused on decision-making and legislative requirements
Reference to just culture	Not about "no blame" or a punitive approach
High reliability settings	Nonhigh reliability settings
Published post 1992	
Peer reviewed publications	
Industry based settings	
Original studies	

Table 2: Codification themes used in the NVivo analysis of the final set of publications.

Codification theme	Description	Origin
Root cause	Reason to establish causation	Focus group
Reporting	Value of reporting to learning from incidents	Focus group
Learning from incidents	Outcomes of learning from incidents	Literature analysis
Just culture	Impact of just culture on learning from incidents	Literature analysis
Precursors	Contribution of precursors to learning from incidents	Literature analysis

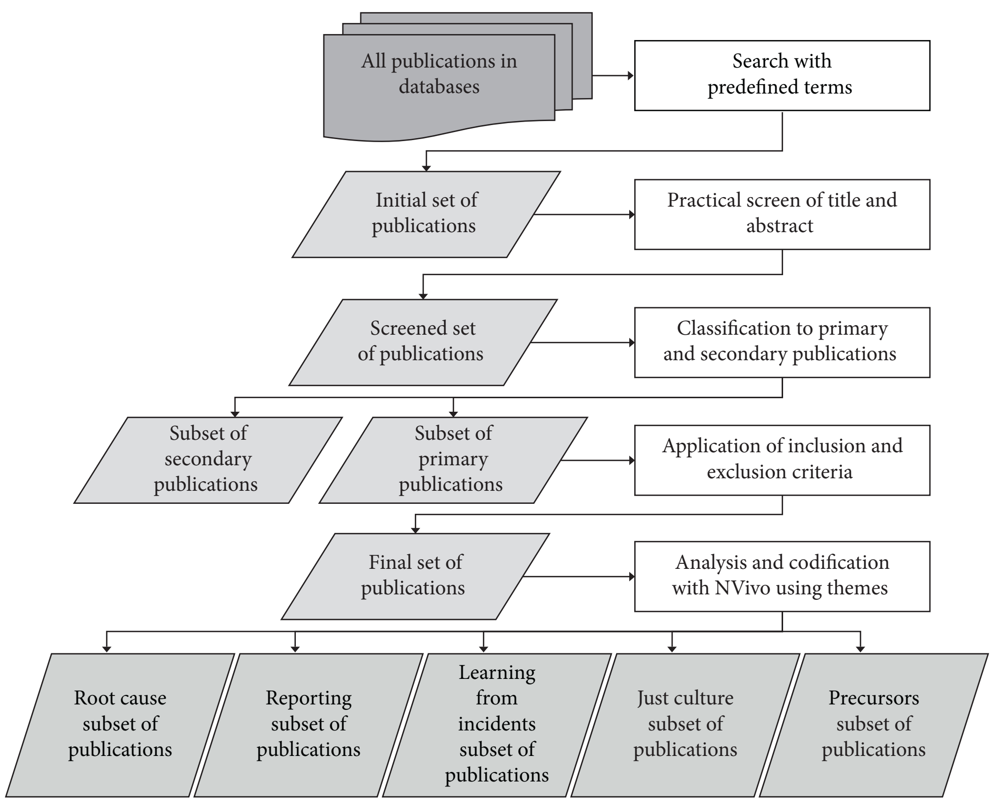

Figure 1: Flowchart of the overall document screening process and associated steps utilised in the systematic review.

unable to diagnose faults in an accurate and timely manner. The results of the study indicated that events are often caused by poorly resourced supports, such as system diagnostics and test equipment. On a practical level, these contributing factors are believed to have a negative influence on the inability to establish adequate root causes and prevent the recurrence of faults.

The Hobbs and Williamson [42] research study explored patterns of potentially unsafe acts often perpetuated by aircraft maintenance staff. Violations (routine and exceptional) and mistakes were found to be closely related to deteriorating maintenance standards. A potential relationship reinforces a link between violations and less than optimal safety standards. According to the researchers, root

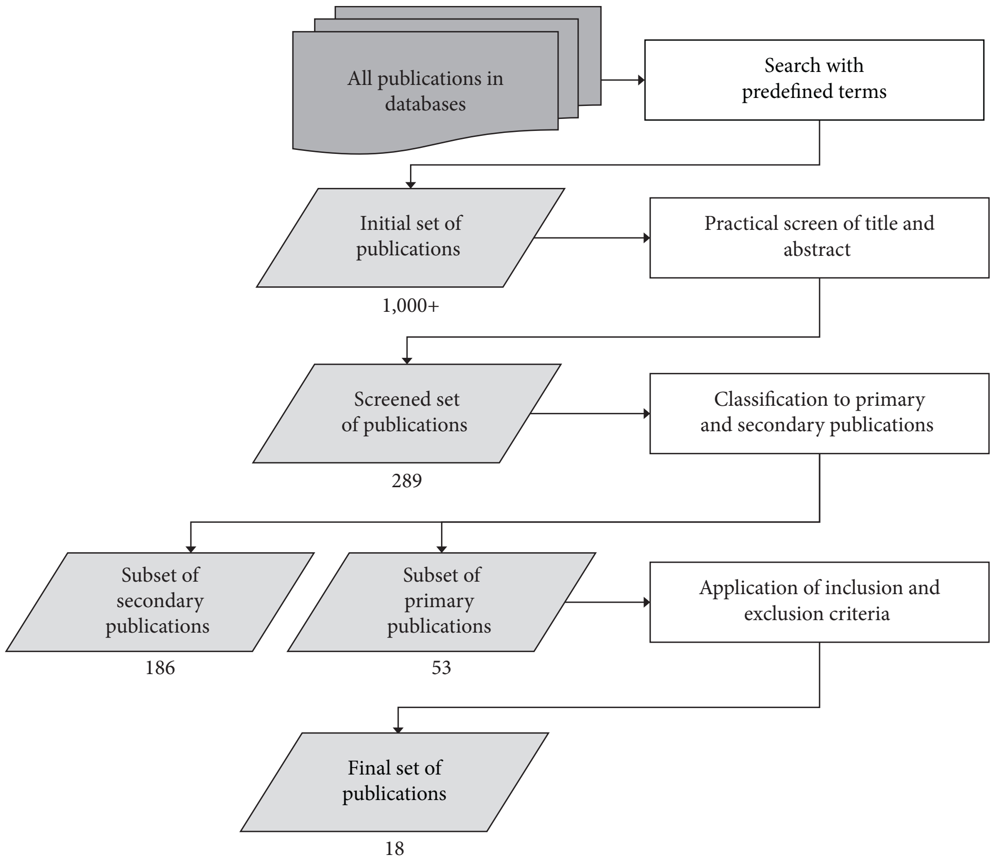

Figure 2: Output of the progressing filtering process applied during the systematic review, leading to the 18 publications (final set of publications).

Table 3: A summary of attributes of the papers arising from the systematic literature search.

Paper	Methodology	Domain
Atak and Kingma [33]	Qualitative	Aircraft maintenance
Drupsteen and Hasle [34]	Qualitative	Chemical, construction, and manufacturing
Drupsteen and Wybo [35]	Qualitative	Healthcare
Drupsteen et al. [36]	Qualitative	Chemical, construction, energy, government, metal, and transportation
Furniss et al. [37]	Qualitative	Technology, transport, energy production, and healthcare
Gartmeier et al. [38]	Qualitative	Healthcare
Gerede [39]	Qualitative	Aircraft maintenance/regulatory
Gray and Williams [40]	Qualitative	Healthcare
Bjerg Hall-Andersen and Broberg [41]	Qualitative	Engineering consultancy
Hobbs and Williamson [42]	Mixed	Aircraft maintenance
Jacobsson et al. [43]	Mixed	Petrochemical, food and drug, and energy
Lukic et al. [2]	Qualitative	Energy
Pickthall [44]	Mixed	Aircraft maintenance
Silva et al. [45]	Mixed	Manufacturing, construction, production, and distribution of energy
Steiner [46]	Qualitative	Production and distribution
Storseth and Tinmannsvik [47]	Qualitative	Railway and maritime
Ward et al. [48]	Qualitative	Aircraft maintenance
Zwetsloot et al. [49]	Mixed	Manufacturing, construction, and others

cause of such violations can often be traced back to the prevailing culture within the organisation itself.

3.2. Reporting. In their work, Gray and Williams [40] examined whether culture surrounding learning from incidents can be compounded by "strategic defence routines," resulting in recurrence of the event or similar ones. Their study was conducted through questionnaire in health services' domains. They found that real learning from incidents can take place as a result of a transformation effort facilitated by a holistic approach. The authors refer to "reframed learning approach;" however, the publication contains little

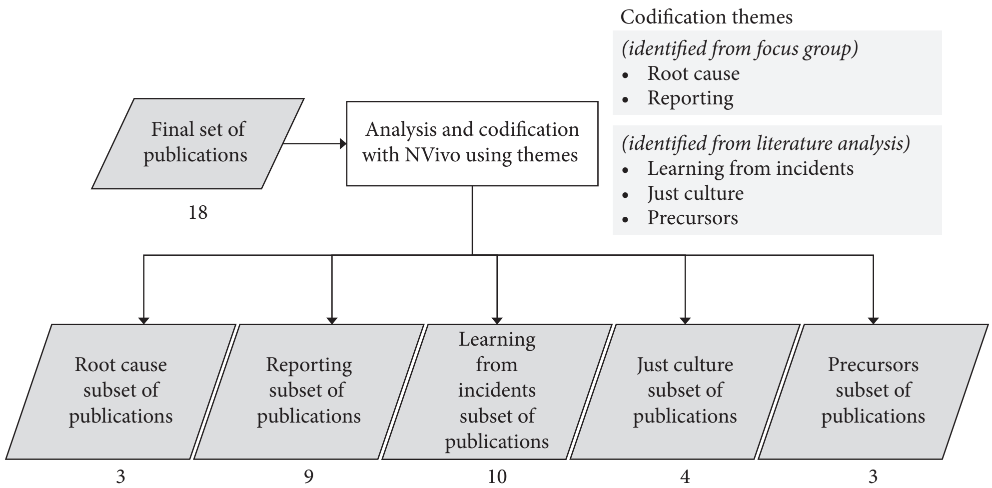

Figure 3: Distribution of the final set of 18 publications in the five codification themes following the NVivo analysis and codification step of the systematic review process.

Table 4: Mapping of 18 publications (final set of publications) against the five codification themes.

	Precursors 3	Just culture 4	Root cause 3	Reporting 9	Learning from incidents 10
Atak and Kingma [33]				X	
Drupsteen and Hasle [34]		X			X
Drupsteen and Wybo [35]	X				X
Drupsteen et al. [36]					X
Furniss et al. [37]					X
Gartmeier et al. [38]				X	
Gerede [39]		X			X
Gray and Williams [40]				X	
Bjerg Hall-Andersen and Broberg [41]				X	
Hobbs and Williamson [42]	X		X	X	
Jacobsson et al. [43]			X		X
Lukic [2]					X
Pickthall [44]			X	X	
Silva et al. [45]		X			X
Steiner [46]				X	
Storseth and Tinmannsvik [47]				X	
Ward et al. [48]	X	X			X
Zwetsloot et al. [49]				X	

practical exemplars which would expand more on the details and the applicability of a similar approach to learning from incidents.

Gartmeier et al. [38] examined if reporting can be used as a strategy for workplace learning in a health service setting. They have considered error reporting attitudes and behaviours in a two-stage study performed via a longitudinal survey. The results suggest that organisations should highlight benefits of error reporting, ease of use and accessibility of reporting systems are important, and barriers can be modified to encourage reporting.

Bjerg Hall-Andersen and Broberg [41] conducted a "natural experiment" in an engineering consultancy firm. Following implementation of an information transfer database, discreet learning processes found to be interconnected within some domain elements. However, there is no evidence of collective interdomain learning across functions. The lessons learned are not through potential negative consequences and respective actions arising from a reporting system input but brokered through a moderated database. A single "embedded" case study may not support the generalizability of the results in other domains. However, for those who wish to develop a better understanding of learning processes across knowledge boundaries, the "implications for practitioners" contained in the study are considered applicable.

Steiner [46] conducted a qualitative study set in a workshop environment with data collected through semi-structured interviews, participant observations, document analysis, and note taking. The theoretical shortcomings defined by the literature that relate to barriers to organisational learning are discussed in the work. One may note that a consolidating feature of organisational learning, such as reporting of issues and data capture, are not adequately discussed in the study.

Atak and Kingma [33] conducted an ethnographic-based case study in an aircraft maintenance environment, augmented by field notes, document reviews, and interviews. Tensions between quality assurance and maintenance management were identified and the prevailing safety culture examined in the context of "integration, differentiation, and fragmentation." The study offers a comprehensive picture of the applied challenges experienced by aviation safety staff from an "embedded" perspective. However, the measures to prevent bias and understanding the issues are not well-defined in the publication.

Pickthall [44] examined the mixed methods approach using a structured interview devised from an academic format. This study examined issues that arose when aircraft maintenance staff interacted with complex aircraft systems for defect rectification. Occasionally a "no fault found" determination has been found to be made. However, the fault-finding inputs in that case were ineffective, and the fault returned soon afterwards. The research considered the management-influenced behaviours such as time pressures, poor communication, failure to adopt and share best practice, inadequate training, and reluctance to change. The work uncovered that indispensable resources, such as aircraft test equipment, integrated onboard diagnostic systems, and maintenance manuals, often fail to support maintenance staff when undertaking diagnosis tasks. The results suggest that these elements can actively constrain maintenance staff when they attempt to consistently manage effective and timely defect rectification. Moreover, the results are well presented and worthy of consideration when developing training material in support of learning from incidents.

Storseth and Tinmannsvik [47] performed a qualitative study, using semistructured interviews in marine and rail industries domains, to examine how individuals retrospectively look back and consider learning from events. Learning indicators for the study were developed by the authors in an earlier related study. The research methods were augmented by theoretical studies and document analysis. They have found that learning within organisations takes place within the parameters of "actor-context constellations" where there are no defined start and finish points. This assumption is not sufficiently balanced against the need to formally consider the exigency for structure when developing learning from incident outcomes.

In their research study, Zwetsloot et al. [49] endorse the importance of learning when implementing a "zero-accident vision" in nonaviation-related domains. The work also highlights safety commitment, communication, and safety culture as learning enablers. Research design was a mixed method approach using a quantitative survey supported by interviews and workshops. The qualitative component of the research verified that learning was evident throughout the featured organisations. "Learning by doing" was considered a more effective approach in support of learning from incidents where employees are motivated to fully engage in the process, and supervisors can moderate theme-based safety dialogue. An extensive survey was performed across 27 organisations. The qualitative methods (interviews and workshops) were applied although they were not formally analysed, and their synopses were used to validate the survey results. The survey component of the research records high scores relating to learning action; however, there were differences noted between staff's perception (and management) of learning action in approximately 25% of cases. Moreover, there was less diversity recorded across the learning condition dimension. The researchers considered this analogous to organisational commitment to safety. Safety commitment, communication, culture, and learning were examined as individual aspects of implementing a zero-accident environment. However, their cumulative relationship was not fully examined and the impact is not discussed sufficiently.

Hobbs and Williamson [42] conducted a mixed method study examining the application of a previously developed "three-way distinction" of unsafe acts questionnaire in an aircraft maintenance context. An initial questionnaire was developed through the application of a disciplined confidential critical interview technique with 72 aircraft maintenance mechanics. The results yielded 48 elements (validated by air accident experts) and transposed into a maintenance behaviour questionnaire distributed to 4,600 licensed and 300 unlicensed aircraft maintenance mechanics (1359 questionnaires were returned). The principle component analysis was the method used to reduce the number of variables in the dataset for analysis by extracting those considered important to the study. The authors' choice of analysis does not appear to consider the competence in the context of skill-based errors and complex situations such as automation. However, the focus the publication brings on the need for aircraft maintenance staff to be aware of the cumulative effect of "seemingly insignificant" incidents fortifies the need to be proactive when it comes to learning from incidents.

3.3. Learning from Incidents. The objective of Lukic et al. [2] study was to highlight factors considered to be important for effective learning, e.g., participants, process, incident, and knowledge. Staff involvement and trust were positive attributes capable of supporting learning. Attributing blame and poorly developed root causation were found to detract from learning. The research also examined impact of formal and informal learning initiatives. Informal learning was found to be more difficult to record and codify, and potential for learning could be limited in some cases. In their paper, Lukic et al. [2] highlighted that the "over-simplification" of incidents and contend id, often the reason of incidents, are misunderstood when attempting to translate incident and accident data into knowledge and learning. It is noted there is an absence of information on the structure applied to the quantitative analysis and how rigour was applied to the process. However, the authors do clarify the analysis was both data and participant driven.

The Gerede [39] study considered some of the challenges associated with the successful implementation of safety management systems (SMS) in aircraft maintenance organisations. The SMS structure is comprised of "safety policy and objectives, safety risk management, safety assurance, and safety promotion." Safety risk management and safety assurance were found to be important elements underscoring the effectiveness of day to day activities. Failure to create a just culture and fear of punishment for reporting shares a common cultural association. The situation is attributed to a potential combination of lack of trust and negative perceptions associated with organisational culture. Moreover, Gerede [39] identified that the absence of communication and trust may present implementation challenges within the maintenance organisations. If a just culture does not exist at national aviation authority state level, then it is questionable if the implementation of an SMS would be effective. It is unclear if the four structural elements of safety management were fully considered during the training or the data gathering phase of the study. This may account for the absence of any direct reference to learning from incidents in the study's findings.

Drupsteen et al. [36] conducted case studies with selected individuals in various domains, including transportation. Their survey considered the following elements: steps in the process where learning is lost, formal organisation of steps, efficiency of steps on a daily basis, difference between espoused and actual performance of steps, and differences amongst featured areas. In their work, they also state that "many incidents occur because organisations fail to learn from past lessons" because the traditional approach often stops short of preventing future incidents. The research paper presented a model that examines the investigating and analysing incidents, planning and prevention, and intervening and evaluating steps in a learning process. The evaluation stage was found to be a primary learning bottleneck and reporting of incidents being next. Results indicated daily practice of learning was good, but follow-up steps in the process are often neglected in comparison to incident analysis. There was a significant difference between how well the investigation and incident analysis stage and the evaluation stage were performed and organised.

In their work, Ward et al. [48] offer a concise overview of key aspects of aircraft maintenance practice and present an accurate snapshot of the development and architecture of pertinent regulation. Understanding the aircraft maintenance system complexities is an essential precursor to implementing improvements. Organisational processes cannot be explained in terms of a linear approach due to the nonlinear characteristics of flexibility and variability of comprising elements. It was found that the resulting relationship between the individuals and the systems have a direct impact upon the system and prevailing environment. Their model comprised of the following elements: system level, process activity, dependencies, and stakeholders. Four reporting veins were uncovered focusing on unique aspects of product airworthiness and system performance, i.e., data inaccuracy, quality assurance, personal injury, and occurrence reporting and suggested changes were highlighted. The researchers found that regardless of how an issue presented, the staff continue to experience performance constraints if communication remains poor.

Jacobsson et al. [43] acknowledge the degree of interest invested in learning from incidents but question the efficiency of learning from incidents in some organisations. They found that event investigations often stop short and only partially deal with some of the elements affecting the event. Although unwelcome events are less prevalent, less severe events provide learning opportunities. Analysis of the learning cycle is valuable and such an approach can offer an insight into inherent precursors to accident conditions. They present a model featuring: reporting, analysis, decisions, implementation, and follow-up in an incident learning cycle format. Assessing effectiveness of an incident learning cycle was designed from analysing each individual step against the following dimensions: scope, quality, time, and information of the first cycle loop. A general assessment of the second learning loop was performed using participant interviews. Subject matter experts applied their judgement in support of developing weighting factors for each of the model elements. The paper refers to the analysis of incident learning systems but the purpose of conducting the safety audit is not specified. The relationship (if any) between the outcome of the safety audits and the efficiency of the learning systems does not appear to be fully articulated.

Silva et al. [45] examine how organisations use accident information to reduce the occurrence of unwelcome events. They suggest it is necessary to achieve a balance between adequately resourcing safety initiatives and maintaining acceptable levels of safety. They suggest that factors such as organisational culture, just culture, and event data, if managed, can contribute to a reduction in events. Learning within organisations should address effective information processing and interpretation. Combining technical and social strategies resulted in uncovering four patterns of practice that corresponded to different levels of learning.

In their work, Drupsteen and Wybo [35] conclude that organisations use experience gained from past events in order to improve safety. They introduce the term "propensity to learn" which refers to an organisation's predisposition to learning and suggest an organisation can apply lessons from past events such as warning signals, mistakes, incidents, and accidents. They found that hindsight can determine if an organisation did learn from an event, but there are no models to assist with gauging the "propensity" of an organisation to learn. The object of the study was to expound two sets of indicators that would contribute to gauging an organisation's inclination to learn. Using a previously validated questionnaire, the participants' perception was assessed on learning indicators. They deduced from the review of literature that organisations displaying high learning propensity were also successful with learning from experience and sharing lessons amongst staff. Indicators based on three categories (attitudes and organisational conditions and systems) utilizing six indicators were developed to gauge organisational learning. A second set of indicators was developed in support of assessing individual propensity to learn from experience, specifically measuring attitude towards each of the stages of a generic learning process, i.e., detection, analysis, follow-up, evaluation, and sharing information. However, as the study was based solely on the perception of staff, it is unclear if the presented indicators alone would be satisfactory to elicit enough potentially subjective data to reinforce the results.

Furniss et al. [37] examined Hollnagel et al.'s [50] Functional Resonance Analysis Method (FRAM) which explores how functional variability resonates within systems, i.e., how well elements work together in a system. They also discuss how FRAM can be modified to support complex socio technical system improvements. This is presented in the context of four principles that encase the main assumptions (equivalence of success and failure, approximate adjustments, emergence, and functional resonance) from a FRAM practitioner perspective. Their study considered how human factor methods "are functionally coupled to a broader system of human factors practice" [37]. The four steps of the FRAM analysis were augmented by two additional steps: the purpose of FRAM analysis and respondent validation.

Drupsteen and Hasle [34] examined if organisations can learn more effectively from past incidents, and future incidents could be prevented. They suggest that learning can be improved if limiting factors are addressed. The learning process in different companies was analysed and discussed. The researchers used a topic list to assess if human, technical, or organisational aspects were being addressed and in which elements were related to specific learning phases. They found that some of the main causes of the constraints to learning can be related to lack of knowledge, unwillingness to report, causation not established, and uncertainty regarding follow-up action. Some conditions that enable these deficiencies are centred around misplaced cultural issues, over-focus on direct causation, and poorly defined safety management procedures for example. The benefits of considering all active and latent failures as direct and indirect causes, respectively, are unclear. The study concentrated on the latency of causation. The authors state learning from incident initiatives should exercise a more generic effort to support prevention. However, one of the limitations stated was the lack of homogeneity amongst the participating organisations.

3.4. Just Culture. Ward et al. [48] endorse the perception that aircraft maintenance is a "highly regulated, safety critical, complex, and competitive industry." They also state that to positively perpetuate the above attributes, it is necessary to further develop an operational model that can account for "what is meant to happen and what actually happens." A just culture is defined as "where people feel they can report mistakes made without fear of punishment (deliberate acts of damage or violations are different)." The researchers proffer that a just culture can be considered as an effective enabler of good quality incident reporting.

Gerede [39] examines some of the challenges associated with the implementation of the ICAO SMS standards and recommended practices which support the aviation industry and regulators to transition from prescriptive oversight methods to those based on performance metrics. These challenges relate to the successful propagation of a just culture which is considered as a basic principle of successful SMS implementation. The study strongly suggests that a failure to foster a just culture would be considered to have a negative impact upon effective data collection (reporting), organisational learning, and the subsequent ability to learn from incidents.

Silva et al. [45] put forward the value of information gleaned from incidents in support of learning and future event prevention. They examine how organisations utilise information and the strategies that assist with the propagation of lessons. They also highlight the need for organisations to encourage a learning culture and suggest the positive contribution made by reporting. It was found that a seminal element of organisational learning is a just culture, where errors and mistakes can be reported, and violations are managed fairly. In parallel, it is suggested that proportionate organisational responses are required to balance safety and accountability.

In their work, Drupsteen and Hasle [34] proffer that learning from past incidents can assist with understanding potential future events and possibly reduce their consequences. The study examines the causes associated with organisations failure to learn from previous events. Trust and openness were identified as key elements necessary for organisational learning. In the absence of these values, under-reporting is often evident. The researchers point out that the presence of what they term a "blame culture" also inhibits learning as potential reporters fear of being treated unjustly for their actions.

3.5. Precursors. Ward et al. [48] suggest improvements can be gained when organisational factors with a potential to contribute to incidents are understood. They consider these elements in the context of the reason [8] taxonomy (immediate, workplace, and organisational) of factors as systemic precursors. An improved understanding of these elements can also shift the focus of unwarranted blame from "the individual" within the system. Aviation maintenance management systems are increasingly adopting an approach where identifying systemic precursors contribute to a just outcome.

The main purpose of the Drupsteen and Wybo [35] study was to develop a set of indicators capable of determining an organisation's "propensity to learn." The researchers argue that the most effective set of indicators are those that could be proactively considered as "leading indicators." Precursors that represent activity-based inputs can signal early degradation of safety systems.

One of the main aims of the Hobbs and Williamson [42] study was to ascertain if unsafe acts could be predicted as a result of analysing self-reported unsafe acts. Their analysis of demographic variables suggested that the occurrence of routine and exceptional violations was associated with a participants' age. Higher levels of associated behaviours were linked with younger participants. The researchers were able to identify potential precursors to aircraft quality issues by association with less than optimal performance of aircraft maintenance staff. The analysis implied a distinction exists between what are termed routine and exceptional violations. The former tends to be more frequent and can be associated with shortcuts linked to routine tasks. The latter group is of a high-risk nature but occurs less frequently.

3.6. Common Limitations Identified in the Reviewed Publications. Although there was a distinctive scarcity of information across the reviewed literature relating to the domain under primary investigation, enablers, and challenges to learning in the featured preserves, which were well noted, learning from incidents across all domains shares a kindred desired outcome of delivering lessons that help prevent recurrence of similar incidents in the future. However, throughout the review, a few common limitations were discovered in the literature and summarised as follows:

(i) All research papers do not follow the same discipline of section title and content.

(ii) Few of the reviewed publications feature enough detail in the methodology sections to aid with the exact replication of the featured study.

(iii) Details of piloting and testing data gathering instruments such as semistructured templates were scarce.

(iv) The robustness of some analyses was difficult to determine.

(v) The study featured participant perceptions, gauging the efficiency of lessons learned was not well supported in the text.

(vi) Safety culture and just culture are mentioned as pivotal to learning. However, there is no solid mechanism featured in support of objectively measuring either cultural component in an aircraft maintenance and continuing airworthiness management environment.

(vii) The literature review uncovered many instances of formal learning. It was noted that informal learning practices were not well represented.

4. Conclusions

The primary aim of learning from incidents is to support actions that contribute to preventing recurrence of unwelcome events. The literature review revealed the existence of a solid formal architecture capable of delivering lessons within the featured domain activities. However, learning from incidents is not specifically articulated as a requirement and therefore presently not all elements required are explicitly articulated with the regulatory code. Although some domain requirements mandate formal training, informal learning initiatives are not required to be capitalised upon. Additionally, inadequate incident causation can deflect from potential learning opportunities arising from reporting. Poorly resourced efforts to establish appropriate causation are recorded as a central impediment to learning. The importance of reporting (incidents) and enabling facilitators such as the presence of a just culture cannot be overstated. Encouraging a reporting culture also reflects positively on the potential to learn from reported incidents.

The literature review also revealed the prevalence of similar constraints to learning in other industries. Lukic et al. [2] highlight the increasing focus on learning from incidents in the health, safety, and environmental areas of the energy industry. They put forward factors they consider to be important for effective learning which bring a focus on; the participants of learning, types of incident, types of knowledge, and learning process. Drupsteen et al.'s [36] industrial research (chemical, construction, energy, governmental metal, and transport) states that "many incidents occur because organisations fail to learn from past lessons." They point out that the traditional approach to learning often features only a careful analysis and formulation of lessons in the hope future incidents will be prevented. They suggest that, in addition to focusing on prevention of reoccurrence, the learning process should be improved which in turn can contribute to making an organisation safer. Others such as Jacobsson et al. [43] question the efficiency of learning from incidents in some organisations (petrochemical, food and drug, and energy) but suggest there is value in the analysis of the learning cycle. Such an approach can offer an insight into inherent weakness that often enables accidents. Silva et al. [45] examine how organisations (manufacturing, construction, production, and distribution of energy) use accident information to reduce the occurrence of unwelcome events. They acknowledge there is a need to achieve a balance between adequately resourcing safety initiatives and maintaining acceptable levels of safety. In healthcare, Drupsteen and Wybo [35] suggest an organisation can apply lessons arising from past events such as warning signals, mistakes, incidents, and accidents. Hindsight can assist with determining if an organisation did actually learn from an unwelcome event, and their study expounds two sets of indicators that could contribute to gauging an organisation's inclination to learn. By considering the outputs of research in domains parallel to continuing airworthiness, the benefits of proven approaches in other industries could be leveraged and applied without further delay.

Many aspects of current literature are developed from a linear or sequential view of how an accident/incident occurs. This of course might be an appropriate place to start to examine the retrospective aspects of learning that an unwelcome event can provide. However, more proactive models such as Hollnagel et al.'s [51] FRAM model, as highlighted by Furniss et al. [37], are very capable of delivering more sustainable lessons. Nevertheless, it is evident from the literature search and review that research in the aircraft maintenance and continuing airworthiness management arena are yet not well represented in respect of learning from incidents.

One potential benefit of digressing from the traditional view of causation is that models such as FRAM can be applied in support of specific analysis frameworks capable of deciphering: what went wrong, hazards that may have not been previously considered, and the feasibility of potential solutions to prevent recurrence. As human systems and artificial intelligence continue to occupy shared workspaces, an appreciation of exactly how the system works is essential in order to deliver effective lessons when unwelcome events do occur. Further research in the continuing airworthiness area utilizing forward looking frameworks such as FRAM will have a positive impact on better understanding event causation. It will also present a need to examine and augment legislative requirements to support the needs of regulatory and ethical oversight of systems that employ a blend of human and autonomous functionality.

It is believed that the systematic review could be used to refine terms of reference for a European legislative working group tasked with improving the content of the implementing regulations in the area of learning of incidents within the context of SMSs in aircraft maintenance and continuing airworthiness management organisations.

Data Availability

The data supporting this systematic review are from previously reported studies and datasets, which have been cited. The processed data are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Review Article

Using the Functional Resonance Analysis Method (FRAM) in Aviation Safety: A Systematic Review

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The functional resonance analysis method (FRAM) is a system-based method to understand highly complex sociotechnical systems. Besides learning from safety occurrences or undesirable states, FRAM can be used to understand how things go well in a system, by identifying gaps between "work as imagined" (WAI) and "work as done" (WAD). FRAM is increasingly used in many domains and can enhance our understanding of a complex system and proposes strategies to refine the work design. This systematic review identified 108 FRAM research papers from 2006–2019. Most of these papers were conducted by European researchers and employed qualitative methods such as document analysis, interviews, and focus groups with subject matter experts (SMEs) and observations to develop WAI and WAD. Despite being used in healthcare, construction, and maritime sectors among others, aviation was the most commonly explored domain in FRAM studies. The 26 FRAM studies in aviation explored many aspects of the aviation industry, including Air Traffic Control (ATC) systems, cockpit operation, ground handling, maintenance, and a range of past safety incidents, like runway incursions. This paper also characterises the FRAM studies focused on aviation in terms of the common methods and steps used to build FRAM and the available software tools to build FRAM nets. Current FRAM illustrates its advantages in capturing the dynamic and nonlinear nature of complex systems and facilitates our understanding and continual improvement of complex systems. However, there are some critical issues in FRAM use and interpretation, such as the consistency of methods and complexity and reliability of data collection methods, which should be considered by researchers and FRAM users in industry.

1. Introduction

Complex systems comprise different groups of humans, technologies, and organisations that may interact with each other in many industrial domains. Ladyman et al. [1] argued that a complex system has the following features: nonlinearity, feedback, robustness and lack of central control, emergence, spontaneous order, hierarchical organisation, and numerosity. The essential characteristic of complex systems is nonlinearity; that is, the presence of factor A does not necessarily lead to outcome B, and vice versa [1]. A complex system consists of numerous interacting components. Components affect and are affected by one another. Normally, this kind of feedback does not affect the overall system's operational status. The system itself is robust enough and able to absorb minor variabilities. Nevertheless, under particular situations, the same set of variabilities may make the system fail. In other words, interactions between different components are dynamic and emergent, rather than static and ancillary. The dynamic conditions and interactions make the system behaviour difficult to predict. The traditional simple linear relationship cannot explain the entire complex sociotechnical systems comprehensively (e.g., [2, 3]).

One increasingly common method for analysing complex systems is the functional resonance analysis method, known as "FRAM." FRAM is a system-based analysis method, which considers the whole system and focuses on its functioning rather than the structure of its components. Originally known as the "functional resonance accident model," FRAM was initially established by Hollnagel in 2004

[4], to investigate accidents and incidents in complex social-technical systems. However, learning only from accidents/incidents is not sufficient to understand the interactions between technologies, humans, and organisations that make up a complex sociotechnical system. This is especially the case when it comes to ultrasafe systems, such as in the aviation and nuclear industries. Safe operation of complex systems requires a better understanding of how the work is actually carried out ("work as done," WAD) [5]. FRAM's scope has been expanded from an accident model to a more general analysis method, termed the functional resonance analysis method. The gaps between WAD and how the work is supposed to be done ("work as imagined," WAI) generate variabilities in the daily working procedure. Any single instance of variability alone is not able to lead to the accident/incident. However, under specific conditions, these variabilities may lead to functional resonance, causing an undesired outcome or even crashing down the entire system.

Since its establishment, experts from different disciplines have applied FRAM to a range of industries or contributed to developing FRAM theory and methods. The advantages of FRAM as a methodology have been suggested by several studies. Applying FRAM can facilitate a better and more in-depth understanding of interactions between complex system functions. For example, Woltjer and Hollnagel [2] applied FRAM to analyse the Alaska Airlines Flight 261 accident. The analysis suggested that FRAM could capture the dynamic and nonlinear nature of this complex system failure. Later on, Hollnagel and colleagues [6] again used FRAM to reanalyse the Comair Flight 5191 accident. The FRAM analysis results suggested a number of additional countermeasures compared to those suggested in the official NTSB report. By monitoring how component variabilities resonate, FRAM modelling can also identify the critical path of variabilities that emerged in the dynamic system [2, 7]. Using FRAM to detect the gap between WAI and WAD helps us improve safety and work design [8]. Compared to currently employed investigation methods and other systematic methods, such as the Domino model, Swiss Cheese Model, and the Bow-Tie model, FRAM is able to analyse complex systems and provide more comprehensive results [6, 9–11]. For example, Hollnagel and colleagues [6] reanalysed the Comair Flight 5191 using FRAM. The National Transportation Safety Board (NTSB) report mainly identified crew members' mistakes and flaws in the Federal Aviation Administration (FAA) requirements for Air Traffic Control (ATC) clearance authorization. By taking the whole context into consideration, FRAM unveiled further details of why the accident occurred than those presented in the NTSB official report. These included that information regarding runway construction and closure was missing in both Notice to Airmen (NOTAMs) documents and the Automatic Terminal Information Service (ATIS) and that the first officer was too busy to monitor the aircraft's position on the runway.

Given the increasing use of FRAM to better understand complex systems and its potential for use retrospectively and prospectively, this paper aims to systematically review FRAM studies, with an emphasis on how it has been applied in aviation. We first outline the principles of FRAM and how the method should be conducted, before reviewing the literature and analysing the methods used, the locations of FRAM studies, and the systems to which FRAM has been applied.

2. Principles of FRAM

The following section outlines the theoretical principles that guide the implementation of FRAM. The first principle is that of the equivalence of success and failures [5]. Traditional safety theories emphasised learning from system failures, such as incidents and accidents [5]. However, learning from failures is not enough for keeping current complex socio-technical systems safe. FRAM can be applied to analyse either system incident/accident or the normal operational procedure. According to FRAM, to understand what goes right when the daily work is carried out is as important as understanding what failed in the system.

The second principle is that of approximate adjustments [5]. Human performance can be influenced by many factors, both internal and external, such as fatigue, stress, emotions and mood, vigilance, task demands, and deadlines. Sometimes organisational factors such as the effectiveness of communication or unclear guidelines can make workers' tasks more difficult. The complex working context may make the work task more challenging and require workers to make their own decisions. Workers have to adjust their behaviour accordingly to meet the system's requirements to produce the desired outcome. They usually need to make some trade-offs between being efficient and to make sure the work can be completed as precisely as possible. Hollnagel [4] termed these kinds of adjustments as efficiency-thoroughness trade-offs (ETTOs). These adjustments are necessary and understandable; however, any changed system behaviour may raise variabilities in the system.

The third principle is that of emergence [5]. Under each analysed case, the context and combination of variabilities in the system are unique. As the interactions within a complex system are dynamic and nonlinear, the occurrence of an outcome is emergent. To be more specific, minor variabilities always exist in normal system operations and do not affect system safety. However, the particular external environment may integrate variabilities and magnify their influence to generate an undesired outcome.

The fourth principle is that of functional resonance [5]. From the FRAM perspective, variabilities exist in normal daily operations. These small variabilities may not be able to crash the system alone, but aggregated with other variabilities in the system may cause resonance, which generates a negative outcome. The whole system should be taken into account, instead of focusing on one segment of the system.

In performing a FRAM analysis, several steps are involved, which then takes these principles into account. The following describes the main steps of conducting a FRAM analysis [5]:

Step 0: define the purpose and scope of analysis.

Before the analysis starts, analysts should clarify whether the analysis would be conducted in relation to an incident scenario or the context of normal operations. As there is no clear boundary to conduct the FRAM and the results of FRAM would be complicated, setting the scope of the proposed analysis can prevent the results from being too detailed and too complicated. For example, to examine the catering delivery procedure during a flight turnaround, it would be good to start from the function "preparing food in the catering department" and end up with "crew confirms catering delivery." Otherwise, the food preparation process could be traced to very early stage functions, like "purchase ingredients," "design menu," or even "grow vegetables." Without a clear boundary, the FRAM analysis might generate a lot of data and appear comprehensive but be ultimately unhelpful in understanding the system of interest.

Step 1: identify and describe the essential system functions.

FRAM deconstructs the complex sociotechnical system into "functions." A function is a task or an activity that is required to produce a certain outcome. According to Hollnagel [5], there are three types of functions: technological functions, human functions, and organisational functions. Each identified function can be described by six aspects (see Figure 1):

Input (I): input is what activates or starts a function and/or that is used or transformed by the function to produce the output.

Preconditions (P): preconditions refer to the conditions that must be satisfied before a function is carried out. Preconditions alone cannot activate a function.

Resource (R): resource is something that is needed or consumed when the function is active. Resources will be consumed up as the function is executive.

Output (O): output is the outcome of a function.

Control (C): control is that which supervises, regulates, or monitors the function such as guidelines, regulations, or even social expectations.

Time (T): time refers to the temporal constraints on the function such as duration and starting point.

Function identification can start from anywhere within a complex system. Documents such as an operation manual or task procedures are useful resources for identifying system functions. Each function interacts with other functions via one or more of their aspects. Interactions connect functions together to form a FRAM net. Figure 2 shows a simple FRAM net related to the cabin crew's work procedure before take-off. Each hexagon represents a function and its six aspects. For example, the output of the function "Greet passenger" is that all passengers are welcomed on board. This output can transform to be the input of the following function "Confirm the number of passengers."

Functions that operate before others, and have a potential effect on others, are termed "upstream" functions. Functions impacted by others are "downstream" functions. For example, in Figure 2, the function "Confirm the number of passengers" is upstream of the function "Close headlock" and downstream of the function "Greet passengers."

Step 2: identify the actual or potential variabilities between functions.

According to Hollnagel [5], performance variabilities can be categorized in terms of their origins, internal (endogenous) variability, and external (exogenous) variability. Internal variability refers to the variation caused by the function itself, such as software pitfalls or operator's experience. By contrast, the external variability refers to the influence of other functions, such as weather conditions and organisation's culture. Hollnagel [4] classified the external variabilities as eleven common performance conditions (CPCs): availability of resource, adequacy of training and experience, communication, adequacy of interface and operational support, availability of procedures or plans, working conditions, number of simultaneous goals, available time, crew collaboration quality, and adequacy of organisation. In 2012 [5], Hollnagel again suggested an elaborate solution and a simple solution to consider the performance variabilities. The elaborate solution identifies variabilities in terms of speed, distance, sequence, object, force, duration, direction, and timing. Meanwhile, the simple solution considers function output variability in terms of timing and precision. According to the simple solution, the output of a function would generate too early, on time, too late, or not at all and can be precise, acceptable, or imprecise. In our example in Figure 2, for instance, the function "Run safety check" could be completed too late and carelessly/imprecisely, which brings variabilities into the system.

Step 3: analyse the aggregation of variability.

In the FRAM net, the output of a function interacts or "couples" with other functions which are represented in the net by lines connecting the functions (known as "couplings"). As illustrated in Figure 2, the function "Conduct safety briefing" couples with function "Run safety check." In this way, the output of an upstream function may vary and then transfer the variability to its downstream function(s). All upstream-downstream couplings can be analysed in terms of timing and precision. Taking one of the couplings from Figure 2, for example, if the output of the upstream function "Conduct safety briefing" comes too late, the downstream function "Run safety check" would experience a delay. The aggregation of these variabilities may cause resonance in the system, which leads to an undesired outcome. In the present case, the flight may not be able to take-off on time.

Step 4: propose ways to manage variability.

The previous steps help to identify the variabilities and their potential aggregation within the system. The last step should be proposing strategies for managing

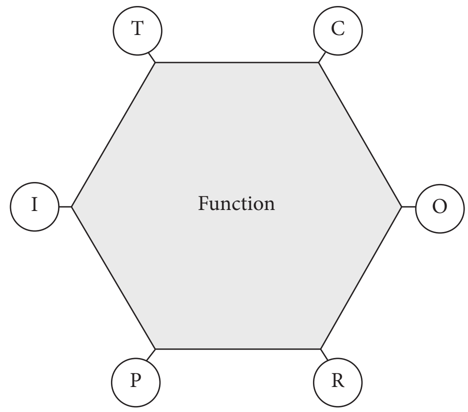

Figure 1: A hexagon representing a function, with the six aspects of input (I), output (O), preconditions (P), resources (R), control (C), and time (T).

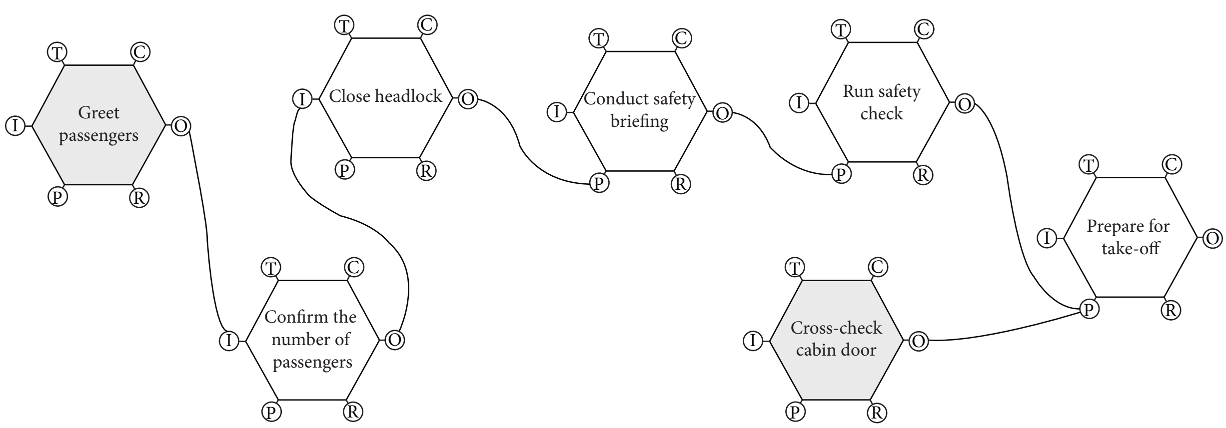

Figure 2: A simple FRAM net related to cabin crew's work before take-off.

variability. The FRAM considers system success and failures equivalently. We should consider different management strategies for variabilities that lead to positive outcomes and those contribute to an undesired result. Clarke et al. [12] assessed the potential risks of transferring cargo between two floating harbour transhippers (FHTs) using FRAM. The results showed the manner in which variabilities are added together to influence the system. Some recommendations were developed to improve system design. For example, the number of crew should be sufficient on both vessels, and equipment should be regularly checked and placed in designated places [12].

Despite the growth in the frequency with which it is used (e.g., [13–15]), there are few systematic reviews that examined FRAM and its implementation. Some reviews have included FRAM papers, but in the context of examining other system-based analysis tools. For example, Hulme et al. [16] reviewed peer-reviewed articles that applied systemic accident analysis methods to understand contributing factors between 1990 and 2018. They chose four groups of system-based accident analysis methods: AcciMap, the Human Factor Analysis and Classification System (HFACS), the System Theoretic Accident Model and Processes-Causal Analysis based on STAMP (STAMP-CAST), and FRAM. Only four FRAM studies were included in their analysis. The authors examined accident contexts, the number of identified functions, source of accidents, the nature of accidents, and features of eligible articles. All these reviewed analysis methods resulted in multiple contributing factors, couplings, and functions. However, they concluded that the results of FRAM would be highly complex and difficult to interpret [16].

Little is therefore known about the pattern of use of this emerging systems safety tool. Accordingly, the present systematic review aims to outline how, where, and for what purpose FRAM has been used, with a particular focus on how FRAM has been applied in the aviation industry.

3. Methodology

FRAM was initially developed to investigate accidents and known as the functional resonance accident model. By adopting the Safety-II perspective [5], FRAM transformed to the functional resonance analysis method and expanded its analysis scope to system normal operation (e.g., [17]). Preliminary searches showed that searching for "functional resonance analysis method" alone returned thousands of papers concerned with "functional magnetic resonance imaging" (fMRI) from medical journals and other methods or theories. Accordingly, the functional resonance analysis method was joined with "FRAM" in subsequent searches. In order to cover all eligible FRAM research studies in English, we used the search item "functional resonance analysis" OR "functional resonance accident" and "functional resonance analysis method" AND "FRAM" in the title and abstract of as a keyword across five online databases: ProQuest, PubMed, ScienceDirect, Scopus, and Web of Science. The search timeframe was unlimited although it is recognised that most FRAM studies have occurred since 2012 when the key resource on the method was released. EndNote X9 for Mac was used to organise all references.

At the screening stage of the review, all records were assessed manually. Records were excluded if they focused on other systematic analysis methods rather than FRAM, such as STAMP (without a focus on FRAM). Book chapters, theses, commentaries, newspaper articles, and corrigenda were excluded. Documents where the full text was unavailable (after library databases and web searches) or the full text is in a language other than English were also excluded.

A taxonomy of current FRAM studies was developed to organise the resulting papers. Our analysis examined the distribution of the number of published papers across years, the regions of current FRAM studies, and the contexts of current FRAM instantiations.

4. Results

Figure 3 is a PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) [18] flowchart diagram showing the search process. The initial search across five databases identified 2212 records. After removing duplicates, the remaining 1651 records were then screened manually by reviewing titles and abstracts. As mentioned above, the functional resonance analysis method is highly similar to fMRI in medical research, and 1481 records were excluded. Furthermore, when the remaining 170 records were assessed for eligibility, 75 records that did not meet inclusion criteria, such as full text being unavailable or the full text was not in English, were removed. In addition to the 95 eligible papers, 13 additional papers were identified from the reference lists of papers that had been found in the search. Finally, 108 papers were included in the analysis (see Figure 3).

Figure 4 shows the number of published papers over time. Before 2012, 10 out of 16 FRAM studies used accidents or incidents as instantiations. Later on, by adopting the perspective of Safety-II, FRAM expanded its analysis scope to normal operational conditions. In 2012, Hollnagel published the first book about FRAM, *FRAM: The Functional Resonance Analysis Method: Modelling Complex Socio-Technical System*. This book provides systematic background information, steps, and principles to use FRAM. The number of FRAM-related papers increased around two years later. However, since 2017, published FRAM papers reduced to 19 and 16 in the following two years, respectively.

The FRAM has attracted researchers' attention worldwide. Among the eligible 108 papers, over half (56.48%, $n = 61$) were conducted by researchers from European countries, such as Denmark, Sweden, and Italy. Asian researchers from China, Japan, and other countries published 22 papers, accounting for 20.37%. South American researchers contributed 10.19% ($n = 11$) FRAM papers, while North American researchers published seven studies (6.48%). Oceanian researchers published seven studies (6.48%) related to FRAM. Studies on FRAM also facilitated international cooperation; however, the analysis above was based on the lead author's location. For instance, Damen et al. [19] analysed preoperative anticoagulation management (PAM) in normal operations using FRAM. The study was conducted in surgery departments in both Australia and the Netherlands.

As a general safety analysis method, FRAM could be applied to a variety of complex sociotechnical systems. Researchers from different areas expanded and illustrated the application of FRAM in a wide range of instantiation contexts. Figure 5 shows that aviation, healthcare, construction, and maritime contexts are the most popular domains of FRAM application. Those contexts with fewer than three papers were categorized as "others" and included applications of FRAM that focused on the environment, policy-making, sport and recreation (hunting), and natural disasters (flood). As some researchers illustrated their proposals by analysing several cases, the total number of selected papers in Figure 2 is beyond 108. For example, Amorim and Pereira [20] applied FRAM to understand the accidents resulting from improvisation in workplaces and used aircraft maintenance, construction, and shoe manufacturing as case studies. Similarly, Moškon and colleagues [21] demonstrated their proposed method in five cases, including emergency room triage, fire prevention, construction management, aircraft take-off, and flight operations.

In terms of existing research methods, the results indicated that current FRAM is still predominately a qualitative method. Eighty-five papers (78.7%) employed qualitative approaches, such as interviews, documentary reviews, focus groups, or observations to develop WAI and WAD. More specifically, a majority of the papers that mentioned their method to map WAI indicated that they used document review and analysis [14, 19, 22–24]. In order to get an insight regarding WAI, the most popular methods are semistructured interviews, direct observations, and workshops with operators and regulators [3, 10, 23, 25–33].

The authors of the remaining 23 (21.3%) papers applied FRAM by using quantitative or semiquantitative methods, such as Monte Carlo simulation and modelling. Furthermore, 19 out of these 23 studies integrated FRAM with other methods to quantify their proposed models, including the Cognitive Reliability and Error Analysis Method (CREAM) (e.g., [34]), the Analytic Hierarchy Process (AHP) (e.g., [35, 36]), and finite state machine (FSM) (e.g., [37]). Among these quantitative and semiquantitative studies, it was much

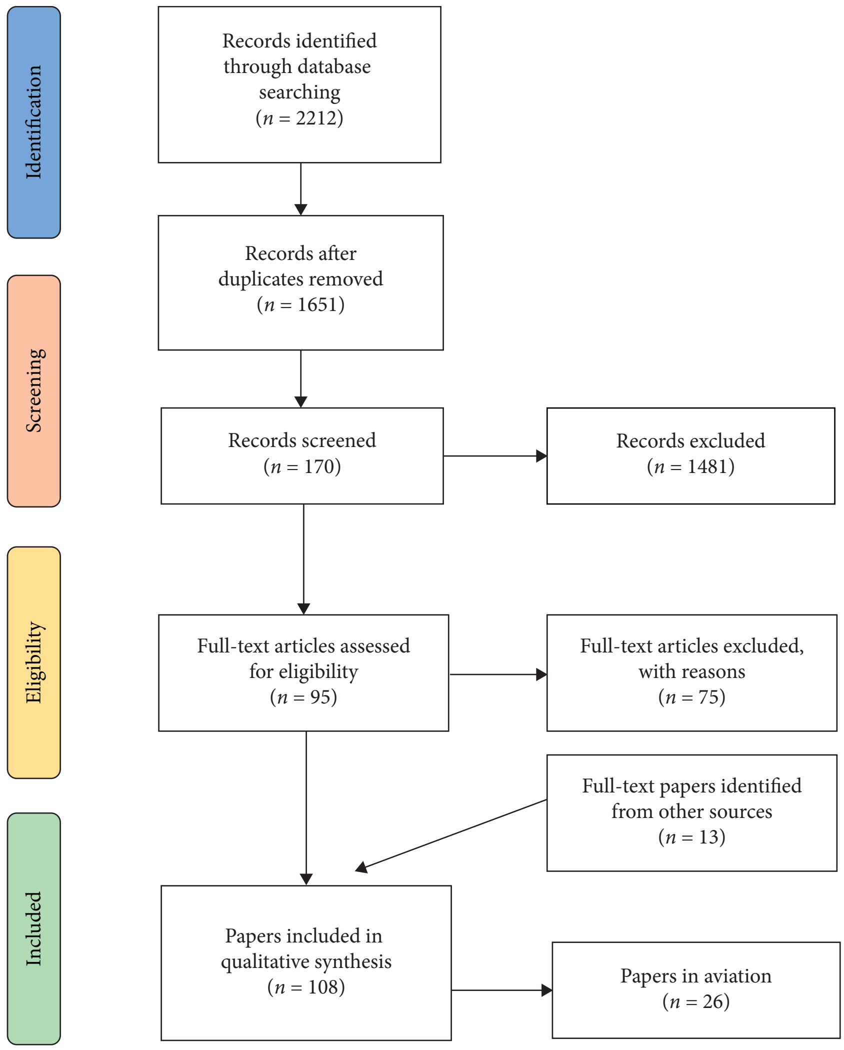

Figure 3: The literature identified and screened is presented as a PRISMA flowchart diagram (the 26 aviation papers were included in the total 108 papers included in the qualitative synthesis).

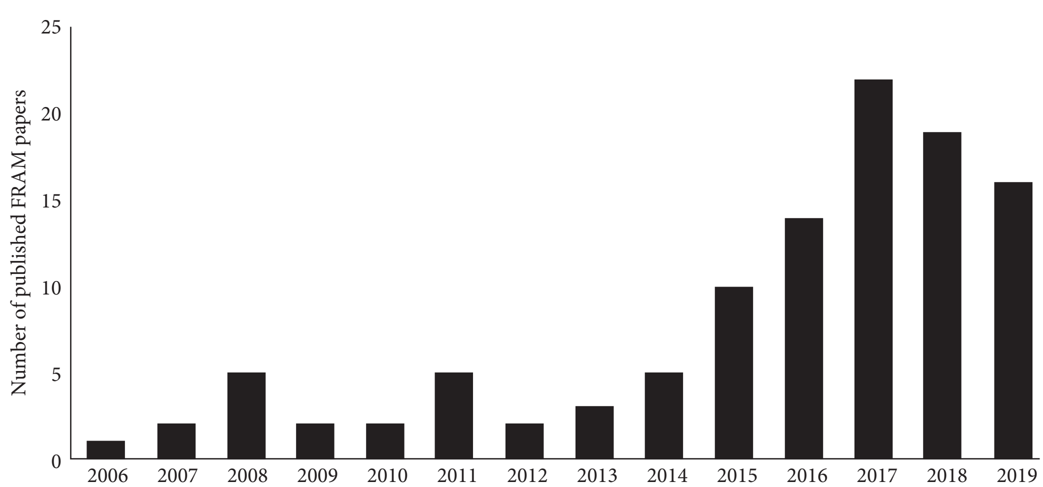

Figure 4: The number of published papers from 2006–2019.

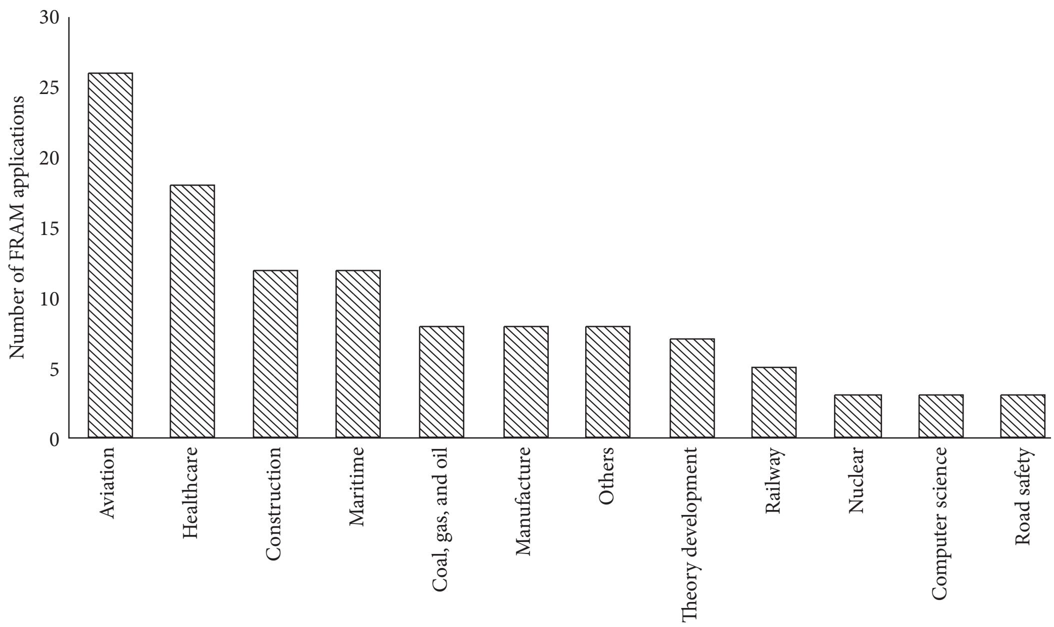

Figure 5: The number of FRAM applications across domains.

more common practice to characterise the performance variability in terms of timing and precision, rather than the 11 CPCs as originally identified by Hollnagel [5].

5. FRAM in Aviation

As reported above, FRAM has been used most frequently in the aviation industry compared to other domains. Hence, we further analysed the 26 papers which applied FRAM to the aviation industry (see Table 1). The pattern of aviation FRAM studies is consistent with what we found in relation to characteristic of FRAM studies in other industries in terms of locations and methodologies.

In most of the 26 aviation FRAM studies, 19 (73.08%) were completed by researchers from European countries, while researchers based in Asia, South America, and Oceania published 4 (15.38%), 2 (7.69%), and 1 (4.35%) paper(s), respectively.

FRAM studies in aviation were also dominated by qualitative methodologies, with 20 papers (76.92%) using qualitative methods. Building the FRAM network to understand WAI and WAD, the common methods were literature reviews (such as examining previous relevant accident reports and operational manuals), direct observations, workshops, and interviews with SMEs, such as pilots and air traffic controllers. After completing the initial FRAM network, researchers invited SMEs to check the completeness and validate the FRAM network. Only 6 (23.08%) of the aviation papers attempted to quantify FRAM. Hirose et al. [34] adapted CREAM to use FRAM in a systematic and quantitative way. Yang et al. [14] used Simple Promela Interpreter (SPIN) to demonstrate the functional resonance in system. Patriarca and colleagues [32] discussed using the Resilience Analysis Matrix (RAM) to enhance FRAM-based accident analysis. Moreover, Patriarca et al. [13] proposed a method to quantify function variabilities in relation to the ATM system based on Monte Carlo simulation.

Hollnagel [5] suggested that variabilities can be defined from several perspectives. Except for five studies that did not clarify how they categorized identified variabilities, most of the existing research used the simple solution, considering variabilities in terms of only time and precision ($n = 9$). Seven studies used CPCs to identify variabilities. Some researchers proposed new ways of defining variabilities. For example, Duan et al. [9] considered variability "within" functions and "between" functions. Variability within a function refers to how an output could be influenced by variabilities from the other five aspects of the same function. Variability between functions refers to how the output variability of upstream functions could influence aspects of downstream functions. Frost and Mo [45] suggested using two sets of guidewords to identify potential variabilities. Firstly, the variability in each of the five aspects (input, time, control, precondition, and resource) is rated as *early, delayed, absent, wrong rate, underspecified, or overspecified*. Secondly, for the same function aspects, variability from the influence of the specific conditions (such as *time pressure, goal conflicts, communication quality*, and *organisation culture)* is assessed.

Half of the analysed papers ($n = 13$, 50%) followed the four-step FRAM analysis method. Few papers ($n = 2$, 7.69%) indicated that their FRAM analysis consists of five steps. However, some of them started the first step from determining the scope of the proposed analysis (see [3]). Some research only focused on the first three FRAM steps. For example, Macchi et al. [40] employed FRAM analysis to assess the risks of the Minimum Safety Altitude Warning system (MSAW). To explore more possibilities of FRAM, some researchers modified the original FRAM steps to satisfy their research goal. For example, Frost and colleagues

Table 1: Studies using FRAM in Aviation from 2006 to 2019.

Author	Year	Aviation area	Case/system details	Instantiation type	Timeframe	FRAM tools	FRAM building methods	Variability	Research type
Sawaragi et al. [38]	2006	Accident	American Airlines Flight 965 accident, 1995	Accident	R	NA	Accident report review	CPCs	Qualitative
Woltjer and Hollnagel [2]	2007	Accident	The Alaska Airlines Flight 261 accident, 2000	Accident	R	NA	Accident report review	CPCs	Qualitative
Woltjer and Hollnagel [17]	2008	Air Traffic Management (ATM)	ERASMUS project	Normal operation	P	NA	Literature review, interview, observation, experiment	CPCs and variability phenotypes	Qualitative
Woltjer [39]	2008	Accident	The Alaska Airlines Flight 261 accident, 2000	Accident	R	NA	Accident report review	CPCs	Qualitative
Hollnagel et al. [6]	2008	Accident	Comair Flight 5191 accident, 2006/departure routine	Accident	R	NA	Accident report review	Time, precision	Qualitative
Macchi et al. [40]	2009	Landing approach-ATC	MSAW system	Normal operation	P	NA	Workshop, literature review, interview	Time, precision	Qualitative
Herrera and Woltjer [41]	2010	Incident	Norwegian Air Flight NAX541 incident	Accident	R	NA	Accident report review, interview	CPCs	Qualitative
de Carvalho [42]	2011	Accident	Midair collision between Flight GL1907 and Flight N600XL, 2006	Accident	R	NA	Literature review, interview	NA	Qualitative
Nouvel et al. [43]	2011	Landing approach	Flight to Paris-Orly, 1997	Incident	R	NA		CPCs	Qualitative
Herrera et al. [25]	2011	Helicopter operation	Helicopter operation	Normal operation and incident	R	NA	Literature review, observation, interview, workshop	NA	Qualitative
Martinie et al. [44]	2013	Cockpit operation	Weather radar interactive system	Normal operation	P	NA		NA	Qualitative
Frost and Mo [45]	2014	Airline operation control system (OCC)	Airline operation control system (OCC)	Normal operation	P	NA	SMEs workshop	Early, delayed, absent, wrong rate, underspecified, overspecified, time-pressure	Qualitative
Ragosta et al. [46]	2015	ATM	Aircraft route change	Normal operation	P	NA		Time, precision	Qualitative
Yang and Tian [47]	2015	Landing process-crew	Landing process based on the flight, crew, training, and manual	Normal operation	P	NA	Document analysis	Time, precision	Qualitative
Duan et al. [9]	2015	Accident	Scandinavian Airlines Flight 686 and a Cessna Citation CJ2 business jet collision, 2001	Accident	R	NA	Report review	Other	Semiquantitative
Amorim and Pereira [20]	2015	Maintenance	Aircraft maintenance	Accident	R	NA		Time, precision	Qualitative

Table 1: Continued.

Author	Year	Aviation area	Case/system details	Instantiation type	Timeframe	FRAM tools	FRAM building methods	Variability	Research type
Hirose et al. [34]	2016	Accident	American Airlines Flight 965 accident, 1995	Accident	R	NA		CPCs	Semiquantitative
Patriarca et al. [13]	2017	ATM		Normal operation	P	FMV		Time, precision	Semiquantitative
Studic et al. [3]	2017	Ground handling	Ground handling services	Normal operation	R	FMV	Literature review, observation, interview, and expert judgment	Internal, external, couplings between functions	Qualitative
Yang et al. [14]	2017	ATM	Minimum Safe Altitude Warning (MSAW) in ATM	Normal operation	P	FMV	Guidelines review	Time, precision, 6 LEVELS	Semiquantitative
Stogsdill and Ulfvengren [11]	2017	ATS	Air Transport System	Normal operation	P	NA			Qualitative
Rutkowska and Krzyzanowski [48]	2018	ATC-ACC APC	Transferring control over the aircraft between the area control centre (ACC) and approach control (APC) units	Normal operation	P	FMV	Document review		Qualitative
Patriarca et al. [32]	2018	ATM	US Air Flight 1493, 1991 (collided with SkyWest Flight 5569)	Accident	R	FMV	NTSB report review, testimonies, documents and coeval accounts review, SME's analysis	Time, precision	Semiquantitative
Ferreira and Cañas [49]	2019	ATC	AUTOPACE project: propose training for ATCo under foreseeable automation scenarios.	Normal operation	P	FMV/ myFRAM		Time, precision	Qualitative
Adriaensen et al. [15]	2019	Cockpit operation	Douglas Aircraft DC-9 cockpit operation during approach and landing	Normal operation	P	FMV/ myFRAM	Document analysis, workshop, interview	Endogenous variability, exogenous, couplings	Semiquantitative
Moškon et al. [21]	2019	Flight operation	Large aircraft flight operation and light sport aircraft take-off	Normal operation	P	FMV		NA	Qualitative

R = retrospective; P = prospective; NA = not applicable.

[45] consulted expert groups to refine and confirm the baseline FRAM model. The validated FRAM model was used to develop instantiations for later analysis in a hazard identification and analysis (HAZID) workshop. The modified FRAM was then used with System Hazard Analysis (SHA) to identify system hazards. Yang and Tian [47] extended the original FRAM to a 7-step method. In addition to the original first three steps, they defined safety requirements and transferred FRAM models into the MuSMV model checker. The proposed approach was evaluated by analysing the landing process from the flight crew's perspective. The analysis identified a series of variabilities which may violate safety requirements.

Topics of FRAM studies in aviation covered different aspects of aviation systems, including the overall air accident/incident analysis ($n = 8$, 30.77%), ATM/ATC system ($n = 8$, 30.77%), cockpit operation ($n = 3$, 11.54%), landing approach ($n = 3$, 11.54%), Airline Operation Control System (OCC) ($n = 1$, 3.85%), helicopter operation ($n = 1$, 3.85%), ground handling procedure ($n = 1$, 3.85%), and aircraft maintenance ($n = 1$, 3.85%).

Among these 26 aviation FRAM studies, 13 of them used FRAM in a prospective way to assess risks, while the remaining 13 studies used FRAM retrospectively to analyse what happened in aviation incidents. Meanwhile, some studies also used FRAM to assess the target system's resilience characteristics. For example, Woltjer [39] reanalysed the Alaska Airline Flight 261 accident using FRAM and evaluated resilience characteristics, such as buffering capacity, flexibility, margin, tolerance, and cross-scale interactions, based on FRAM analysis.

Currently, there are two software tools developed specifically for FRAM: the FRAM Model Visualiser (FMV) and myFRAM. Both of them are useful tools to build a FRAM model net.

FMV works using Adobe Air, while myFRAM can be used in Microsoft Excel. The output of myFRAM can be exported to FMV. Only 7 out of 26 studies indicated the software they used to build and visualize their FRAM. All of these seven used FMV, while two of them also used myFRAM.

6. Discussion

The present study aimed to review existing FRAM studies to understand how, where, and for what purpose FRAM has been used, with a special interest in its application in the aviation industry. Our analysis provides a taxonomy of current FRAM studies with respect to their origins, contexts, and research methodologies. It can assist users of the method to interpret the assumptions in the implementation of FRAM and evaluate recommendations for system improvements.

Another recent review (see [16]) considered a range of systems safety analysis tools over a similar time period yet had a limited inclusion of FRAM, finding only 4 FRAM papers. By contrast, our systematic review found 108 FRAM papers from 2006–2019. Most FRAM research was conducted in Europe. While there was a wide distribution of focal domains including healthcare, construction, and maritime, most papers focused on systems in aviation such as ATC and aviation incidents. This suggests that FRAM is an emerging methodology in aviation safety, which may influence its adoption in other domains. Most of the aviation papers adopted a qualitative approach to gather information to build the FRAM net (e.g., using focus groups to collect data) and were evenly distributed in terms analysing past incidents and current systems operations.

Despite there being similarities in the general approach adopted (such as qualitative methods of interviews and focus groups and qualitative methods including Monte Carlo simulation) across all papers selected in the review, there was no standard method for completing FRAM. Hollnagel [5] indicated particular steps to conduct FRAM analysis in the first book about FRAM. Nevertheless, there was a significant variation in the number of FRAM steps used in papers (e.g., [34, 47, 50]).

Similarly, this diversity was reflected in the manner in which variability is indexed within FRAM. Several researchers used the "simple solution" (e.g., [7, 13, 19, 33, 51–55]), while others use more detailed indices of variability, such as the 11 CPCs (e.g., [23, 56–60]).

Given that FRAM is focused on mapping and understanding variability within complex systems, the divergent approaches to indexing variability could be a concern in relation to consistency and reliability. FRAM analysis is used to understand a sociotechnical system under specific conditions [5]. The result from one analysis cannot be generalized to another context [22, 61], and typically, it is not intended to be generalized. However, the issue of consistency of implementation of the method is relevant to evaluate the method itself. That is, like all systems analysis tools, while we may not be able to compare the outcomes because we are analysing different systems, it is still important to assess and compare the methods used to generate these outcomes. Doing so can result in refinement of the method and identification of practice that violates it assumptions.

Variations in methods when implementing FRAM has implications for users of FRAM and those interpreting FRAM results in industry. It is important to consider how these different methods could be used and compared: why they are used and whether they are appropriate for the system and users in question and how they may have influenced the outcomes of tool. In addition, it may be that particular methods for indexing variability are useful for particular purposes. For example, the simple solution of indexing variability only by time and precision may be most effective for FRAM users in industry. In this context, more streamlined versions of the method may be desirable so that it is easier to collect data in the field and to interpret and use the method in practice. Alternatively, other systems for which highly precise data are already available may lend themselves to collecting and analysing additional metrics of variability and to more complex analysis methods.

As reflected in our analysis, the majority of existing FRAM studies employed qualitative methods. While FRAM has been shown to be a very useful tool for analysing complex systems (e.g., [2, 19, 33, 53, 62, 63]), it has also been suggested that its qualitative nature means it cannot provide an accurate calculation of risks [64, 65]. Furthermore, due to such qualitative methods, FRAM can be very time-consuming and complex to learn and to interpret the results [56, 63, 64, 66]. Ways of simplifying FRAM while maintaining its rich analysis of complex systems require further exploration.

A consequence of the reliance on qualitative methods is that current FRAM results largely rely on the knowledge of subject matter experts to inform WAI and validate WAD. The typical SMEs in existing FRAM studies include accident investigators, ATC officers, safety experts, and pilots. Compared to novice users of the system, SMEs have more of an idea of how different system components work together. At the same time, the experience of (nonnovice) system users is desirable for FRAM. While it is difficult to train day-to-day system users in the use of FRAM, methods for collecting data from their direct experience are needed to inform WAD with sharp-end operational performance.

An alternative to qualitative analysis is to apply FRAM to simulated systems. Based on our analysis of the overall FRAM papers, the majority of quantitative research uses simulation data rather than data from real-working scenarios [8, 13, 45, 48, 60]. Simulation makes it possible to get a vast amount of data quickly and at low cost, while also avoiding the difficulty in data collection in the real world. Both approaches have their advantages and disadvantages. As mentioned above, qualitative methods are problematic because the time involved and the lack of quantification while quantitative methods do not take account of data from real-working scenarios.

One solution might be a hybrid model, whereby in addition to using SMEs' knowledge in constructing WAI, the FRAM net is refined by data collected from system users, who are not experts in FRAM but are experts in the system use. Examples would include flight and ground crew, front-line maintenance engineers, and ramp workers. These data can be generated from real processes and collected automatically or from system user inputs and ratings.

A further potential criticism of FRAM is that it is usually applied to a relatively small part of a complex system rather than the entire system, while it attempts to understand complex systems. For example, aviation is a complex system that consists of numerous complex components, ATC being just one of them. Existing FRAM studies on ATC systems are more likely to analyse only one phase, such as the aircraft landing phase (e.g., [40]). FRAM results from the selected phase are already complex and difficult to interpret. Using the same method to analyse the whole system would be impractical in terms of time and resources. Some research has used FRAM to examine a more extensive system, such as accident reanalysis studies (e.g., [2, 6]). The functions were identified at macrolevels, where macrolevel functions could be examined further in detail to understand microlevel functions within them. In this way, FRAM could be used at different levels within a system, to build a "FRAM of FRAMs." For example, a higher-level function may be a summary of a group of functions (a FRAM net of a lower level set of functions).

Interestingly, most aviation FRAM studies did not specify which software products they used to generate FRAM nets. The analysis software should be reported in the future to facilitate replication of results, as well as an understanding of the particular constraints under which FRAM nets are constructed and analysed. This is especially the case given that there are platforms other than FMV and myFRAM with which to build FRAM nets. Microsoft Visio and Power BI are two options that provide data visualisation solutions and are compatible with other system information. Using these new tools to visualize FRAM may provide more detailed, dynamic, and interactive information. These platforms are consistent with those currently used in industry for displaying a range of other data, such as finance and marketing [67], and should be further explored for FRAM and related complex systems analysis tools.

One of the limitations of this paper is that grey literature was not examined. There may be instances of FRAM use that exist in the grey literature or that have not been published. The focus of this review was to assess publicly available and published accounts of FRAM use. It would be interesting to analyse all instances of FRAM; however, companies may wish to maintain the confidentiality of their systems.

7. Conclusion

This study introduced and described the FRAM perspective, methods, and steps. We identified 108 existing FRAM studies from 2006 to 2019 and further analysed those applied in the aviation industry. Our findings added to our understanding of how, where, and in what systems FRAM has been used so far and its potential for understanding aviation safety occurrences. The present analysis also identified critical issues in FRAM use, which need be considered by researchers and FRAM users in industry, such as consistency, data collection methods, ease of use, and expanding the range of subsystems analysed and the analysis scope.

These results highlighted a range of issues for future research. While FRAM has been applied to various aviation areas, there are many other unexplored aviation systems that may benefit from FRAM analysis. Examples include cabin crew's operations and catering. As discussed previously, the scope of the FRAM analysis could be expanded, to cover broader systems and understand how components interact. Nevertheless, while considerable effort has been made to implement FRAM in industry, some obstacles limit their application in practice. Future studies need to adapt FRAM implementation by simplifying methods for training in how to implement and interpret FRAM and methods for collecting system user data. The potential for using new tools to represent and analyse FRAM nets in a manner consistent with existing platforms already embedded in industry needs to be considered.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Civil Aviation Occurrences in Indonesia

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Globally, civil air traffic has been growing rapidly in recent years, and with this growth, there has been a considerable improvement in air safety. However, in Indonesia, the recent rate of incidents and accidents in aviation is far higher than the global average. This study aims to assess civil aviation safety occurrences in Indonesia and, for the first time, to investigate factors contributing to these occurrences within commercial Indonesian aviation operations. In this study, 97 incident/accident investigation reports published by the Indonesian National Transportation Safety Committee between 2007 and 2015 were analysed. The most common occurrences involved Runway Excursions, Loss of Control In-Flight, and Controlled Flight into Terrain. In terms of the likelihoods of the occurrences and the severity of consequences, Runway Excursions were more common while Loss of Control In-Flight and Controlled Flight into Terrain events were more severe and often involved fatalities. In Indonesia, Runway Excursions were usually nonfatal and comprised 45% of the occurrences for commercial flights, compared to 34% globally. Further, in this study, weather and Crew Resource Management issues were found to be common contributing factors to the occurrences. Weather was a contributing factor for almost 50% of the occurrences involving Indonesian commercial flights. Adverse weather contributed to Loss of Visual Reference for visual flight operations in mountainous areas, which contributed to the majority of Indonesian fatal accidents. The combination of Indonesian monsoon climate and mountainous weather characteristics appears to provide many risks, mitigation of which may require specialist pilot training, particularly for multicrew aircraft. In identifying the main contributing factors, this study will hopefully provide motivation for changes in training and operations to enhance future aviation safety in Indonesia.

1. Introduction

Globally, civil aviation has been marked by two general trends: increasing traffic volume and an improving safety record. The International Civil Aviation Organisation (ICAO) notes that air traffic internationally has increased by 78% in the last two decades, from 18 million aircraft departures in 1995 to 32 million in 2014 [1, 2], and to 34 million departures in 2015 [3]. Concurrently, global safety statistics are improving [4]. The International Civil Aviation Organisation (ICAO) notes that the accident rate of commercial aviation has dramatically decreased from 4.8 per million departures in 2008 to 2.78 million in 2015 [5, 6].

Indonesian domestic civil aviation traffic is also growing rapidly. Scheduled commercial air traffic has grown from 377,632 departures (or 0.37 million departures) in 2008 to 729,448 departures (or 0.73 million departures) in 2015 [7, 8]. Concurrently, the Indonesian rate of accidents has declined from 13.92 per million departures in 2008 to 6.06 per million departures in 2015 [9].

While there is a declining accident rate in line with the global trend, the Indonesian accident rate is still considerably higher than the average global rate [10]. The Chief of the IATA Accident Classification Task Force (ACTF) also noted that Indonesia's accident rate has been and still is an area of concern [11, 12]. This was highlighted in the public eye in October 2018 and February 2019 by accidents which involved the same operator, Lion Air [13, 14]. The earlier accident resulted in 189 fatalities, while the later was a nonfatal overrun incident. The fatal accident occurred over the Java Sea during climb, while the other was at Pontianak airport during landing. Aircraft design failure was a major contributing factor for the fatal, while the overrun occurred in heavy rain [13, 14].

In contrast to most other States where safety records and contributing factors have been comprehensively analysed and discussed in the literature, the Indonesian record has not been evaluated in any substantive form. Previous studies that have discussed Indonesian Aviation safety performance were limited to specific aspects, ranging from the strategic to operational levels, such as financial-related issues, airport infrastructure policy, aircraft maintenance, and the level of pilots' adherence to standard operating procedures (SOPs) that contributed to the incidents [10, 15–17]. Earlier work describing safety in the least well developed countries [15], includes Indonesian airport operations [16], poor aviation maintenance [10], and safety being viewed from a regulatory perspective [17], as well as cultural factors that might contribute to the Indonesian accident rate [18]. The latter article suggested that cultural factors play an important role in aviation safety and should be incorporated into investigation reports; however, the study does not elaborate on the ways in which cultural factors might contribute to Indonesian aviation safety. In addition, none of these papers discuss factors that may contribute to the Indonesian rate of accidents such as weather, terrain, runway surface conditions, and unstable approaches. By contrast, more detailed studies have been undertaken on factors that contribute to incidents for other countries including India [19], Canada [20], the USA, Australia, New Zealand, and Norway [21]. Therefore, it is instructive to consult with incident/accident investigation reports which comprise considerable useful pieces of information that enable us to reconstruct and to learn from the incidents [22–24].

The uniqueness of Indonesia's terrain and weather is of interest since these factors may be associated with accidents. Indonesia is an archipelagic country situated along the equator and surrounded by oceans with high sea surface temperatures, which drive a tropical monsoon climate that creates precipitation of more than 4,000 mm per year in some places during the wet season which often lasts for more than 250 days per year [25]. Embedded in a monsoon climate, orographic weather which is often found in mountainous areas can also degrade visibility for pilots who are flying visually. Hays [26] stated that in mountainous areas, weather is highly unpredictable because of atmospheric processes by which heavily moisture laden air turns into cloud and rainfall, commonly occurring in valleys or saddle point gaps between mountains.

According to the National Transportation Safety Committee from 2010 to 2016, incidents/accidents were distributed across most major islands of Indonesia but were concentrated in Papua (25 accidents, 35 serious incidents) and Java (20 accidents and 35 serious incidents) followed by Sumatera (10 accidents and 18 serious incidents) [27] (KNKT (in Bahasa Komisi Nasional Keselamatan Transportasi) or NTSC (National Transport Safety Committee) uses definitions of accident and incident from the ICAO Annex 13 as stated in KNKT website). Java has many major airports located in flatter topography with jet services, while the Papua highlands have many poorly developed airstrips served by smaller turbo-propeller powered aircraft [27].

Indonesian civil aviation is dominated by domestic flight services rather than international services. Most of the domestic flights are served by Indonesian operators, operating as Full Service Carriers (FSC) or Low Cost Carriers (LCC). Since deregulation began in 2000, the number of air operators has grown. Indonesian commercial flights fall within ICAO Operational Classification Part 121 for scheduled flights and Part 135 for unscheduled flights. Both of these types of commercial flights serve major airports. General Aviation (GA) flights, governed by Part 91 for private or charter and Part 137 for aerial work are most common in remote and mountainous where airports are less well developed, navigational facilities are rare, and weather is often poor and rapidly changing. Despite the fact that the weather Visual Flight Rules (VFR) are the only possible option for many sectors in mountainous areas, Instrument Flight Rules (IFR) cannot be used without the required navigation aids, and GNSS (Global Navigation Satellite System) approaches have not been developed for many of the smaller regional airports.

Cloud, rain, and wind are important elements of weather-related incidents and are associated with the tropical monsoon climate. According to the Indonesian Meteorology Bureau (BMKG), average annual rainfall for Indonesia during wet seasons is over 3,000 mm and is a result of the large scale air circulation of the Indian and the Pacific Oceans [25]. The Indonesian wet season usually spans from October to April, while the dry season spans from May to August and is much influenced by the Australian desert climate. The complexity of mainland Asia and Australian continental weather, coupled with local topographical terrain, are contributors to irregular weather patterns. In addition, the large topographical variations across Indonesia, varying from lowland coastal areas to the highland interior, also make winds difficult to predict [26].

Due to the higher rate of incidents when compared to global figures and a lack of previous evaluation of safety records, this study aims to analyse the nature of commercial aviation safety occurrences in Indonesia, and their contributing factors.

2. Methods

In choosing the methodology for this study, the authors noted that there are no previous studies at all which have attempted to describe the nature of civil aviation accidents in Indonesia, or to ascertain which are the important factors which contribute to those accidents. The Indonesian government, as a signatory to ICAO, has established the air accident investigation bureau and placed this agency under the National Transportation Safety Committee (NTSC) which oversees the safety of all modes of transport. The air investigation bureau has a requirement to analyse all fatal and major accidents and to report in accordance with ICAO Annex 13. Investigating authorities will often be left with incomplete records and incomplete or inaccurate personal accounts and have to use their professional judgments to assess contributing factors.

Therefore, it was decided to firstly analyse all such reports in a given period in order to determine in a descriptive fashion what types of accidents occurred, and where. The second phase of this study concerns analysing which contributing factors are associated with these events. We have chosen to list all contributing factors but not attempted to identify those that are most important. While we understand that human factors are probably associated with some accidents, and that weather may play a role since Indonesia has a long and intensive wet season, we have simply chosen to list the contributing factors, noting that there may be several for each accident, and determine a list of those factors which are most common, whether contributing alone or in association with others. In this way the list of contributing factors has been determined by those listed in the reports themselves, not prejudged by the authors of this paper. We believe this an objective methodology and the analysis is at a level of interpretation equal to that of the reports which are the foundations of this analysis.

2.1. Data. The data used in this analysis were derived from NTSC incident/accident investigation reports, which present the accidents and serious incidents that occurred in Indonesian territory between 2007 and 2015. The reports are maintained by NTSC and available in the NTSC website (http://knkt.dephub.go.id/knkt/ntsc_aviation/aaic.htm). NTSC air investigators were sent to accident/incident sites to conduct investigations and summarize findings. The incident/accident investigation reports provide details on the nature of accidents and serious incidents and contributing factors. All publicly available incident/accident investigation reports maintained by NTSC from 2007 to 2015 were accessed for use in this study [14].

2.2. Research Procedures. The reports were downloaded between January and March 2016. Next, information from the reports was extracted on the basis of flight features: occurrence categories and contributing factors. In order to extract this information, the most salient sections of the investigation reports were inspected closely, these being the introduction, the conclusion, and safety recommendations. The lead author extracted information about these features of each incident, which was later verified by another author. The ICAO Aviation Occurrence Categories (AOC) [28] and the ACTF of IATA [29] were used to analyse the investigation reports. Definitions of these categories are provided below.

Flight features refer to flight registration (country of registration: Indonesian or foreign-registered); flight carriage (passenger or cargo); flight functions (commercial, private; training or agriculture); flight weight (measured in MTOW: large aircraft having MTOW >5,700 kg and small aircraft with MTOW <5,700 kg); and engine type (jets or turboprops).

Occurrence categories refer to the nature of either an accident or an incident.

These include the following:

(i) Controlled Flight into Terrain (CFIT): when an airworthy aircraft under complete control of flight crew is unintentionally flown into terrain, water, or obstacles.

(ii) Loss of Control In-flight (LOC-I): an extreme manifestation of a deviation from the intended flight path.

(iii) Runway Excursion (RE): a single aircraft that inappropriately exited from the runway: landing long/overrun and lateral Runway Excursion, including landing short.

(iv) Abnormal Runway Contact (ARC): any landing or take-off involving abnormal runway or landing surface contact, such as heavy landing and gear-up landing as well as tail strike.

(v) System/Component Failure or Malfunction (SCF): failure or malfunction of an aircraft system or component related to the power plant, or other systems.

(vi) Runway Incursion—Animal (RI-A): collision with, risk of collision, or evasive action taken by an aircraft to avoid an animal on a runway or on a helipad/helideck in use.

(vii) Runway Incursion—Vehicle, Aircraft, or Person (RI-VAP): any occurrence at an aerodrome involving the incorrect presence of an aircraft, vehicle, or person on the protected area of a surface designated for the landing and take-off of aircraft.

(viii) Cabin safety Events (CABIN): miscellaneous occurrences in the passenger cabin of transport category aircraft.

(ix) Fire/Smoke (Nonimpact) (F–NI): fire or smoke in or on the aircraft, in-flight, or on the ground, which is not the result of impact.

"Contributing factors" are defined as 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 [30]. In terms of the contributing factors to this analysis, it should be noted that official NTSC reports list contributing factors, but not in coded form. Therefore, the authors of this analysis needed to assign contributing factors based on the written listings provided by the NTSC. The coarse discrimination between factors as defined in this paper facilitated common agreement between the present authors. For example, any communication failures between pilots or pilots and ATC were defined solely as CRM issues. Similarly, any deviation at all from SOPs which were relevant to the accident was designated as deviation from SOPs without further discrimination. Even if there were several SOP deviations during the one flight, the contributing factors "SOP" were only listed once.

In Indonesia, aircraft incident investigations conducted by the NTSC have specific guidelines [31]. During the investigation process, the NTSC may form a number of investigator groups, one of which is an operations and aircraft performance group. This group deals with the information pertaining to the operation of the aircraft prior to and during the occurrence. The group focuses on the information flow to pilots from all sources and then uses that information to understand pilot decisions and actions. The group examines many aspects, including flight planning, flight profile, crew experience, air traffic services, and communications made among crew [31]. The group coordinates with other investigator groups, including a data recorder group which is responsible for providing relevant data obtained from Flight Data Recorder (FDR) and Cockpit Voice Recorder (CVR). The findings of the operation and aircraft performance group are then shared and verified by other parties involved on a consultation basis before the factual information is finalised. Other concerned parties include specialists, accredited representatives, and advisers participating in the investigation. The purpose of the consultation is to ensure that the gathered information is complete and accurate.

3. Results

Between 2007 and 2015, there were 128 accidents or serious incidents that were reported by the NTSC: 123 Indonesian-registered aircraft and five foreign-registered aircraft. The latter were excluded from analysis due to the objectives of the study. A further 26 General Aviation (GA) incidents were also excluded from our present analysis. This section presents the incident-based analysis of the 97 remaining reports which relate to commercial aviation occurrences, with a particular focus on the 84 with multiple contributing factors. Runway Excursion was the most frequent occurrence, and Crew Resource Management (CRM) was shown to be the most frequent contributing factor, followed by weather (WX) and Unstable Approaches (USAPP).

This section presents a descriptive analysis of the categories of the incidents/accidents. Figure 1 shows the distribution of incident/accident investigation reports across Commercial and GA and is divided into various subcategories of fixed wing and rotary wing aircraft, and large and small aircraft.

3.1. Flight Features. As shown in Figure 1, commercial flights were the most common ($n = 97$) of the total 123 incidents/accidents reported amongst the categories of aircraft. Of these 89 commercial flights, 80 were passenger flights, 12 were cargo, and three were a combination of passenger and cargo flights. Of the commercial flights, 48 were large jet-engine aircraft, while 41 were turboprop-driven aircraft, which were comprised of 18 large aircraft and 23 small aircraft. In addition, there were eight helicopters involved, comprising 7 passenger flights and one cargo.

3.2. Incident/Accident Categories. As shown in Figure 2, Runway Excursions were the most common category (44), featuring in 42 occurrences during the landing phase, comprising 11 overruns, 27 runway veer-offs, and four undershoots. There were only two excursions during take-off.

Figure 2 also shows that all overrun events involved jet-driven aircraft while more than two-thirds of the veer-offs involved turboprops. Undershoots involved the same number of jet-driven aircraft as turboprops, while the two take-off-related occurrences were turboprops. Although Runway Excursions were the most common occurrence, they contributed little to fatalities. Of the 44 excursions, only two were fatal and both happened during landings (one overrun and one undershoot/landing short), and together resulted in 45 fatalities.

Figure 2 shows that the 13 LOC-I and 12 CFIT events each comprised 11 fatal incidents (22 of the total 24 fatal incidents) accounting for 411 fatalities. Despite that, Figure 2 also depicts other events, leading to nonfatality. They are three particular nonfatal events: Abnormal Runway Contact, Runway Incursion (RI), and wrong-runway landings and all involve multiple contributing factors.

The remaining 84 of the 97 occurrences were caused by multiple contributing factors, including weather (WX), CRM, Runway Conditions (RW) and technical malfunction (TECH). These occurrences include the 24 flights on which fatalities were experienced. Flights with fatalities were most common on Papua Island, followed by Kalimantan, Sulawesi and Sumatera, Java, and then Nusa Tenggara. The 13 single-factor incidents comprise 11 with System Component Failures (SCF), one with a Cabin Safety Event and one Fire/Smoke (nonimpact) event. These are also excluded from the following discussion as they were only caused by a single (technical) factor as coded in the NTSC reports, leading to an unknown incident/accident category.

Table 1 highlights that incidents/accidents were most common in Papua, followed by Java and Sumatera, and then Kalimantan and Sulawesi with the remaining four large islands contributing with a further 10 occurrences. The Runway Excursion events were most common in Papua, followed by Java and Sumatera, and then Sulawesi and the remaining four islands had eight Runway Excursion events. The LOC-I and CFIT events were most common in Papua, followed by Kalimantan, and then Sulawesi and Sumatera. The ARC/RI/wrong-runway landings mostly occurred in Java, followed by Sumatera, and then Papua and the remaining four islands combined with four. In addition, Table 1 shows the distribution of aircraft categories across the islands. Papua involved more turboprops, followed by Kalimantan and Sulawesi while jet incidents/accidents were more common in Java and Sumatera.

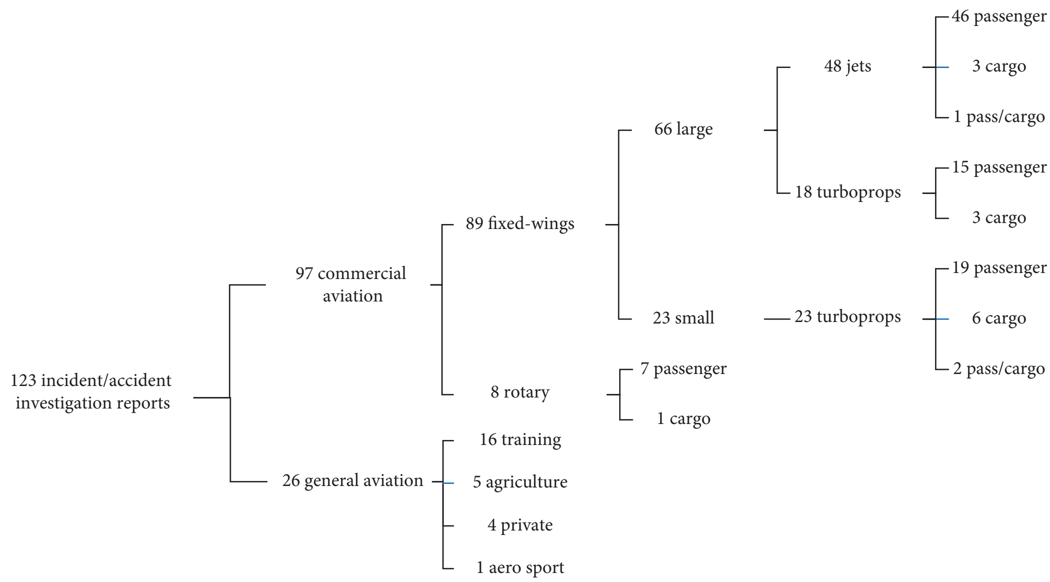

Figure 1: Categories of aircraft involved in the 123 incident/accident investigation reports from 2007 to 2015 (note that General Aviation occurrences were not further considered in the current analysis).

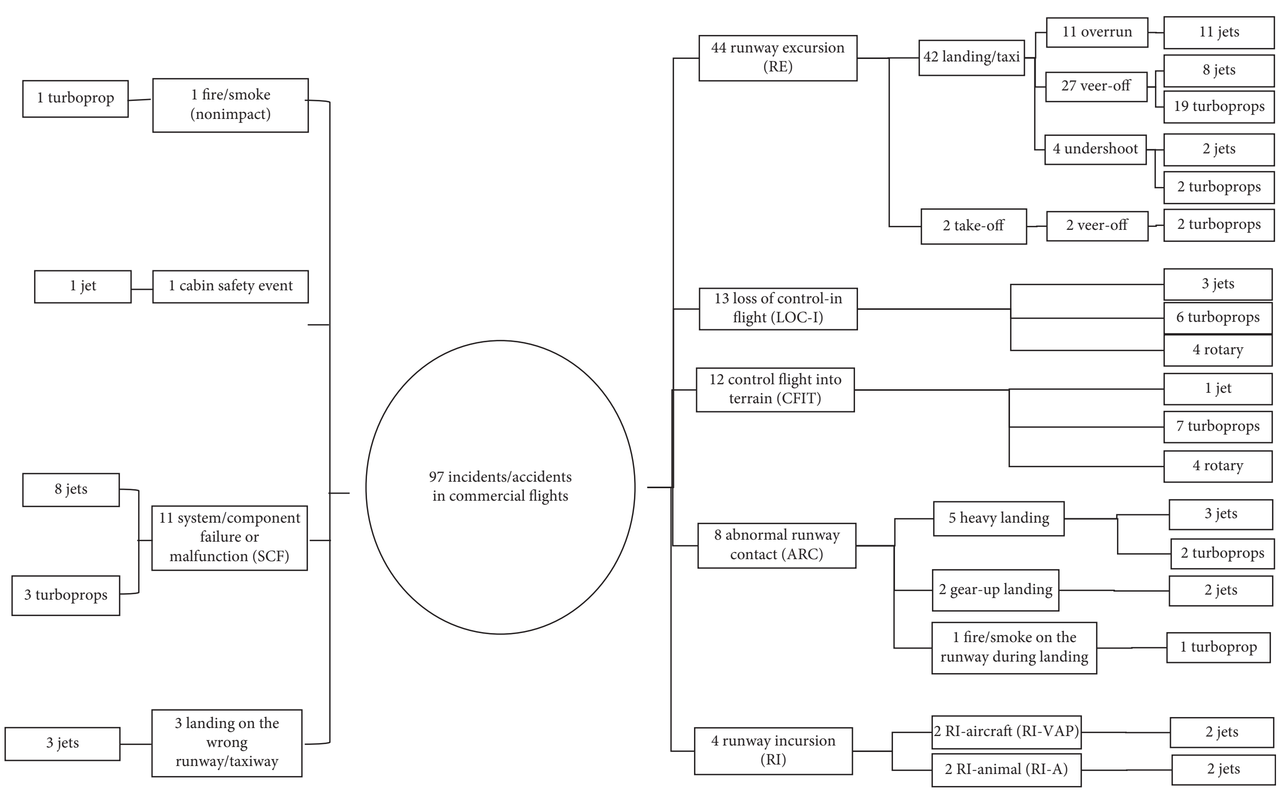

Figure 2: Incident/accident categories involving commercial flights in Indonesia occurring between 2007 and 2015.

3.3. Contributing Factors. This section describes factors nominated in the incident reports which, both alone and in combination, contributed to the incidents. Poor CRM (pilot leadership, teamwork, decision-making communication between pilots, or pilots and Air Traffic Control, etc.) was the most common factor contributing to incidents/accidents on commercial flights (74%), followed by weather (58%) and USAPP (Unstable Approaches) (45%), and then Runway Conditions (30%) and technical failures (19%). In terms of the 24 fatal occurrences, CRM contributed to the most (96%), followed by weather (63%) and technical (21%), and then Runway Conditions and USAPP (8%). Technical failures, while playing a role, are only mentioned in 16 reports, while CRM issues were by far the most prevalent, contributing to 62 incidents.

Table 1: Distribution of the 84 incidents/accidents in terms of geographical places of occurrence and aircraft categories.

Occurrence category	Place of occurrence																										
	Bali			Batam			Java			Kalimantan			Maluku			N. Tenggara			Papua			Sulawesi			Sumatera		
	Aircraft category (Jets = J; Turboprops = T; Rotary = R)																										
	J	T	R	J	T	R	J	T	R	J	T	R	J	T	R	J	T	R	J	T	R	J	T	R	J	T	R
RE	1						6			2	1			1		2	1		3	16		3	2		6		
CFIT											2	1							1	3	1		1	1		1	1
LOC-I			1				1				2	1						1		3		1	1			1	1
ARC/RI/wrong-RW landings				1			6			1				1			1		1	1					3		
Total (N)	1		1	1			13			3	5	2		2		2	2	1	5	23	1	4	4	1	9	2	2

Note. Data sourced from NTSC, 2016.

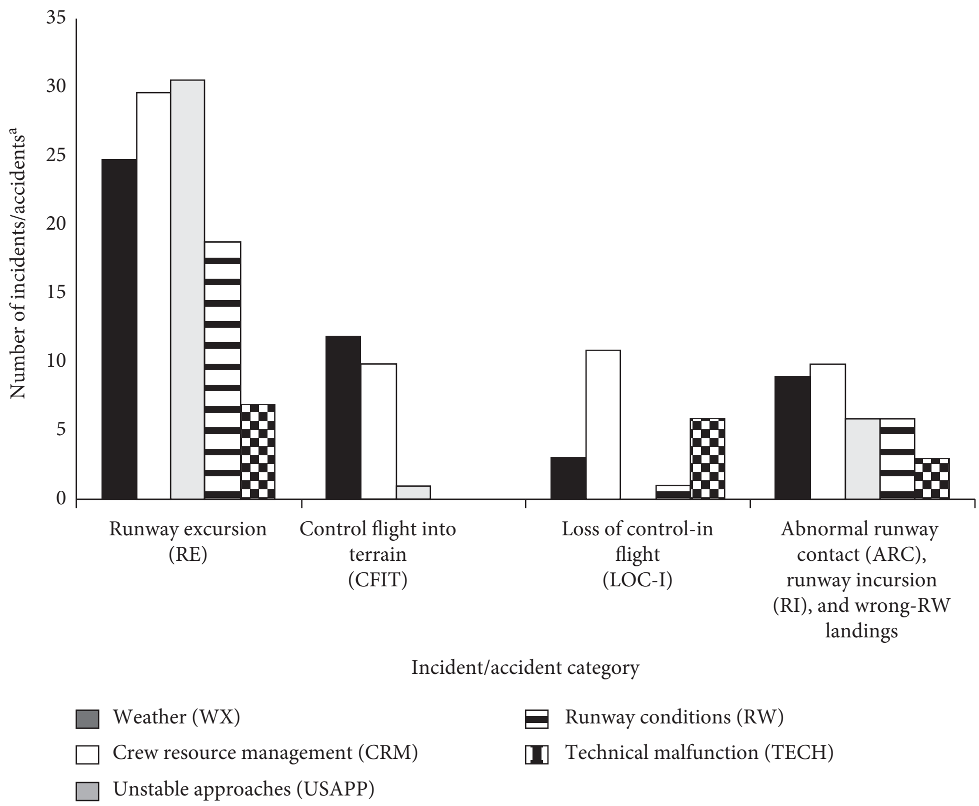

Figure 3: Distribution of contributing factors to the RE; LOC-I and CFIT and ARC, RI, and wrong-runway landings incidents/accidents on the 84 commercial flights. [a]Note that more than one contributing factor was possible for each occurrence.

Figure 3 demonstrates that CRM communication breakdowns and weather were factors which were present across all types of occurrences. More specifically, for the Runway Excursion occurrences technical malfunction was the least common factor while USAPP was important. In the CFIT events, weather was the most common factor, followed by CRM, with USAPP the least common. In the LOC-I, CRM issues were the most prevalent, followed by technical issues and weather. In the ARC, RI, and wrong-runway landings events, CRM breakdowns were most common, followed by weather, USAPP, and Runway Conditions while technical factors were least common.

The Runway Excursion and Abnormal Runway Contacts, RI, and wrong-runway landing occurrences mostly occurred during the wet season, which spans the period from October to March [32]. The Runway Excursion events mostly occurred in December while the Abnormal Runway Contacts, RI, and wrong-runway landing events occurred in November. By contrast, the LOC-I and CFIT occurrences mostly happened outside the rainy season, reaching their peak in the months of April and August. But we note that cloud and weather changes involving cloud are common through any season in the highlands.

3.4. Runway Excursions (RE). Runway Excursions, where aircraft ran off the end or the side of the runway or taxiway, were a major component of incidents/accidents, accounting for 44 of the 84 occurrences. To understand if there were common contributing factors across incidents, the five main contributing factors (WX, TECH, CRM, USAPP, RW) were examined. While this is a very broad classification, this approach permits a straightforward first-order analysis and understanding of the key features. Reports for each incident/accident were analysed to determine which factors played a role. From Figure 4, it is evident that technical malfunction, while playing a role, were only mentioned in seven reports, while unstable approach issues were by far the most prevalent. CRM issues, weather, and Runway Conditions also contributed highly to the Runway Excursion incidents/accidents.

In terms of multiple factors (Figure 5), the pair of CRM-USAPP had the highest prevalence. The triplet of weather-CRM-USAPP had the highest prevalence, while the four-factor combination of WX-CRM-USAPP-RW was the largest in that respective category. The combination of weather-CRM-USAPP issues in 19 Runway Excursion occurrences involved more jets than turboprops and, with the exception of two cargo accidents, all 19 were passenger aircraft. According to the NTSC reports, the contributing factors were mostly a lack of the compliance of the flight crew to the SOPs, inadequate training for pilots, the inability of air traffic controllers to relay current weather information, and a lack of current information on runway surface conditions.

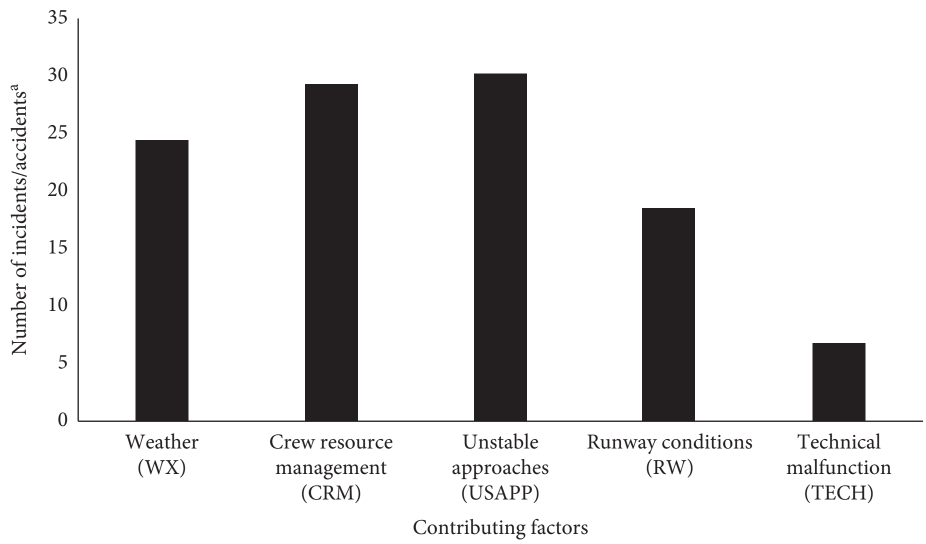

Figure 4: Distribution of contributing factors over the 44 Runway Excursion incidents/accidents. [a]Note that more than one contributing factor was possible for each occurrence.

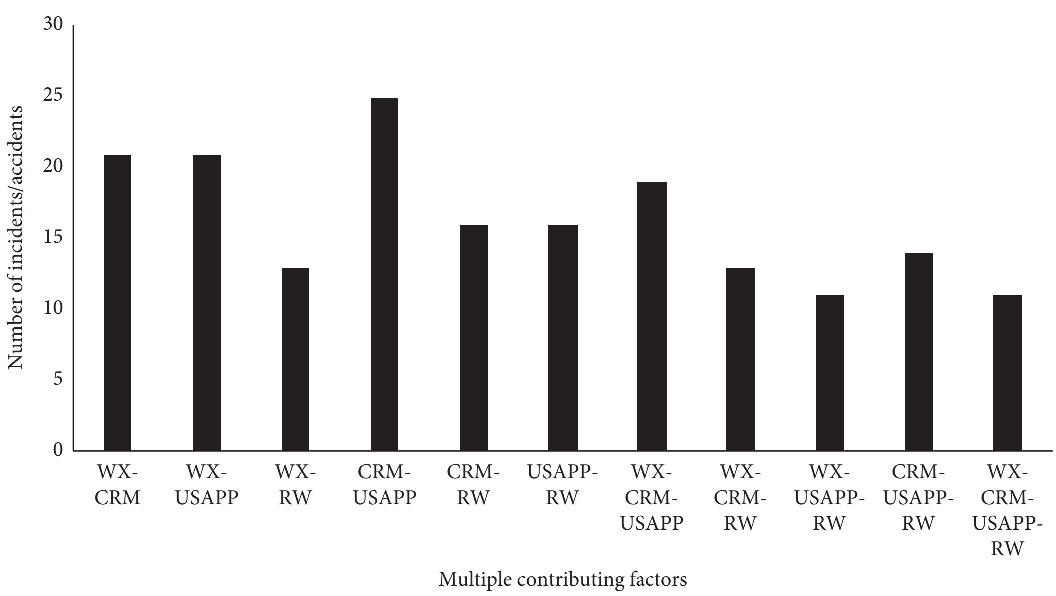

Figure 5: Distribution of multiple contributing factors over the 44 Runway Excursion incidents/accidents. *Note.* The following abbreviations are used: weather (WX); Crew Resource Management (CRM); Unstable Approaches (USAPP), and Runway Conditions (RW).

3.5. Incidents/Accidents in Mountainous Regions. Papua Island, which is characterised by mountainous regions, was significant as a location of 29 of 84 incidents/accidents and nine of 24-fatal accidents across Indonesia. By contrast, Java and Sumatera were the next highest as the location of 13 incidents/accidents each. Accordingly, factors contributing to the incidents in Papua were further examined.

Figure 6 shows that Papuan incidents/accidents involved a large number of Runway Excursions. These were usually nonfatal while CFIT events, which were less common, contributed with more fatalities. In addition, LOC-I, which occurred less often than the CFIT events, also contributed to fatal accidents. There were nine fatal incidents in Papua. This figure also shows that there was no incident involving wrong-runway landing in Papua island.

It is evident that technical malfunctions, while playing a role, are only mentioned in four incident/accident reports, while CRM issues were by far the most prevalent. Other factors of weather and Unstable Approaches were also significant. In terms of dual or multiple factors (Figure 7), the pair of WX-CRM played the largest role, followed by CRM-USAPP. The WX-CRM-USAPP combination played the largest triplet role, closely followed by the triplet of CRM-USAPP-RW.

For Runway Excursions, the triplet of WX-CRM-USAPP was the most common combined contributor. The

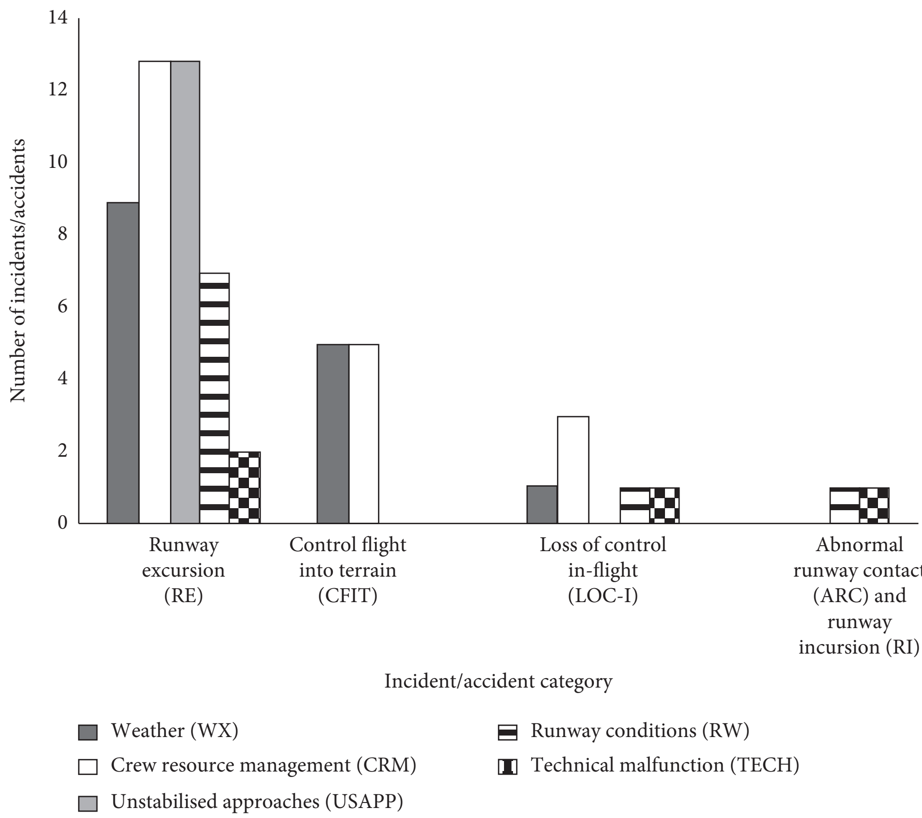

Figure 6: Distribution of contributing factors over the 29 incidents/accidents on Papua Island. *Note.* More than one contributing factor was possible for each occurrence.

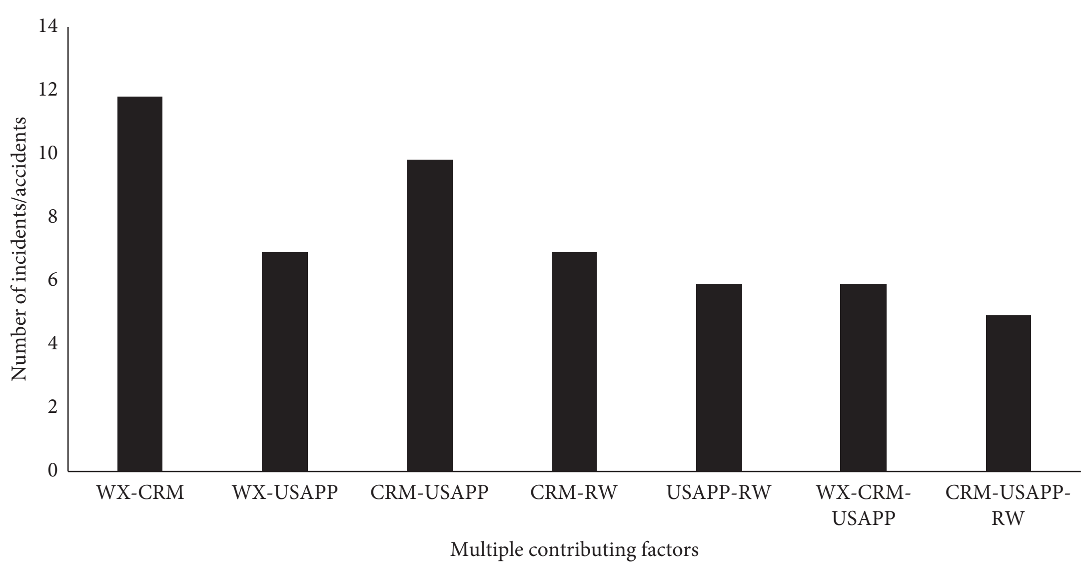

Figure 7: Distribution of multiple contributing factors over the 29 incidents/accidents on Papua Island. *Note.* The following abbreviations are used: weather (WX); Crew Resource Management (CRM); Unstable Approaches (USAPP), and Runway Conditions (RW).

occurrences in Papua, of the pair of WX and CRM, were more important, although the two combinations contributed equally at approximately 40%. In Papua, weather was shown to be an important factor in fatal accidents.

All fatal CFIT accidents were weather-related, and the wreckages were often found at an elevation of at least 8,000 feet which imply that the aircraft were quite possibly in cloud among higher mountains and not visual. Although the final height of aircraft position was not clarified in one investigation report, the report indicated that flight crew experienced a Loss of Visual Reference when flying into cloud prior to the incident. Two investigation reports indicated that a deliberate flight deviation from the company's prescribed visual routes was a factor in the incident [33, 34]. Anecdotally, deliberate flight deviations when flying VFR arise when pilots feel pressured to complete the flight, regardless of poor weather. These reports suggest that these actions were taken by pilots without sufficient prior assessment of the risk of colliding with terrain. For the LOC-I events the wreckage of aircraft was found near ridges of mountainous areas. In these occurrences the aircraft experienced a stall condition followed by improper corrective actions.

For nonfatal incidents, there were often other factors in play. These include the operator's safety management, meteorological facilities, and airstrip information [35]. In some cases it appears that management did not have route-familiarisation programs for newly recruited pilots or failed to oversight the training or familiarisation programs, leading to an incident/accident [34, 36]. Furthermore, putting crew in a pair for the first time as well as assigning crew who had not recently flown to airstrips that were considered as high-risk also contributed to incidents [37, 38]. In addition, having no access to meteorological information at some airstrips increases pilots' workload and leads to poor decisions when poor weather is encountered [39].

4. Discussion

In this study we have analysed the incident/accident investigation reports for aviation occurrences in Indonesia occurring between 2007 and 2015, providing for the first-time detailed analyses of occurrence event types and of contributing factors. Multiple factors contributed to these occurrences, with Crew Resource Management, weather, and Unstable Approach being the most important of these, followed by Runway Conditions and technical malfunction. Runway excursions were the most prevalent type of incident during this period, followed by Loss of Control In-Flight, Controlled Flight into Terrain, and the remaining three categories, Abnormal Runway Contact, Runway Incursion, and wrong-runway landings. The following discusses the major factors contributing to the incidents in Indonesia, discusses how these compare internationally, and highlights potential ways forward in improving Indonesian Aviation safety practice.

4.1. Crew Resource Management and Communication. CRM was the most prevalent contributor to aviation occurrences in Indonesia during the period studied. Theory of the development and improvement of CRM suggests that in training and in practice, CRM should consider cultural preferences of individuals involved [40, 41]. Consistent with such theory, a range of background issues may contribute to poor CRM in Indonesian aviation, including CRM training and issues of national and professional culture. There has been an increased focus recently on the training of pilots internationally, with multicrew training now compulsory for airline pilots in Australia and other countries including the USA and Canada [42–44]. This is also the case in Indonesia. However, poor communication between Indonesian crewmembers is evidenced by the large contribution of poor CRM to many nonfatal and fatal accidents [45]. (*Fatal accident*: accident where at least one passenger or crewmember is killed or later dies of their injuries, resulting from an operational accident. Events such as slips, trips and falls, food poisoning, or injuries resulting from turbulence or involving onboard equipment, which may involve fatalities, but where the aircraft sustains minor or no damage, are excluded.) The incident/accident investigation reports often recommended that crew training was insufficient in the area of CRM and that this needed to be addressed [46–49]. More recent studies of CRM indicated that this is an ongoing issue and even involves other crew outside the flight deck, such as cabin crew [50, 51], air traffic controllers (ATC) [52, 53], and flight dispatchers [54].

These factors are often exacerbated by hierarchical structures and poor communication among pilots. A number of the incident/accident investigation reports indicated that miscommunication between pilots and copilots was often a major cause [46, 47, 55, 56]. M. Mulder [57] defined power distance as the degree of inequality in power between a less powerful individual and a more powerful other, in the same social system. Some global fatal incidents around the world have been associated with power distance issues in the cockpit, for example, Asiana Airlines Flight 214 and KLM Flight 4805 [58, 59]. The accident investigation findings suggested the critical role of crew cultural factors as it could give an impact to pilot performance. The accident of KLM Flight 4805, also known as "Tenerife" showed the importance of the controller clearance for pilots on the deck, particularly in poor weather condition, and that the pilot flying must listen to crew comment. The role of broader cultural dimensions influencing communication and coordination on the flight deck has been confirmed by several researchers, including [60, 61]. Similarly, some Indonesian incident/accident investigation reports have found that the first officers did not call out, cross-check, question, or challenge Captains in many of the critical situations leading up to an incident, particularly where a newly recruited pilot was involved [46, 47, 55, 56]. The steep authority gradient was offered as an explanation by an investigator in an incident where the first officer, functioning as a pilot monitoring, did not take control of the aircraft when he deemed safety to have been compromised, but instead only offered verbal warnings [48]. In another incident, it was suggested that a Captain who failed to order a missed approach, or take over flying from the copilot, did so because of a heightened cockpit authority gradient due to the copilot being a Director General of Civil Aviation flight operations inspector [49].

Indonesians have been identified as having a relatively higher power distance index culturally, compared to those from other Asian countries and Australians [62, 63]. Indonesian culture, which is highly patriarchal and hierarchical, is an important factor to consider when considering the role CRM plays in incidents [64]. In the IATA safety report of 2015 [11], the Chairman of the Accident Classification Task Force questioned whether it is individual frontline actions or the attitude within the Indonesian culture that stretches far beyond the individual that contributes to the higher national accident rates. Alam [65] suggested that such a culture would require more vigorous intervention for successful cockpit learning than other low power distance cultures. The extent to which this type of behaviour impacts CRM in Indonesia and how to shape plans for improvement in this area warrants further investigation.

In addition to power distance, previous studies have suggested that the failure of CRM might be attributable to the cultural factors of the flight crew [40, 58, 66]. Research has been conducted to look at the impact of different cultures, namely, Eastern and Western cultures, on the performance of pilots in the cockpit [65, 67]. However, within the Indonesian archipelagic territory, there are over 1,300 tribes that are scattered amongst 17,508 islands, with the Javanese ethnic group being identified as a dominant amongst other groups [68]. Ananta and Arifin [69] noted that Javanese made up slightly over 40 per cent of Indonesians. As a consequence of the dominance of the Javanese, Irawanto and Ramsey [70] claimed that social structural societies include Indonesian public sector institutions run in "Javanese style." Javanese style, which is strongly characterised by social qualities, including "tepa selira" (known as a mutual respect), is a factor to the high Indonesian power distance score and consequently, it may impact the way Indonesians communicate with others. Being less assertive and less direct in communication are behaviours that characterise typical "Javanese style." This could become an important concern in relation to multicrew communication in the cockpit. It is possible that cultural issues such as power distance may interact with cultural differences based on more local, or subcultural factors, given the particular cultural diversity present in Indonesia.

4.2. Terrain and Weather. Along with issues around CRM and training, the uniqueness of Indonesia's terrain and weather also played a critical role in aviation incidents, with 58% of the incidents that we examined including the contributing factor of weather such as rain or wind. This may account for some of the variation when comparing the Indonesian data to global incident rates. R.K. Jenamani and A. Kumar [19] noted that weather only contributed to 8% of commercial incidents in the US. The ASC [71] found that this figure was 16.3% in Taiwan, while [72] noted a global average of between 21 and 26%. This variation in rate is even more pronounced when one considers that the lower contribution of weather in other locations occurs despite the fact that they include consideration of wider weather conditions in these figures, such as snow and ice.

There are a variety of reasons why weather plays a larger role in Indonesian aviation incidents. In scenarios where poor weather was encountered, visibility was often a determining factor for the severity of the incident; that is, the presence of clouds was identified as a major factor for fatal accidents in Papua, while for nonfatal incidents, rain and wind were more critical. At times pilots were flying off-track to avoid cloud and then entering cloud either inadvertently or deliberately [33, 34, 46, 73–75]. These events involved more aircraft flown under Visual Flight Rules (VFR) and fewer flights under Instrument Flight Rules (IFR). For the incidents involving VFR flights, investigation reports indicated that there were events where pilots may have experienced spatial disorientation because of lack of visual reference, leading to Controlled Flight into Terrain [33, 46, 75, 76]. Further, in IFR occurrences, the incident/accident investigation reports suggested that spatial disorientation due to pilots being unfamiliar with an airport environment was a contributing factor, despite onboard navigational instruments. It was suggested that this was due to both an absence of on-ground navigational support and a lack of a published instrument approach and landing procedure [77, 78]. However, even when both of these were available, incidents were still occurring due to a loss of situational awareness by the pilots when entering a rain cloud during the final approach below Minimum Descend Altitude (MDA) [79]. Therefore, having a shared team performance among multiple crew in the cockpit is critical, particularly during approach and landing where pilots decision has to be made upon crew's mutual situational awareness [66, 80]. The unserviceability of airports/airstrips and/or a lack of meteorological information may have contributed to incidents, particularly in Papua [33, 46, 75, 76] as well.

4.3. Major Airport Runway Excursions. A combination of both CRM issues and adverse weather conditions, as well as other factors such as technical failure, may be the reasons for the increased presence of unstable approach-related Runway Excursions in Indonesia. Most of the investigation reports examined aircraft Cockpit Voice Recorder (CVR) to analyse pilot's performance; however in some cases the CVR were unserviceable or overwritten. Some reports identified that prior to incidents/accidents a crew briefing was not performed in the cockpit, leading to the miscoordination of pilots that resulted in an undesired aircraft state, including an unstable approach. In addition, company pressures to land immediately after an unstable approach can often lead to Captains ignoring CRM philosophies and procedures by overriding or ignoring first officer comment or advice. There are many other ways in which it might, and since poor CRM is such a broad risk factor, we have discussed this only generally here. During the period studied, there were 97 commercial flight incidents, and 45% involved Runway Excursions, most of these being in Java. This is a much higher rate of Runway Excursion compared to other parts of the world where, on average, Unstable Approaches are a less important contributing factor for commercial operations than we have observed for Indonesia. For example, in Taiwan between 2007 and 2016, only 28% of incidents involve Runway Excursions, while internationally between 2008 and 2016 the figure is 34% [71, 81].

When there are issues with CRM, weather can become a significant factor in the occurrences involving an unstable approach in a jet aircraft in Indonesia. Degraded visibility as a resulted of winds, heavy rain, and cloudy conditions can create circumstances leading to an Unstable Approach. Unstable Approaches occur due to excessive speed, glide slope deviations, and localizer azimuth deviations of the runway and can result in floating landings with a touchdown beyond the normal touchdown zone. Flying Unstable Approaches, while not always lead to an excursion, are recognised as a significant risk factor for excursions. Based on the Flight Safety Foundation findings of 2006, Moriarty and Jarvis [82] suggested that landing in a stable approach is 60 times safer than that in unstable one. Therefore, discontinuing or performing a missed approach when an unstable approach occurs is essential, as recognised by company SOPs.

Runway surface conditions were identified as a factor common to the Indonesian Runway Excursion incidents. Landing on a wet runway is between 8 and 13 times riskier than landing on a dry runway [83]. Wet and contaminated runway surfaces might be a result of inadequate maintenance, standing water, or rubber deposits on the runway as well as the lack of runway friction information. Braking information provided in the Aircraft Flight Manual is dependent on Runway Conditions [84]. These wet and contaminated surfaces of runway decrease aircraft deceleration and reduced runway friction will extend runway landing distance. Information relating to the current Runway Conditions is essential, so that incoming and outgoing flights can understand the condition of the runway in use. Also, airport operators have a responsibility to conduct runway surface checks periodically as well as informing air operators of the relevant friction performance. Some incident/accident investigation reports indicate that this may not be happening in Indonesia at least some of the time [47, 85, 86].

Information on braking action across Indonesian airports is not provided by airport authorities [87]. Indonesia currently has 299 airports across its territory [88], 76 of which are classified as "major airports" where the runway dimensions exceed 1,800 m in length, and large jet aircraft (such as B 747/B, 777/B, 737, or A320) are able to operate. Of the remaining 223 airports, 102 have runway dimensions less than 800 meters [89]. These 102 airports are mostly less developed, particularly those located in remote areas such as Papua. Airstrips are more numerous than airports in these locations, and these airstrips tend to be operated with limited resources in terms of meteorological, navigational, or radio communication aids. A number of airstrips in Papua are considered to be poorly developed and most of them only serve visual flights because of a lack of suitable navigation aids [90]. In addition, only four Papuan airports have a Terminal Controlled Area (TMA), which provides air traffic control support within a limited local radius for flights. Radar is also rare so that flights must be performed visually [90], or by reference to air navigation aids which are also rare.

4.4. Incidents/Accidents in Papua. The result of a combination of CRM, training, and weather is highlighted in the increased rate of fatal incidents in Papua, where steep topography, unpredictable weather, and short narrow landing fields create the most difficult flying conditions in Indonesia. Papua accounted for 35% of the 84 commercial occurrences from 2007 to 2015 which have been considered here, with a higher rate of fatal incidents when compared to the other islands. All of these fatal accidents occurred when the aircraft were performing visual flights and most of them were turboprop aeroplanes. In many cases, there was no Flight Data Recorder or Cockpit Voice Recorder fitted to the smaller aircraft. The incident/accident investigation reports suggested that the fatal flights involved a "VFR into IMC" situation and these were also associated with a breakdown of CRM, which is magnified in these conditions. The investigation reports also indicated that the decisions to fly into IMC coupled with inadequate implementation of CRM were a consequence of inadequate training and the unfamiliarity of mountainous weather and geographical terrain. LOC-I and CFIT occurrences were not necessarily associated with monsoon weather, but probably to weather patterns unique to mountainous areas, where atmospheric processes promote the establishment of cloud and rainfall in Papua.

While operating the aircraft according to company procedures and the aircraft's flight manual is exceedingly important, the investigators suggested that most accidents occurred due to poor judgment in adverse weather circumstances and deviation from the SOPs issued by the operators. They also suggested that safety related issues of mountain flying require practical experience obtained under the guidance of a pilot who has flown specific routes many times before and can make sensible judgments about the likelihood of a successful visual approach.

Anecdotally, inadequate training and a lack of standardised captaincy qualifications have been identified as factors which contribute to the occurrences. Flying in mountainous areas and in uncontrolled airspace such as in Papua involves dealing with weather factors such as orographic cloud, rainfall, frequent changes in wind direction, and turbulence. These conditions require considerable judgment skills for pilots that can only be obtained with experience. Many of the incident/accident investigation reports indicate lack of flying experience, including a lack of familiarisation with air route or airport location, as contributing factors [34, 36, 77]. Mountain flying is a specific skill for pilots, but training in mountain flying is not taught in any depth at Indonesian flying schools. Pilots only develop these skills while working for airlines operating in the mountainous areas. Consequently, the development of mountain flying skills differs from one airline to another, and we could not locate any standardised syllabus issued by the Indonesian DGCA. In addition, captaincy qualification for mountain flying is varied among operators. In some incidents it was noted that some pilots had minimum flight hours on type [91, 92]. This might be an indication that there is no standard DGCA regulation for captaincy qualification, particularly in Papua. Based on incident/accident investigation report safety recommendations, one major airline flying in Papua has increased the minimum required flying hours from 1,000 to 1,500 hours for first-officer pilots to become Pilot In Command [77, 93]. It will be interesting to review whether this change in standards leads to a decreased rate of incidents in this area.

4.5. Strengths and Limitations. One of the strengths of the study is the requirement under national law that all aviation accidents and serious incidents are reported to the NTSC. Therefore, we can be confident that our study has covered all the occurrences of this nature in the time period in question. Furthermore, the incident/accident investigation reports (particularly the recommendation sections) have been discussed by all parties involved, including the regulatory body, airport authority, air navigation Indonesia, air operator, aircraft manufacturer, and designer, and, in some cases, experts from foreign safety boards and academics.

The study has a number of limitations. Not all incidents have been thoroughly investigated, as at the time of analysis, 18 were still listed as having a "preliminary status." This could be due to a variety of reasons, including a lack of reliable or available sources, such as the shortage of investigators. The current politics and prevailing regulation, based on budget allocation, regulate that the number of air investigators should not exceed 10 persons [94]. This is arguably insufficient to cover a whole Indonesian territory and a wide range of contributing factors. Secondly, not all incidents have been investigated by NTSC. Those not considered an accident nor a serious incident may be investigated internally by the air operator. During the period of incidents studied, there were a further 202 incidents that were internally investigated by the operators [95]. If these were able to be analysed, by being collated into a central database, they may shed further light on the factors discussed in this paper, as well as other potential contributing factors [23, 96]. The nature of the investigation reports themselves can represent limitations for any study of factors contributing to incidents as the reports considered human, technical, and environmental factors and fail to delve more deeply into the possible influence of societal or cultural factors [18]. Studies based on incident reports are limited by the nature of the information available, including structures and the methodologies used to construct patterns and variations in investigation and reporting procedures in different jurisdictions [96]. Nonetheless, the incident/accident investigation reports as used in this study constitute the best available data from which to derive patterns and trends in Indonesian aviation incidents. All in all, although learning from postincident reports is important for the quality of reports is varied from one to other States.

5. Conclusions

The methodology used here is basic, yet effective, and has identified for the first time that the types of accidents comprise mainly Runway Excursions by jet transport aircraft at major airports in flatland regions, and fatal accidents which occur in highland areas due to Controlled Flight into Terrain. The study is primarily data-driven, yet the reports show clear evidence that weather and poor crew communication provide uniquely difficult circumstances in terms of civil aviation safety. Further the results presented here will provide the basis for studies involving greater depths of analyses.

In terms of Runway Excursions there is some evidence that organisational influences play a role in that safety related cultures appear to be less well developed at management level. Lack of adherence to standard operating procedures (SOPs) and poor Crew Resource Management (CRM) is common and contributes to the continuation of instrument approaches which ideally should have been discontinued through being unstable. Unstable Approaches seem to be often occurring in poor weather, and their continuation results in the aircraft being too high, too fast, or nonaligned when visually over the runway threshold, and steering and braking on touchdown can be affected by poor runway condition. Fortunately, the high rainfall occurring on and around major coastal airports ensures that surrounding grounds are very wet and soft, and Runway Excursions are most often nonfatal.

In the highlands, mainly Papua, most flying is visual, and there are pressures to operate during the early part of the day when the weather is usually better. In addition, many highland communities have no road transport so there is pressure on organisations and pilots to satisfy the high demand for air services. Mountain flying requires pilots to be experienced in understanding the weather influences and topography of specific airports and approaches and most flying is visual. Yet there appears to be no specific mountain flying syllabus or guide available in basic training and pilots are taught mountain flying "on the job." In mountain regions, decisions to continue visual flight into cloud or rain, or to deviate from standard routes, often lead to Controlled Flight into Terrain, or loss of control.

In summary, this paper describes analyses of civil aviation safety occurrences in Indonesia, which have been officially investigated, and highlights significant safety related issues which are quite different from those which occur in other ICAO states. References [45, 97] identified that insufficient regulatory oversight and Safety Management System were factors that contributed the most to the global incidents/accidents during 2010–2018. Worldwide, poor visibility and terrain/obstacles contributed less to the Runway Excursion events, yet they are a major factor in Controlled Flight into Terrain incidents [97, 98]. However, in Indonesia the unique combination of high rainfall and mountainous terrain, along with Crew Resource Management, training and hierarchical issues, provide significant risks leading to higher incident rates compared to many other parts of the world. While weather cannot be changed, better CRM and better training can mitigate the risk posed to the aviation industry. To effect this change, a better understanding of cultural and hierarchical factors is required, to enable more vigorous intervention for successful cockpit learning and enhance training for some aspects of flight.

Data Availability

The incident/accident report data used to support the findings of this study are publicly available, at the online locations specified in the paper.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Change-Oriented Risk Management in Civil Aviation Operation: A Case Study in China Air Navigation Service Provider

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Change-oriented risk management is the key content of civil aviation safety management. Hazard identification is considered as one of the most difficult and flexible parts. To address the risk management due to changes introduced in existing systems, in this paper, a system change-oriented hazard identification (SCOHI) model is firstly proposed. The SCOHI model identifies hazards by integrating "5M" (mission-man-machine-management-medium), and hazard and operability (HAZOP) techniques specify changes in a system and the associated impacts on the surrounding environment. Compared with the traditional brainstorm process, the SCOHI model provides an explicit way for hazard identification in a dynamic environment. Then, taking an air navigation service provider (ANSP) in Northwest China as an example, a case study of system changes from nonradar control operations to radar control operations is analyzed. The effectiveness and applicability of the SCOHI model are tested with a risk assessment. The results from the preliminary evaluation show that the four key system change-oriented hazards are air traffic control (ATC) skills, staff capacity, control procedures, and airspace structure. In addition, the "Man" category accounts for around 55% of the total risk, ranking number 1, followed by "Management," "Medium," and "Machine" categories. Finally, a sound risk control strategy is provided to the ANSP to help in controlling the risk and maintaining an acceptable level of safety during system changes.

1. Introduction

Safety assessment and risk management play an important role in civil aviation safety. They continuously help identify and trace hazards and suggest mitigation against risks in order to maintain an acceptable level of safety and enable systems to function in a proper manner. Hazard identification aims to find adverse sources and unsafe conditions that may lead to the occurrence of undesired events. Hazard identification is considered one of the most difficult and flexible parts for safety analysis and hazard prevention [1].

In an air transportation system, there are a set of procedures, people, and equipment. Explorations regarding hazard identification have been undertaken by numerous researchers, scholars, aviation experts, airline managers, and policy makers. Depending on the hazard identification sources and the approach to hazard identification, three groups of methods for identifying hazards in civil aviation are defined in the International Civil Aviation Organization (ICAO) Doc. 9859 Safety Management Manual (SMM). (1) Reactive: A reactive method collects hazards by looking into incidents and accidents that have already occurred. (2) Proactive: A proactive way uses all possible means to address hazards before it brings out any adverse effect. These techniques may include safety survey, safety audit, or voluntary safety reporting system. (3) Predictive: Predictive refers to the applications of statistics with the purpose of predicting future potential hazards [2]. However, due to the fact that there are no two identical systems in the world, the one-size-fits-all hazard identification technique does not exist. As a result, various researchers and practitioners and aviation industries such as airport, airlines, and air navigation service providers (ANSPs) developed their unique methods and techniques for hazard identification. For example, in the field of ANSPs, the European Organization for the Safety of Air Navigation (Eurocontrol) released its regulatory document named risk assessment and mitigation in air traffic management (ATM) in early 2001, which mandated the safety assessment in the ATM industry. Eurocontrol also established a set of methodologies and tools called the safety assessment methodology (SAM) to guide the implementation of the ATM safety assessment in Europe [3]. In the U.S., the System Safety Handbook (SSH) was published by the Department of Defense (DoD) and the Federal Aviation Administration (FAA) [4].

As air transportation is a highly technology-driven industry, upgrading existing systems is frequently happening in operational centers. The changes to a system will definitely lead to changes of system risk. Thus, safety assessment in civil aviation should find out what could be the new risks caused by system changes and to what extend the system safety output could be affected. The conventional hazard identification techniques, such as failure mode and effect analysis (FMEA), fall short. First, current hazard identification techniques are designed to apply to an existing system, and the changing risk and impacts are generally not included in hazard identification procedures. Second, the aviation operation system is a large-scale, embedded, real-time, and safety-critical system, with a complex human-machine-environment interaction. System changes are recognized to be a difficult and costly problem and a major source of risk in terms of cost, schedule, and quality. A change analysis is generally conducted at the last stage of current safety assessment. A more proactive approach should be taken to the hazard identification and analysis of changes and the associated risk.

Therefore, the objective of this study is to propose an effective risk management method for hazard identification and risk control under system changing circumstances. Taking an ANSP center in Northwest China as a study case, the main tasks are to identify new risks associated with the operational changes of the existing system, subsystem, or system components, measure the associated risk, and finally provide an efficient guideline for risk control.

2. State of the Art

2.1. Civil Aviation Safety Management System. Nowadays, a great number of methods and techniques have been successfully developed for safety practitioners to enhance aviation safety in real world applications [5–8]. In particular, the PDCA cycle (plan-do-check-action), total quality management (TQM), quality management system (QMS), and safety management system (SMS) have archived great impacts on air safety improvement [9–11]. The ICAO has mandated the implementation of a SMS in airlines, airports, ANSPs, and aircraft manufactures [12]. A SMS includes necessary organization structure, accountability, policy, and procedures [13]. It not only employs the PDCA cycle and deals with safety issues in quality, environment, and finance sectors, but also incorporates safety under a general management framework [14]. In 2006, the ICAO developed a comprehensive framework named Doc. 9859 safety management manual for SMS. Then in 2013, the ICAO further upgraded the requirements of SMS by releasing a new Annex 19 Safety Management. Annex 19 discusses state safety program (SSP), SMS, and other safety management practices and establishes an aviation safety management framework for the ICAO's contracting states [2, 13]. In SMM and Annex 19, the ICAO outlines four fundamental pillars of SMS; they are safety policies and objectives, safety risk management, safety assurance, and safety promotion. Safety policies and objectives provide a framework and benchmark for the SMS achievement. Safety risk management plays an important role in identifying hazards, assessing related risks, and developing appropriate mitigation. Safety assurance monitors the compliance with standards and regulations in conjunction with the routine usage of gap analysis (GA). It also provides a confidence level for SMS operations and evaluates the effectiveness of SMS strategies. Safety promotion provides training and other necessary activities in order to increase safety awareness and generate positive safety culture within the organization [2, 13].

2.2. Safety Assessment Process. As shown in Figure 1, the general process of safety assessment includes hazard identification, risk analysis, risk control, and assessment documentation or report [1]. Theoretically, identified hazards are assessed in terms of severity (S) and likelihood/probability (P) of consequences, and they are prioritized in the order of risk-bearing potentials. Then, hazards are generally assessed by a group of experienced professionals through standardized techniques and analytical procedures. If the risk ($S \times P$) is considered acceptable, operation continues without any intervention. If it is not acceptable, a risk mitigation process will be engaged. During these processes, documents that record the whole process are generally produced as evidence to show that all risks have been identified and managed and will not bring any unexpected consequences [1, 4].

2.3. Conventional Hazard Identification. Even though there is a large body of research dealing with hazard identification and management [1, 15, 16], predictive studies are commonly used in the aviation industry; they are presented as follows:

(i) Functional hazard assessment (FHA). The FHA is a predictive technique that attempts to explore the effects of functional failures of parts of a system. Hazards are extracted through consequence analysis on certain functions lost or degraded. Eurocontrol uses the FHA as part of the safety assessment methodology (SAM). As a primary hazard identification tool, the FHA is usually used in the early stage of system design. It is directive and excessive information is not mandatory. Meanwhile, it has limitations, for instance, it may not go thoroughly throughout the system, and external conditions are not fully considered.

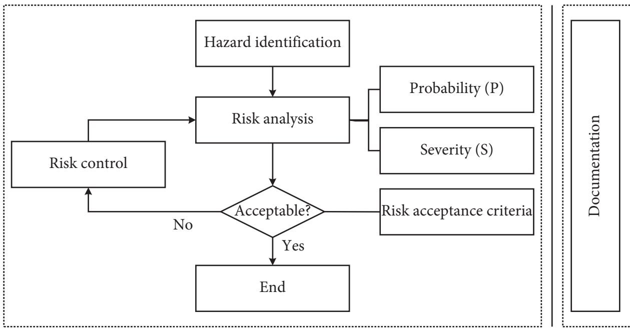


Figure 1: General process of safety assessment.

(ii) Hazard and operability (HAZOP). The HAZOP methodology is a process hazard analysis (PHA) technique used worldwide for studying not only the hazards of a system, but also its operability problems, by exploring the effects of any deviations from design conditions [17]. The technique takes different parts of a system into consideration, such as hardware, software, procedures, and human operators. An important feature of the technique is the application of a combination of parameters and guide words, which are used as the hazard index. The parameter pressure, for example, is generally combined with the guide words "more," "less," or "other than." The HAZOP is widely adopted in safety-critical industries; however, it is sometimes subject to participants' expertise and experience.

(iii) Failure mode and effect analysis (FMEA). The FMEA aims at analyzing potential failure modes of a system and evaluating possible negative effects related to systems, designs, and processes [18, 19]. The FMEA generally works out a worksheet, which includes descriptions of components, failure modes, failure rate, causal factors, effects, detection, and actions. The FMEA is one of the earliest structured reliability and risk analysis methods, and its advantages and disadvantages are also obvious. Decades of application provide helpful guidance to users. However, properly executing a FMEA generally means lots of paperwork and is time-consuming. In some instances, information missing or incorrect output may also exist due to an expert's "blind spots."

(iv) Fault tree analysis (FTA). The FTA uses a binary tree-structured notation based on Boolean logic to identify root causes of an undesired event and to calculate related probability. The purpose of the technique is to graphically present a tree representing possible normal and abnormal events that can result in a top-level undesired event. The FTA is commonly regarded as a classic quantitative technique in reliability and risk analysis. It provides a powerful tool to let people see the paths between causes and accidents; thus, it can find key points to accidents prevention. The FTA starts with a fault or a failure, not a process or parts of the system, so its result may not present a holistic view. On the other hand, when a system is huge and/or complex, the FTA will be difficult to finish without professional software.

Most of these hazard identification and analysis techniques originated from industry and work well in a hardware system. However, things become quite different when applying them in a complex system with a more human-machine-environment interaction. On the other hand, these techniques are generally designed to apply to an existing system or daily operation. As for the safety assessment caused by system changes, especially changes that happen in complex system such as aviation, these techniques normally fall short.

3. System Change-Oriented Hazard Identification

3.1. System Changes. In this paper, a conceptual framework for system change-oriented hazard identification (SCOHI) is developed that is intended to have the effect of facilitating the changes from the current 5M model to one in which the change is anticipated and managed in an informed way (see Figure 2). The framework illustrates the relationship between them in the influence of system changes.

The "5M" refers to mission, man, machine, management, and medium; those are the five core areas in which accident/incident causing factors may appear. The "5M" provides a clear frame for the description of the system and its working environment. Each element of the "5M" could be broken down into subelements or factors based on the specific system that needs to be assessed. As shown in Table 1, the relevant factors in the ANSP field are listed as an example. The "C" refers to changes. The changes are a difficult and costly element because of the uncertainties and risks associated with them. The Hazard and operability (HAZOP) methodology will be applied to support the system change analysis. First, a list of key features or elements is developed in the identification of the malfunction of a specific process. Second, a set of guide words, such as "more or less," "early or later," and "increased or decreased," are used to reflect the changes of system in different 5M areas. Table 2 provides a framework to identify any changes of a system in the civil aviation ANSP field.

3.2. Hazard Identification and Risk Assessment. Hazard identification is regarded as the key for safety assessment. Developing a rational change identification worksheet is extremely important for hazard identification when using the SCOHI. To assess the risk associated with a change, it is necessary to be able to assess both the probability of change and the impact of that change [20]. Therefore, the change analysis should consist of both the sensitivity analysis and impact analysis. The sensitivity analysis predicts which changes are highly sensitive to the system. The impact analysis predicts the consequences of change. The combination of sensitivity and impact provides a measure of risk consequence. Based on the general safety assessment procedure, the SCOHI model employs a three-step hazard

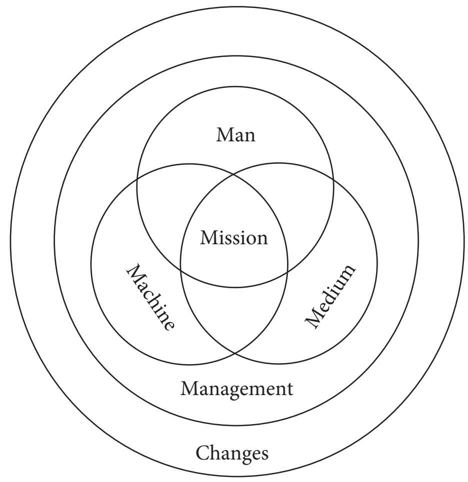


Figure 2: SCOHI-5M1C model.

Table 1: "5M" and its implications.

Elements	Factors
Mission	The type of task implemented, such as conflict detection and resolution, traffic planning, and coordination..
Man	Human elements inclusive of physiological, psychological, proficiency, skills, and qualifications.
Machine	The design, manufacture, operation, and maintenance of aircraft and related aviation equipment.
Management	A set of policies, procedures, and regulations involved in operating, maintaining, installing, and decommissioning a system.
Medium	The environment where the task is to be conducted inclusive of airspace, weather conditions, terrain, and navaids.

Table 2: System change analysis process.

Elements		Guide words
Mission	Task	Increased/decreased
	Function	More/less
Man	ATC ratings	Up/down
	ATC skill	Enhanced/abated
	Staff capacity	Increased/decreased
	Training	Increased/decreased
Machine	ATC automated system	Enhanced/nonenhanced
	Surveillance system	Enhanced/nonenhanced
	Communication system	Enhanced/ nonenhanced
Management	Control procedures	Change/unchanged
	SOS procedures	Change/unchanged
Medium	Airspace structure	Change/unchanged
	Meteorological condition	Change/unchanged

identification approach (see Figure 3). In the first step, a system and its environment should be clearly described so that the system, its subsystems, and components are well understood by the people working on the task of safety assessment. All factors within the working environment that may affect the operational result are required to be clearly identified and defined as well. The second step will work on the change identification worksheet, i.e., to identify changes that might happen pertaining to the system and its working environment. The third step will be based on the information provided by the sensitivity analysis and impact analysis of changes to define the consequence score of the risk.

After the application of the SCOHI model, the risk assessment could be conducted. Assuming that there are risk consequences $c \in N\{0, 1, 2, 3, 4, 5\}$ and the likelihood associated with this risk $p \in N\{0, 1, 2, 3, 4, 5\}$, then, the normalized risk score r of this hazard is

$$r = \frac{(c \times p)}{\mu}, \quad (1)$$

where μ is a measure of scale; here, we use the maximum value of $\mu = 25$. If $c = 0$and $p = 0$, it means there is no system-oriented change happening. Then for all r, three levels of risk R are designed for this hazard:

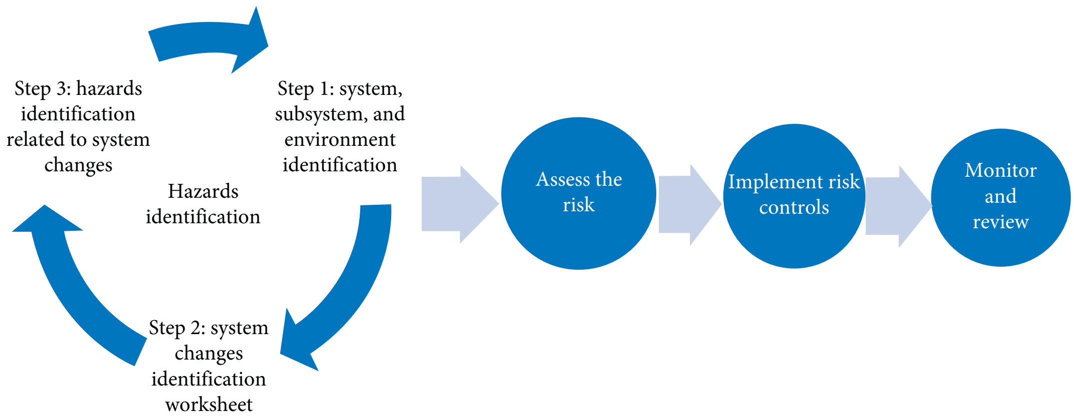


Figure 3: Three-step hazard identification approach in the SCOHI model.

$$R = \begin{cases} \text{Acceptable}, & \text{if } r < 0.2, \\ \text{Tolerant}, & \text{if } 0.2 \le r \le 0.4, \\ \text{Unacceptable}, & \text{if } r > 0.4. \end{cases} \quad (2)$$

4. Case Study

The case study is conducted on an air navigation service provider (ANSP) named "Z" in China. The ANSP is an organization that provides the air navigation service on managing the aircraft in flight or on the maneuvering area of an airport. Air traffic control (ATC) service is the most important service provided by an ANSP, which is to prevent collisions, organize, and expedite the flow of air traffic and provide information and other support for pilots. Controllers provide instructions, clearances, and flight information to guide the flights from one point to another point. The separation between aircraft depends on the communication, navigation, and surveillance technologies. The accuracy of aircraft position provided to controllers directly affects the minimum separation between aircraft; thus, the number of aircraft that could be handled by one controller. In our study case, "Z" manages one of the busiest airspaces in China. Along with the fast growth of daily flights, air traffic controllers' workloads have been complex and stressful. Therefore, operational optimization and effective means are expected to maintain or even smoothly expedite air traffic flow. Transition from a traditional procedural control (or nonradar control) to a radar control is considered as one of the important approaches that have been taken to accommodate the rapid growth of air traffic in the airspace. Thus, radar control implementation is identified as a vital change to the current system.

Some background knowledge needs to be understood before the application of the SCOHI method. The traditional nonradar control runs based on pilots' position reports and time-speed calculation from point to point and solves the conflicts between aircraft by applying complex separation standards. Under the nonradar control situation, controllers require pilots to continuously report their position when passing by specific navaids or waypoints and send instructions to pilots based on the reports. The fact is that due to invisibility of aircraft by line of sight, controllers have limited the holistic picture of the entire air traffic situation. For safety purposes, controllers have to separate aircraft with a little more-than-needed separation (or safety margin), which means less capacity in the airspace. On the other side, when radar control is applied, the position reports are no longer considered as a mandatory action performed by pilots. With the direct monitoring airplanes on the radar screen, controllers could vector aircraft effectively and manage more aircraft, which reduce largely the air to ground communication. Moreover, as radar provides a much more precise position to controllers, compared with pilot's oral position reports, the required minimum separation between aircraft is largely reduced. Consequently, the capacity in the airspace could be increased.

4.1. Application of SCOHI. First, a group of 12 participants were formed as a safety assessment working team. A relevant air traffic managerial department was notified to provide support for the working team. The working team consists of air traffic controllers and aviation experts (their expertise ranges from aeronautical telecommunication, navigation, and radar to ATC-integrated automation system). In addition, safety experts from universities and experienced air traffic controllers from other air traffic control centers are invited to work together. Second, a general safety assessment procedure was followed in the safety assessment for the transition of the air traffic control surveillance method in "Z" air traffic control center. Together with the application of the proposed SCOHI model, safety assessment requirement for ANSPs issued by the Civil Aviation Administration of China (CAAC) was applied in the assessment, particularly for the classification of the hazard severity, likelihood, and risk classification matrix. Third, within the "5M" framework, a safety assessment worksheet was developed to find changes at different levels of the system. Parts of the safety assessment worksheet and its outputs, the "Man" part, is showed in Table 3. Several sessions of brainstorming processes that involve controllers, technicians, and safety experts had been undertaken, and possible changes and derivative hazards

Table 3: Safety assessment of "MAN" category worksheet.

No.	Risks	Change	Details	Hazards	Risk level	Risk control
1	ATC rating	Y	Radar control license is required for the controllers that operate under radar control.	Person without a radar control license on control position.		
2	ATC skills	Y	Skills and experience of aircraft vectoring and deconflicting are required.	Flying out of or close to the boundary of the designated sector, or conflict caused by the controller's nonproficiency of radar control.		
3	Training	Y	Radar control training is required.	Lack of or inadequate training		
4	Staff capacity	Y	According to the China civil aviation regulation (CCAR), on-console time cannot exceed 2 hours and breaks between works cannot be less than 30 minutes for the radar control.	Being short of controllers when 2 sectors are open simultaneously.		

were addressed and analyzed through free and open discussions.

4.2. Results and Discussion. The safety assessment results were obtained after several meetings that were guided by safety experts, and documents were recorded afterwards. They are shown in Table 4 and Figures 4(a) and 4(b).

As shown in Table 4, four key hazards were identified with the risk level labelled as "Unacceptable," and they cover man, management, and environment categories. The four key system change-oriented hazards are ATC skills, staff capacity, control procedures, and airspace structure. One hazard was identified with a risk level labelled as "Tolerant," that is training. It is found that for risk titles with functionality and task, the risk score r is 0. It means that no changes are found in this area, so the risk level R is acceptable. In total, the risk assessment heat map with all the thirteen risk items is shown in Figure 4(a). It is easier to find out the relative position of different risk titles in terms of likelihood and consequence. In addition, different risk categories have different risk impact due to system changes. As shown in Figure 4(b), the "Man" category counts for around 55% of the total risk, ranking number 1, followed by "Management," "Medium," and "Machine" categories.

The most important 5 hazards associated with transformation from the nonradar control operation to the radar control operation and the risk control suggestions to mitigate those risks could be described as follows:

(i) ATC skills: controllers' previous working experience is not suitable for radar control operations; they need to improve their skills on radiotelephony communication, conflict detection, and resolution with the application of radar separation standard, situation awareness, and radar screen scanning. To control the risk, first, the associated simulation training must be accomplished before the implementation of radar control on-site. Second, several supervisor positions should be open at the beginning of the test phase of radar control operation. Third, training should be updated to target new problems emerging during the radar operation.

(ii) Staff capacity: in radar control operations, the traffic flow volume will be much higher than that in nonradar control operations. Due to a workload issue, the required number of controllers must be increased. However, there is a long cycle to train a controller in the field; thus, it is necessary to develop the workforce gradually in several years. The number of sectors in future radar-control airspace should be carefully considered due to staff capacity.

(iii) Control procedure: most of the control procedures will be modified to adapt to radar control operations, especially the transference of flights between two sectors, coordination between different control units, flow management procedure, minimum radar vectoring altitude, and flight procedures. To control the risk, simulation training and theoretical assessment are necessary.

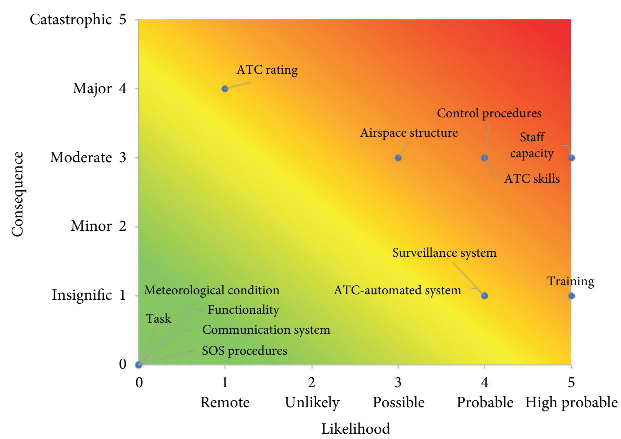
(iv) Airspace structure: under radar control airspace, sufficient maneuvering airspace is necessary to solve the conflict. Well designing the airspace structure, routes, and sectors makes a foundation for the future operation. A better airspace structure will increase the airspace capacity and safety. To mitigate the risk associated with airspace structure, a team that consists of controllers, airspace design experts, and different airspace users should be set up to discuss and find a suitable solution for the future airspace structure.

(v) Training: training is vital for the successful transformation of nonradar operations to radar operations. The training schedule and topics should be designed in consideration of controllers' workload. According to the CAAC aviation law, no less than 40 hours radar training is mandatory for each controller. The performance of each controller must be assessed at the end of training.

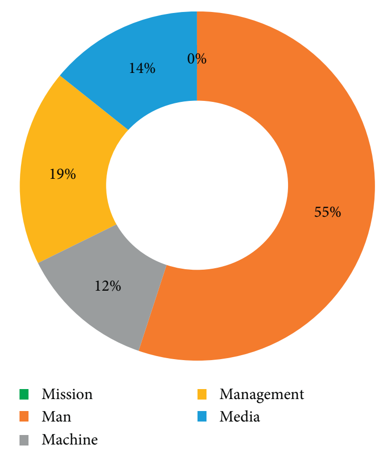
Following the CAAC aviation law, planning the training program is important to control the associated risk because the aforesaid risk control processes have different risk control impacts on the time scale. Based on experiences, it may take several years to mitigate those hazards from "Unacceptable" or "Tolerant" levels to an "Acceptable" level.

Table 4: Results of case study.

Risk	Risk title	Changes	Risk category	Consequence c	Likelihood p	Risk score r	Risk level R
1	Functionality	0	Mission	0	0	0	Acceptable
2	Task	0	Mission	0	0	0	Acceptable
3	ATC rating	1	Man	4	1	0.16	Acceptable
4	ATC skills	1	Man	3	4	0.48	Unacceptable
5	Training	1	Man	1	5	0.2	Tolerant
6	Staff capacity	1	Man	3	5	0.6	Unacceptable
7	ATC-automated system	1	Machine	1	4	0.16	Acceptable
8	Surveillance system	1	Machine	1	4	0.16	Acceptable
9	Communication system	0	Machine	0	0	0	Acceptable
10	Control procedures	1	Management	3	4	0.48	Unacceptable
11	SOS procedures	0	Management	0	0	0	Acceptable
12	Airspace structure	1	Medium	3	3	0.36	Unacceptable
13	Meteorological condition	0	Medium	0	0	0	Acceptable



(a)



(b)

Figure 4: Risk assessment results. (a) Risk assessment heat map. (b) Risk category by total risk rating.

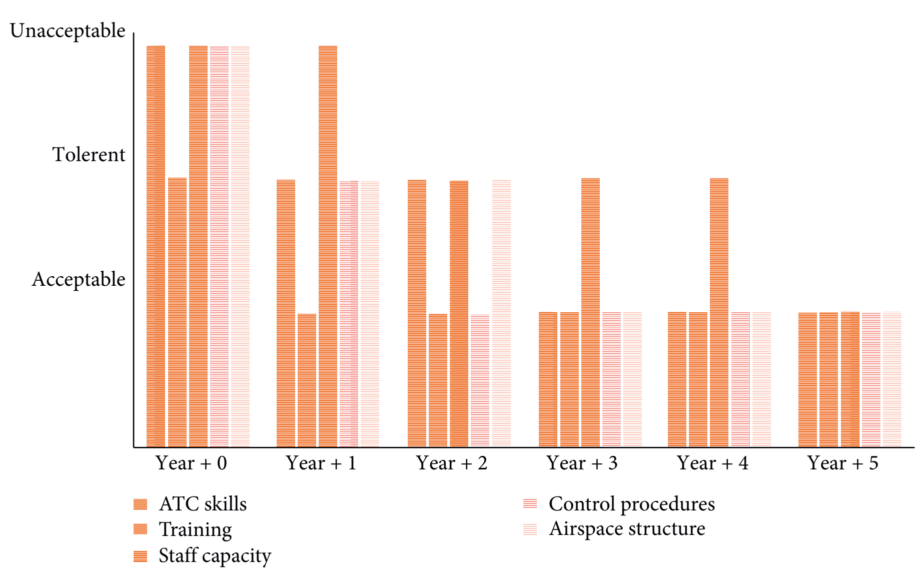


Figure 5: Risk control plan for next five years.

In the case study, the risk control plan for the next five years is illustrated in Figure 5. In this plan, we attempt to control the risk step by step. In one year, the four key hazards should be mitigated to a "Tolerant" level, then to an "Acceptable" level in the next two or three years. It should be emphasized that staff shortage problem is a mid to long term issue; so, it takes more time to finally decrease the risk of "Staff capacity" to an "Acceptable" level.

5. Conclusion

This paper mainly focused on hazard identification that is commonly regarded as one of the most important considerations in aviation risk management and safety assessment. In order to deal with the system-oriented changes and the associated risk, a hazard identification SCOHI model combining the "5M" model and HAZOP techniques was proposed. By applying the proposed methods on a real ANSP in China associated with professionals, it is found that the "Man" category should be paid extreme attention for risk control in comparison with the other four categories: machine, management, medium, and mission. Moreover, referring to the four key system change-oriented hazards, such as ATC skills, staff capacity, control procedures, and airspace structure, and one tolerant hazard, such as training, a risk analysis and a control plan were discussed. In the end, the SCOHI model was regarded as effective in an on-site safety assessment activity of an air traffic operation center in China. This study was one of the first of safety assessment probes in China's civil aviation industry, and it was regarded very useful to the upgrade of air traffic control operation in other regions.

Data Availability

The datasets generated and/or analyzed during the current study are not publicly available due to security issues but are available from the corresponding author upon reasonable request.

Disclosure

The views expressed in this paper are entirely those of Man Liang and do not necessarily reflect UniSA or Australian government policy.

Conflicts of Interest

Man Liang works for the University of South Australia (UniSA).

Authors' Contributions

Yiran Xie assists in some of the paper draft preparation.

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