Safety and reliability in aviation – a systematic scoping review of normal accident theory, high-reliability theory, and resilience engineering in aviation

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Safety and reliability in aviation – a systematic literature review of normal accident theory, high-reliability theory, and resilience engineering in aviation

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ABSTRACT

Aviation is a complex system with different interconnected and interdependent subsystems that rely on each other to ensure safety and reliability. The technological progress in the sector has increased safety, but incidents and accidents still happen. However, accident analyses and safety research have not paid equal attention to all aviation subsystems resulting in possibly undetected or underestimated risks. This study systematically investigates the literature on aviation safety from 1984 to 2021 with a particular focus on Normal Accident Theory (NAT), High-reliability Theory (HRT), and Resilience Engineering (RE) as their underpinning theoretical perspectives. The analysis of the 77 records that were screened as most relevant shows that the studies underpinned by these theories were mainly looking at the ‘primary operational aviation subsystems' such as air traffic control (ATC) and flight operations and significantly less at the 'secondary operational subsystems' such as ground operations and aircraft maintenance. In addition, the analysis showed that research building on RE has increased in recent years and is now the predominant theoretical framework in studies of this type. Nevertheless, NAT and HRT are still relevant and are often employed in conjunction with RE. Future research should pay more attention to the role of secondary subsystems and their impact on the safety, reliability, and efficiency of the aviation system. Moreover, there is perhaps a need for researchers to develop a more integrative framework that includes valuable components of all three theories and to create a set of safety and reliability strategies suitable for both primary and secondary aviation subsystems, hence, benefiting the entire aviation system.

KEYWORDS

Aviation
High Reliability Organisations
Normal Accident Theory
Resilience Engineering
Systematic Scoping Review
System Reliability

1. Introduction

Commercial aviation is a complex socio-technical system consisting of several diverse interconnected subsystems that operate passenger and cargo flights. A safe and reliable flight operation requires the coordination and effective interaction of several subsystems, and their human and technical components. These subsystems are flight operations with the crew flying the aircraft, ground operations with the ground crew loading, unloading, and servicing the aircraft, Air Traffic Control (ATC) managing the airspace at different levels, or aircraft maintenance crews conducting the scheduled and unscheduled maintenance, repair and overhaul for the aircraft (Rodrigues, 2021). Therefore, risks and undesired events must be foreseen, properly managed and effectively recovered if they occur. However, not all risks and undesired events can be foreseen in complex systems such as aviation, thus they need to be anticipated through sensemaking and imagination (Adamski & Westrum, 2003; Westrum, 2006). An unsafe operation in one subsystem can lead to accidents, incidents, or occurrences, but at least to risks at different levels, because the different subsystems and their operation are largely sequential and rely on the processes' efficiency and safety (Das and Dey, 2016; O'Neil and Kriz, 2013; NTSB, 2015).

Changes in the operating environment such as the digitisation of air freight documentation or, the automation of in the cockpit or of handling processes can increase safety, but also the complexity of the aviation system and the need for an enhanced approach to safety management (Valdés et. al., 2018; Becz et. al., 2010; Ripley & Larkin, 2005). A fast-paced technological change in the aviation industry might not always concern the aircraft itself, but several aviation subsystems that may have to deploy new software and equipment and may change the current way of looking at accidents and incidents or even change the nature of these. New hazards emerge, old ones evolve, while others disappear, but all must be identified and addressed by individual aviation subsystems and the system as a whole. It is, therefore, imperative that research in the field of aviation safety is conducted taking into consideration a broad spectrum of subsystems that will include the operational subsystems, such as flight operations, air traffic control, ground operations, and aircraft maintenance. Flight operations and air traffic control are the two operational subsystems directly controlling the execution of the flight, thus considered the primary subsystems, while ground operations and aircraft maintenance influence flight safety indirectly, as processes take place before and after the flight, and are therefore defined as the secondary subsystems. Hence, secondary subsystems may produce latent flaws or 'resident pathogens' (Reason, 2000) rather than active failures. Thus, for primary subsystems it may be said once the flight is over, the associated risk is over, while for secondary subsystems once the maintenance or turnaround is over, some associated risks are beginning. In the context of this study, we simplify the air transport system and have a specific look at the four operational subsystems. Nevertheless, the air transport system is more complex and can be clustered in even more subsystems, containing of activities such as flight planning, airspace design, and training.

Even though technological progress in aviation has increased flight safety, accidents still happen and, although some are directly attributed to the aircraft, a significant number of them are attributed to human error somewhere within the system. Three major theoretical perspectives approach accidents in complex socio-technical systems and are critically discussed by researchers through their theoretical lenses and/or on practical cases over various industries: Normal Accident Theory (NAT) (Perrow, 1984; Shrivastava *et al.*, 2009; Tamuz & Harrison, 2006), High-reliability theory (HRT) (O'Neil and Kriz, 2013; Sutcliffe, 2011; Roberts & Rousseau, 1989), and Resilience Engineering (RE) (Patriarca *et al.*, 2018; Hickford *et al.*, 2018; Hollnagel, 2014; Stroeve and Everdij, 2017). Research on aviation system safety and system accidents makes no exception to this tradition (Brown, 1995; Batteau, 2001; Cooke and Rohleder, 2006; Lofquist, 2010; Rijpma, 1999; Gross, 2014).

However, from reviewing the relevant literature, it appears that there exists a skewed focus on the primary subsystems as most studies applying the theoretical frameworks focus on flight operations and air traffic control (Jakšić and Janić, 2020; Karanikas and Nederend, 2018; Fraher, 2015). This is to an extent understandable but also leaves out a significant gap in the safety literature related with the secondary subsystems. Even though ground operations and aircraft maintenance failures may not often be the direct causes of an accident, there is still a need to understand how these can cumulatively or indirectly create one, on the ground or in the air. Thus, this study focuses on gaps in safety research, methods and tools applied in or adapted to secondary subsystems, but not analysing the work done of safety investigators and their consideration of the different subsystems in the accident analysis at this stage. The need to gain more understanding of secondary subsystems triggered the systematic scoping review presented in this study aiming at (a) identifying the most prominent theoretical approaches applied in aviation, (b) assess the aviation operational subsystems in which those theories are applied, and finally (c) to propose a research agenda to address the gaps identified during the assessment.

2. Theoretical perspectives for achieving system reliability

2.1. Normal Accident Theory (NAT)

A system accident also referred to as a 'normal' accident, is called normal because it is considered "inevitable in extremely complex systems", such as nuclear power, petrochemical plants, or aviation (Perrow, 1984). System accidents involve the unanticipated interaction of multiple failures" and "no matter how hard one may try, the unanticipated interaction of errors will defeat the safety systems" (Perrow, 1999, p.1). To make an accident a system accident or normal accident, the high-complex and high-risk systems for instance aviation must not only be complex but their characteristics, as identified by Perrow (1984), also include being tightly coupled and having a catastrophic potential. Normal accident theory provides this often classified as 'pessimistic view' on inevitable accidents (Le Coze, 2015): In complex and tightly coupled systems, sooner or later, errors occur and have the potential to lead to a catastrophic outcome. Even though normal accidents rarely occur, they have severe consequences for the whole system and system components, such as people, equipment, and information. In general, an accident in the context of NAT is defined as "a failure in a subsystem, or the system as a whole, that damages more than one unit and in doing so disrupts the ongoing or future output of the system" (Perrow, 1984, p.66).

2.2. High-reliability Theory (HRT)

The theory on high-reliability organisations (HROs) was developed in the late 1980s and has a different angle on the high-risk system (Roberts and Rousseau, 1989). HROs are defined as "those organisations that function in hazardous, fast-paced, and highly complex technological systems essentially error-free for long periods of time" (Baker, Day and Salas, 2006, p.1586). Common HRO examples are aircraft carriers, air traffic control and nuclear power plants. The HRT focuses on those organisational characteristics that enable operation in high-risk environments whilst experiencing a zero number of accidents and incidents. Roberts and Rousseau (1989) identified eight characteristics of HROs: (1) hyper-complexity, (2) tight coupling, (3) extreme hierarchical differentiation; (4) large number of decision-makers; (5) degrees of accountability that does not exist in most organisations; (6) high frequency of immediate feedback about decisions; (7) compressed time factors; and (8) more than one critical outcome that must happen simultaneously. These have been confirmed as distinguishing HRO characteristics in several subsequent studies (Baker, Day and Salas, 2006; Le Coze, 2019).

2.3. Resilience Engineering (RE)

A system is defined as resilient "if it can adjust its functioning prior to, during, or following events (changes, disturbances, and opportunities), and thereby sustain required operations under both expected and unexpected conditions" (Hollnagel, 2016). Resilient socio-technical systems show different characteristics (Uday & Marais, 2015; Fujita, 2006; Jackson & Ferris, 2017). Some of these properties include robustness, redundancy, resourcefulness, response and recovery, as used by the World Economic Forum to assess global risks (WEF, 2013), or discussed by Woods (2015). Resilience engineering is a safety paradigm that "uses the insights from research on failures in complex systems, including organisational contributors to risk, and the factors that affect human performance to provide systems engineering tools to manage risks proactively" (Woods, 2003; Gravio and Patriarca, 2016). It focuses mainly on total system functionalities and hazard/risk assessment rather than on technical engineering.

2.4. Similarities, Differences, and Complementarities between NAT, HRT and RE

The commercial aviation system is a high-risk system being complex caused by many characteristics, such as the number and nature of aircraft operations, the number and nature of systems and components involved, and the tight coupling of the sub-systems (e.g. ATC and flight ops). All or at least a high number of those components interact, and sub-systems are dependent on each other to enable one flight to operate. In all these areas, errors and failures may occur and potentially can lead to a catastrophic outcome.

Normal accident theory (NAT) and High-reliability theory (HRT) look at these areas and thus on safety from different angles in systems and organisations working in high-risk environments. NAT maintains that in complex and tightly coupled systems some accidents cannot be anticipated and are inevitable. This rather 'pessimistic' view has a sociotechnical focus and does not look at control or management strategies to avoid these normal accidents – as these are considered inevitable. This inevitability in NAT is explained to be originated in the tightly-coupling and interactive complexity of the system, that can neither be most effectively controlled centralised nor decentralised. (Le Coze, 2015; Haavik et al., 2019)

In contrast, HRT seeks to enhance the organisations' ability to function essentially error-free in high-risk environments (Sutcliffe, 2011; Baker, Day and Salas, 2006). Dependent on the situation, HROs can provide centralised and decentralised control, which is enables controllability by adaptability to achieve essentially error-free performance despite the tight-coupling and interactive complexity (Haavik et al., 2019). HRT, therefore, searches for continuous improvement in their operation and management to prevent or quickly recover from errors or failures. Hence, they are often described as reliability-seeking rather than reliability-achieving organisations (Sutcliffe, 2011).

This continuous effort on system safety and reliability can also be found in the concept for resilience engineering (RE). Resilience engineering is a paradigm and tool provider for safe system functioning and management (Patriarca et al., 2018; Woods, 2015). It is defined as being "about the characteristics of resilient performance per se, how we can recognise it, how we can assess (or measure) it, how we can improve it" (Hollnagel, 2019). RE is mentioned as a starting point for understanding how an organisation or system functions, responds, monitors, learns and anticipates (Hollnagel, 2016). While HRT provides the organisational perspective, NAT and RE have a more systemic perspective.

In general, HRT and RE focus on social conditions and potential organisational strategies and abilities to address the organisations' or systems' complexity. Thus, they are considered as less pessimistic with a greater focus on how to maintain and advance a systems or organisations strategies and abilities to address complexity and tight-coupling while working in high-risk environments. This positive view in HRT and RE also looks at what goes or went right under dynamic conditions (associated with Safety II), rather than only at what went wrong as compared to NAT (associated with Safety I). (Hollnagel, 2014-2; Haavik et al., 2019)

Even though, the similarities between HRT and RE seem obvious, differences must also be acknowledged to unveil the full potential of considering and exploiting both theoretical frameworks for understanding safety. HRT and RE are not considered as the same nor contrary, but rather complementing each other, with both having added value for the safety and accident theory. RE can complement HRT and anticipate situations that may have been previously defined as normal accidents by providing an increased system and subsystem understanding, including interrelations, lessons learned and informed monitoring. HRT is looking at errors and how they can be avoided by adjusting themselves under varying dynamic conditions, while RE does not focus on error but rather on studying normal operations - how work is done and why things go right. HRT and RE have the added value by providing the diversity of looking at complex high-risk organisations and systems, with researchers studying safety and accident phenomena looking through different lenses, coming from different backgrounds and having different research specialisations. HRT, with roughly 30-35 years of research history, has its roots in social sciences, while RE, with roughly 15-20 years of research history, has its roots more in the domains of system engineering, human factors, and the human-machine interface. Thus, the discussion of safety, error, and accidents can benefit from both theories. (Le Coze, 2019; Haavik et al., 2019)

In this study, we focus on the attention that is given to aviation subsystems by the three theoretical perspectives. The recommendations do not focus on enhancing a specific theory, but rather studying the different aviation subsystems more adequately and potentially more equally through the different theoretical lenses to enhance subsystem and, system and organisational understanding.

3. METHODOLOGY

Aviation organisations, such as airlines, airports, ground service providers, air traffic control, and aircraft maintenance organisations are tightly coupled, building a highly complex system with different sub-systems. The guiding thesis in this review is that not all operational subsystems with a high influence on aviation system safety are considered in the academic landscape of NAT, HRT, and RE. Therefore, this systematic scoping review pays specific attention to the area and approach of theory application in aviation subsystems.

The difference between this systematic scoping review (SSR) approach and a systematic literature review (SLR) lies in the scope and nature of guiding research questions and if a thorough quality assessment is executed (Munn et al., 2018). SSRs aim to “map the key concepts underpinning a research area and the main sources and types of evidence available” (Arksey & O’Malley, 2005, p.21), thus they typically address broader questions, potentially using a number of methodologies, and do not undertake a quality assessment of the literature. In contrast to the SSR, the SLR has focused research questions, which should be answered using a relatively narrow range of quality-assessed studies (Arksey & O’Malley,2005).

Scoping reviews can be executed using systematic and non-systematic approaches (Davis et al., 2009). In this review we employed a systematic scoping review approach which is oriented on the systematic collection of data, similar to systematic literature reviews, such as the Systematic Literature Review Process, adapted from Pickering & Bryne, 2014. This approach, including the thick description of this systematic steps, allows for consistency and replicability (McKinstry et al., 2014).

This systematic scoping review (SSR) aims to evaluate the application of three different approaches to discuss safety and in particular accidents in aviation, namely NAT, HRO, and RE.

This review aimed to answer the following questions:

- Which theoretical approaches are more prominent within the aviation safety literature?
- Which aviation subsystems have received most attention when applying these theories?
- Which research methodologies and methodological approaches are primarily used to apply NAT/HRT/RE in aviation?
- What are the key findings of these studies and what are potential areas needing further research?

This review was conducted by systematically collecting and evaluating the literature in scope to combine the results in a structured quantitative summary which was then analysed qualitatively in themes (Green, Johnson and Adams, 2006; Pickering and Byrne, 2014). This method was employed as an initial step to compare the application of NAT, HRT and RE theoretical frameworks in aviation safety research, enabling the inclusion of a large number of studies with different research designs and settings.

The systematic scoping review process has major differences in the literature search, extraction, and synthesis (Figure 1) compared to a classic narrative literature review (Green, Johnson and Adams, 2006; Pickering and Byrne, 2014). The main advantage is that the literature collection process is sufficiently detailed and structured to be repeatable and it quantifies the existing research. However, a quantitative approach cannot be used if there are too few or too many papers on a topic. Even though different advantages and disadvantages are identified, the comprehensive, structured, and detailed process description is deemed to overcome potential biases and provides a transparent review process (Pickering and Byrne, 2014).

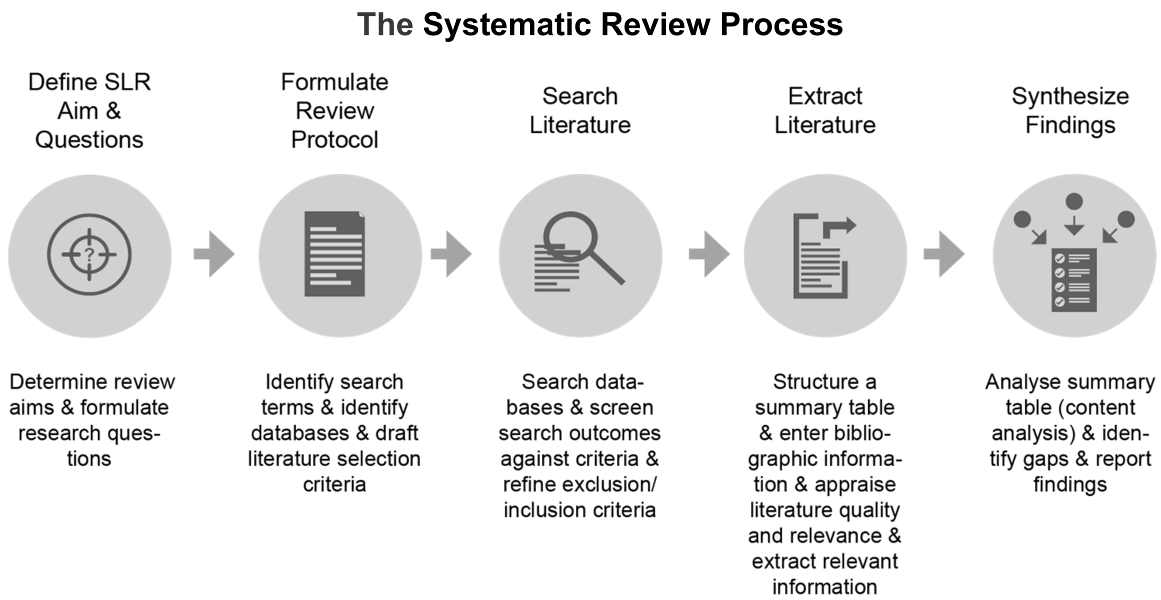

Figure 1: Systematic Review Process - adapted from Pickering & Bryne, 2014

The first step of this systematic scoping review (SSR) was to define the topic and its scope. This paper set out to review how NAT, HRT, and RE underpin research in aviation system safety and reliability taking a subsystems' perspective. It aimed to specifically map out which subsystems have received the most attention from researchers to identify if some of them need to be further explored in terms of their impact on safety and efficiency.

The significance of this review was fourfold: First, it would provide evidence as to whether aviation safety researchers' attention in the primary aviation subsystems is equal to the one given to secondary subsystems, and if the latter are seen as also playing a central role for a safe, efficient, and reliable system operation. Second, it would show whether NAT and HRT are still considered relevant in aviation research or if RE is taking over. Third, it would offer a thematic analysis of the extant literature that may unveil gaps in aviation safety research; and fourth, based on these gaps, it would propose a future research agenda considering a wider systems approach in the application and advancement of aviation system reliability and safety.

The second step was to define the literature databases to use, suitable search keywords aligned to the research aim and questions, and define literature selection criteria.

Five databases were selected to ensure that a significant number of relevant literature can be identified through the search: Google Scholar, Science Direct (Elsevier), ProQuest, Sage, and Emerald. The databases were selected based on the type and collection of sources, such as the number of peer-reviewed research articles in the database and the nature and collection of journals, including the Scientific Journal Ranking (SJR). The search keywords were agreed upon and used to search selected databases to reach this aim and answer the questions. Those keywords aimed to guide the search to identify potentially relevant literature. 'High-reliability' and 'aviation', 'air transport', 'air' were chosen to identify the use of HRT in these aviation studies. 'Normal accident' and 'aviation', 'air transport', 'air' were chosen to identify NAT application. 'Resilience Engineering', 'resilience' (deeper content check required) and 'aviation', 'air transport', 'air' were chosen to identify RE application. The search keywords were allowed to appear in the title, the abstract, or the main body of the record.

In the next step, literature was identified and screened for quality, relevance, and eligibility. Articles not fitting the study's criteria were eliminated and the remaining articles were included in the analysis. Criteria for quality, relevance, and eligibility included: the nature and quality of the source, meeting the selection criteria as described below, and the articles should sufficiently discuss the theories in an aviation context.

Databases and literature screened were evaluated against generally accepted selection criteria such as those proposed by Zhang *et al*., (2021). Eligible records were written in English language and academic and peer-reviewed literature. Non-peer-reviewed literature was excluded, whereas grey literature such as conference proceedings or technical reports was also included. The focus was placed on original studies rather than reviews, but reviews were not excluded in general if they contained relevant information on the theories and their application. No specific timeframe was applied to the database search. As a result, this SSR covered studies ranging from 1984 until April 2021. Finally, the record content was screened as relevant to the purpose of this SSR. Therefore, the record included (any combination of) the keyword search terms in its title, the abstract or the main document.

The Flow Diagram in Figure 2, adapted from the PRISMA Group (Moher et. al., 2009), shows that 269 records were identified through the database search containing the search keywords. PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) are guidelines for reporting systematic reviews, the four-phase flow diagram developed by the authors has been adapted and applied for this review (Moher et. al., 2009). As five different databases were used, the search resulted in multiple duplicates. These duplicates (n=62) were removed, leaving the remaining 207 records to be screened for the use or discussion of NAT, HRT or RE. 89 records have been excluded in this first screening stage for not meeting this criterion. More in-depth content screening was conducted in the remaining 118 records also evaluating their relevance resulting in the exclusion of records deemed records of low relevance, because they were not referring to the application of NAT, HRT, or RE in aviation. (see Figure 2) If, despite of the keywords being mentioned, the articles do not apply or discuss the theories in an aviation context, the articles have been excluded. In the final step, further 41 records were excluded after a full-text screening as they were not discussing in sufficient depth one or more of the theories or their application in one or more aviation subsystems. Articles excluded under the criteria 'not discussing in sufficient depth' revealed that the main body of the text only mentions or references the theories and/or the subsystems, but is not discussing or applying the theory in an aviation (sub-)system context. In the end, 77 records, were included in the synthesis.

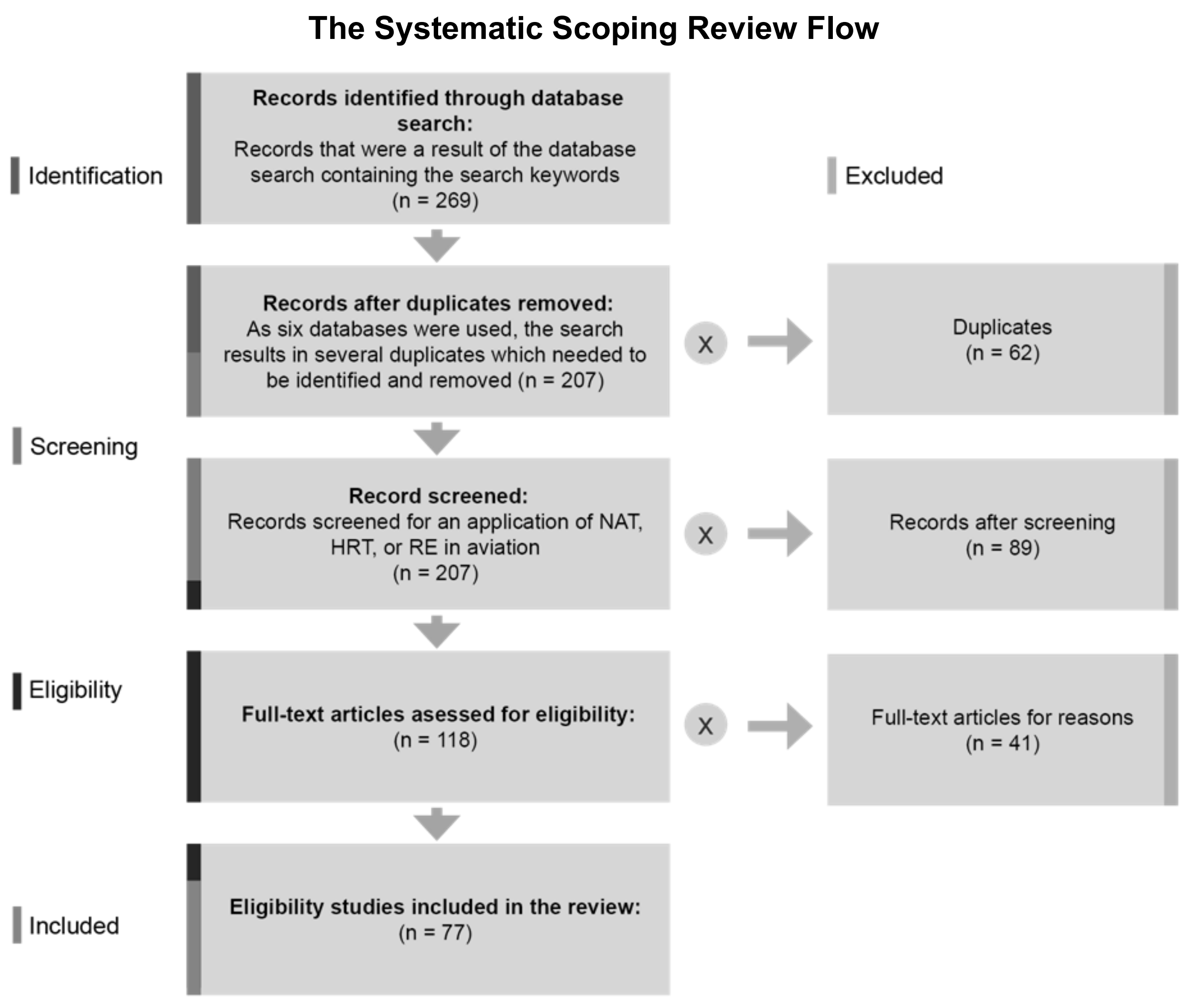

Figure 2: SSR Flow Diagram - adapted from Moher et al., 2009

4. Results

This chapter is divided into two subsections. The first subsection provides and overview of the results of the quantitative assessment, while the second subsection details the results of the thematic analysis. The subsequent section (5. Discussion) will discuss those results and provides a research agenda.

4.1 Results of the quantitative assessment

The 77 selected records were published in a variety of journals, but the three main publication outlets were (1) Safety Science; (2) Transportation Research; (3) Public Administration Review.

The number of aviation studies using NAT/HRT/RE as a theoretical foundation has significantly increased from less than 1 article per year between 1984 and 2005 to an average of 4.5 articles per year in the period 2007 – 2020 (Table 1). Many of the recent articles have been published in the journals Safety Science (n=10), Transportation Research (n=6), and Public Administration Review (n=4). The remaining articles were published in a variety of journals, including Reliability Engineering & System Safety (n=2) or Accident Analysis & Prevention (n=2).

Table 1: Publications per year and theory applied to aviation

Theory / Year of Publication	1980 – 1985	1986 – 1990	1991 – 1995	1996 – 2000	2001 – 2005	2006 – 2010	2011 – 2015	2016 – 2020	2021	**# of records**
NAT	1	1	0	1	2	2	0	0	0	**7**
HRT	0	1	1	0	3	4	5	5	0	**19**
RE	0	0	0	0	0	4	9	20	1	**34**
NAT & HRT	0	0	1	2	1	3	1	0	0	**8**
HRT & RE	0	0	0	0	1	1	2	3	0	**7**
NAT & RE	0	0	0	0	0	0	1	1	0	**2**
TOTAL	**1**	**2**	**2**	**3**	**7**	**14**	**18**	**29**	**1**	**77**

The selected records (n = 77) have been screened for their discussion or application of NAT and/or HRT and/or RE in aviation. A total of 61 articles employ a single theoretical framework, and 16 articles are a combination of two theories. Only 9% of the selected records (n=7) discussed or applied NAT in the context of aviation, while in total NAT in combination with other theories makes 21% of the records (n= 17). High-reliability theory accounts for 25% (n=19) records, while in combination with another theory for 44% (n=34). 44% (n=34) of the records discussed RE, and 12% (n=9) of the articles discussed Resilience Engineering and another theoretical approach in one record – this makes more than 55% (n=43) of the selected records in the context of RE. Hence, resilience engineering is the most discussed or applied theoretical framework in the context of aviation, followed by high-reliability theory and normal accident theory (Table 2). It is worth mentioning that RE was often discussed in combination with high-reliability theory, e.g., (Pariès et al., 2019; Lofquist, 2010), and both theories together account for more than 80% of the records.

The theoretical frameworks are discussed or applied in one or more different aviation subsystems. Table 2 shows the aviation subsystems that could be identified in the selected literature in which the theories were considered. More than 29% of the records were researching the selected theories in the aviation subsystem around air traffic control (ATC) – either only ATC or in combination with another subsystem. Flight operations alone account for 10% of the records and in combination with another subsystem for approximately 16%. Airport operations/ground operations account for 6.5% of the selected records and subsystems handling organisational, policymaking, or rulemaking for ~10% in isolation and in combination with another subsystem. Aviation in general or various (more than two) subsystems were discussed in ~30% of the records. Other topics that are included account for 15.5% of the selected records. Aircraft maintenance for only 1.3%.

Hence, ATC and flight operations are the most discussed subsystems in the context of NAT/HRT/RE, followed by organisational/policymaking/rulemaking subsystems (such as national civil aviation authorities), airport operations/ground operations, and aircraft maintenance (Table 2).

Table 2: Distribution of identified records across the different aviation subsystems, including years of publication

Aviation subsystem	# of records	%	NAT, HRT, RE application or discussion in the subsystem	References
Flight Operation	8	10.4	NAT = 1 HRT = 3 RE = 1 NAT & HRT = 2 HRT & RE = 1 NAT & RE = 0	O'Hare (2000), Batteau (2001), Flin et al. (2002), Chialastri & Pozzi (2008), Gross (2014), Fraher (2015), Powell-Dunford et al. (2017), Karanikas & Nederend (2018)
Air Traffic Control	17	22.1	NAT = 1 HRT = 4 RE = 10 NAT & HRT = 0 HRT & RE = 2 NAT & RE = 0	Weick (1987), Brown (1995), Weick (2004), Teperi & Leppänen (2010), Lofquist (2010), Gander et al. (2011), Heese (2013), O'Neil & Kriz (2013), O'Kelly (2015), Cook et al. (2015), Palumbo et al. (2015), Errico et al. (2016), Gravio & Patriarca (2016), Stroeve & Everdij (2017), Lalis et al. (2019), Pariès et al (2019), Jaksic & Janic (2020)
Airport Operations, Ground Operations	5	6.5	NAT = 0 HRT = 1 RE = 4 NAT & HRT = 0	Frederickson & Laporte (2002), Blok et al. (2018), Comes et al. (2020); Zhou & Chen (2020); Guo et al. (2021)

			HRT & RE = 0 NAT & RE = 0	
Aircraft Maintenance	1	1.3	NAT = 0 HRT = 0 RE = 1 NAT & HRT = 0 HRT & RE = 0 NAT & RE = 0	Herrera & Hovden (2008)
Organisational/ policy- making/ rulemaking	3	3.9	NAT = 1 HRT = 2 RE = 0 NAT & HRT = 0 HRT & RE = 0 NAT & RE = 0	McFadden & Hosmane (2001), O'Neil & Krane (2012), Mills (2016)
Flight Operations **and** Air Traffic Management	3	3.9	NAT = 0 HRT = 1 RE = 2 NAT & HRT = 0 HRT & RE = 0 NAT & RE = 0	Brown (1995), Belkoura et al. (2016), Holbrook et al. (2019)
Organisational/policy-making/ rulemaking **and** Air Traffic Management	2	2.6	NAT = 0 HRT = 2 RE = 0 NAT & HRT = 0 HRT & RE = 0 NAT & RE = 0	LaPorte & Consolini (1991), O'Neil & Kriz (2013)
Organisational/policy-making/ rulemaking **and** Flight Ops	2	2.6	NAT = 0 HRT = 1 RE = 0 NAT & HRT = 0 HRT & RE = 1 NAT & RE = 0	Downer (2017), Adjekum & Tous (2020)
Various*	10	12.9	NAT = 2 HRT = 1 RE = 6 NAT & HRT = 0 HRT & RE = 0 NAT & RE = 1	Perrow (1984), Wiegmann & Shappell (2001), Batteau (2001), LaPorte & Consolini (2007), Steele & Parties (2008), Brooker (2011), Herrera (2012), Hudson (2012), Penaloza et al (2017), Zio et al. (2019)

General**	14	18.2	NAT = 1 HRT = 2 RE = 8 NAT & HRT = 2 HRT & RE = 1 NAT & RE = 0	Rijpma (1999), Dijkstra (2007), Johnsen et al. (2009), Akselsson et al. (2009), Tjorhom (2010), Antunes & Murao (2011), Vieira et al (2014), Righi et al. (2015), Turan et al. (2016), Lofquist (2017), McCall & Prunchnicki (2017), Patriarca et al. (2018), Hickford et al. (2018), Agwu et al. (2019)
Other (Aviation not in focus but mentioned as application area, space, air networks, air cargo, Military aviation)	12	15.6	NAT = 0 HRT = 3 RE = 3 NAT & HRT = 3 HRT & RE = 2 NAT & RE = 1	Rijpma (1997), Woods (2003), Cooke & Rohleber (2006), Boin & Schulmann (2008), Shrivastava et al. (2009), Saleh et al. (2010), Sutcliffe (2011), Hollnagel (2014), Malish & Sargent (2019), Janic (2019), Wong (2020), Karanikas et al. (2020)

**the category 'Various' corresponds to articles/studies that mention a greater number (>2) of aviation subsystems; **the category 'General' mentions aviation in general, but does not study or discusses a specific aviation subsystem*

The included studies employed different research approaches to assess and discuss their topics. Mainly qualitative methods have been chosen in 49% (n=38) of the records, while quantitative methods were used in 18% (n=14) and multi-method designs using both qualitative and quantitative approaches in 23% (n=18).

When a qualitative approach was used in the selected records, case studies or strategies employing a mix of qualitative methods were adopted (Fraher, 2015; Mc Call and Prunchnicki, 2017) as well as document/archival analysis (Viera, Santos and Kubo, 2014; Johnsen *et al.*, 2009). Quantitative approaches utilised methods such as time series analysis (O'Neil and Kriz, 2013), or models estimating, predicting, and measuring resilience (Janić, 2019; Zhou and Chen, 2020; Guo *et al.*, 2021), framework modelling (Jakšić and Janić, 2020; Comes *et al.*, 2020) and agent-based modelling (Stroeve and Everdij, 2017) or, a mixed survey and interview approach (Agwu, Labib and Hadleigh-Dunn, 2019).

4.2. Results of the thematic analysis

The records reviewed show different areas of theory analysis, discussion, or application. Table 3 shows different research areas of the selected articles, all considering one or more theoretical frameworks within an aviation context. Based on a detailed screening of the selected records, five main themes were identified. Those main themes focus on the general theory discussion or theory discussion in the context of risk management, human factors/human error management, safety management and assessment, or accident analysis (Table 3).

Themes from the table are emerging themes from the content analysis and categorise the research topic, focus and/or findings from the selected records. It is a condensed summary of the 77 records. It must be noted that some records fit in to more than one area or main theme (e.g. Gravio & Patriarca, 2016), because the topics under the header 'Improving Safety' are often interconnected and have advancements in different fields, such as risk management being one pillar of the safety management framework. Nevertheless, topic such as safety and risk management have been listed separately to distinguish the focus of the papers on the leading topic(s).

Table 3: Themes analysis of the selected records (more details in Appendix B)

Main Theme	Sub-category / Topic-areas	Number of records per theme	Theories used per theme*
Theory focused discussion	- Controllability of safety events - Review and discussion of the theory - Modelling of the theory - Effects of theory application - Business Process Management - Performance measurement - Lessons-learned - Assessment of theory characteristics and development - Theory transferability - Discussion/debate of two or more theories - Organisational culture - Decision making - Disruptive events / management of disruptions - Disaster/crisis management - System challenges and system understanding - Individual, group and organisational learning - Training and communication	39	NAT = 5 HRT = 19 RE = 23
Theory discussion in the context of risk management	- Risk governance - Risk assessment and safety improvements - Hazards management - Fatigue risk management - Organisational management - Safety performance indicators - Safety I and Safety II	5	NAT = 1 HRT = 1 RE = 3
Theory discussion in the context of Human Factors / Human Error Management	- Crew Resource Management - Influence of human behaviour - Examination of human factors concepts - Human factors in accident investigation and analysis - Human error evaluation criteria - Human performance contributions	7	NAT = 3 HRT = 4 RE = 2
Theory discussion in the context of Safety Management & Assessment	- Safety culture - Safety Management Systems - Disaster prevention - Learning systems - Risk/safety governance - Risk & reliability assessment - Safety performance analysis - Challenges and improvement - Safety Investigation - Modelling of safety	16	NAT = 5 HRT = 6 RE = 13
Theory discussion in the context of Accident Analysis	- human and technological contributions to accidents - assessment of high-risk operations - Accident causation - Safety Culture	5	NAT = 2 HRT = 2 RE = 1
Other	- Lessons-learned - Gap analysis and system characteristics - Modelling of theory(ies) - Accountability relationships - Governance	5	NAT = 2 HRT = 1 RE = 2

*More than one theory may be present in one record, therefore the simple addition of the number of articles may not sum up to the total number of records per category.

5. Discussion of findings

This scoping review set out to evaluate the application of three different theoretical approaches to assessing safety in the aviation operational subsystems. The first section discusses the role of primary and secondary subsystems in the academic landscape around NAT, HRT, and RE, the second subsection details the currently state of the theories, while the third subsection examines on the thematic analysis. In summary, the review showed that these theories were mainly looking at the 'primary operational aviation subsystems' such as air traffic control (ATC) and flight operations and significantly less at the 'secondary operational subsystems' such as ground operations and aircraft maintenance (key finding 1 - shown in 5.1), that research building on RE has increased in recent years and is now the predominant theoretical framework in studies of this type (key finding 2 - shown in 5.2), and that the main themes in this theoretical and operational context focus on the general theory discussion, theory discussion in the context of risk management, human factors/human error management, safety management and assessment, or accident analysis (key finding 3 – shown in 5.3).These findings are discussed in further detail and directions for further research are offered. All subsections provide recommendations for researchers, resulting in a research agenda.

5.1. Primary and secondary subsystems in aviation safety research

The first part of the quantitative assessment aimed at identifying 'Which sub-systems have received most attention when applying these theories?'. The review confirmed that air traffic management and flight operations are the most investigated subsystems in aviation safety studies underpinned by NAT, HRT and RE followed by organisational/policymaking/rulemaking subsystems, airport operations/ground operations, and aircraft maintenance (Table 2). Subsystems such as aircraft maintenance and ground operations received less attention from researchers because of their perhaps different hazards and risks structure, and their lower visibility in the broader aviation system. Nevertheless, it must be noted that aviation safety research involving ground operations was increased in the last 5 years (Table 2), but it cannot be concluded whether this will be a permanent trend. The increase in theory application to aviation within the last 12 years is mainly focused on resilience engineering (Chialastri & Pozzi, 2008; Errico et al., 2016; Patriarca et al., 2018). This does not necessarily mean that NAT and HRT become redundant, but it may show the strength and compatibility of RE with complex and tightly coupled systems, such as aviation or healthcare (Errico et al., 2016; Anderson et. al., 2016). In addition, the finding of the unequal treatment does not unquestionably mean that this focus was wrong, researchers have good reasons for their choice, such as a specific accident or application scenario (e.g. Errico et al., 2016; Flin et. Al., 2002). Nevertheless, with the shift to the total system view (Hollnagel, 2014-2), it should be assessed if, how much, and in which areas aviation safety can benefit from applying and discussing different theoretical perspectives in the secondary system context to increase understanding and reduce risks.

Additionally, the research focus in the selected records was often on disaster resilience, event resilience, and controllability of events (see Table 3). On the one hand, having this topic focus on controlling events and disasters, while one the other hand authors focus on primary subsystems seems contradictory, as a one-sided view may leave important aspects apart. Therefore, the theoretical frameworks and tools provided with them, are recommended to be used and applied to primary and secondary subsystems. This application to different subsystems is only possible if one understands the characteristics and the role of all subsystems within the broader system and operational context. Otherwise, important influencing factors might get lost, such as the influence of efficient resource management in ground operations on the punctuality of flight operations and with it the influence on a whole network or airport operation.

Having a tightly coupled, interconnected, and interdependent system in high-risk environments demands for a system view and a broad understanding of sub-systems and their interdependencies. Especially when considering the increasing challenges stated in Section 1, it could be considered a good practice that these subsystems receive similar attention to reduce accidents and incidents. Consequently, research and industry focus in those secondary subsystems should be increased for a more in-depth understanding of the subsystems, their characteristics, their role and interdependencies with other subsystems, and what impact they have on the system safety and reliability. As an example, the reduction of ground operations incidents or accidents may increase reliability of the system by decreasing delays, decreasing human error in the system, decreasing equipment and aircraft damage, thus decreasing costs, and increasing the overall safety and efficiency of the system. Thus, it is recommended to analyse aviation accident and incident reports, specifically for the influence of secondary subsystems, to better understand their influence on aviation system safety (see next subsection for a relation to the theoretical approaches).

Nevertheless, more research on secondary subsystems will not naturally improve safety of the aviation system, but the knowledge and understanding for secondary subsystems must be properly adapted and implemented in the industry. It must not only be assessed if more focus and understanding of the secondary subsystem can improve the total system view, and especially the safety of working in and with the secondary subsystem, but this knowledge must also be transferred to the system and subsystems by practitioners.

5.2. Normal accident theory, high-reliability theory, and resilience engineering in aviation safety research

The second part of the quantitative assessment aimed at addressing the questions: ‘Which theoretical approaches are more prominent within the aviation safety literature?’ and ‘Which methodological approaches are primarily used to apply NAT/HRT/RE in aviation?’. The main results related to the three theories in an aviation context are discussed. In this subsection, the paper switches from the subsystems issue to the question of the potential contribution of the three referred theories in emancipating from dogmatic theses underlying the current aviation safety paradigm and developing new knowledge and theoretical frameworks in aviation safety.

In particular, high-reliability theory and resilience engineering were used by scholars in several studies and different aviation subsystems. This indicates a growing relevance of the concepts in aviation, especially of RE. In comparison, NAT was not extensively used in aviation safety studies and, on many occasions, it was used in combination with another theory (Table 1).

RE appears to be the favourite theoretical framework in aviation safety research - over the past 10 years, while the underpinning capacity of NAT and HRT has decreased. Nevertheless, HRT is still used in conjunction with RE. This is perhaps because NAT is viewed as a more pessimistic or fatalistic approach to accidents, whereas HRT and RE take a more active approach to them. A possible explanation of this shift towards RE is that HRT is focused on error management principles for near error and accident-free operations. In contrast, RE offers a broader spectrum of approaches for achieving resilience of a system, such as looking at why things went right and why things went wrong, focusing on how the system works. Thus, resilience engineering is not focused on avoiding errors in a system, but to maximise the ability of the system to “adjust its functioning prior to, during, or following events (changes, disturbances, and opportunities), and thereby sustain required operations under both expected and unexpected conditions.” (Hollnagel, 2014, p.1) In addition, RE offers the more systemic approach, rather than the organisational viewpoint in HRT.

The positive implications from an increased system understanding can be derived from the developments in primary subsystems in the past decades. Safety thinking has evolved, from accidents being understood from a purely technical perspective to a human factor, an organisational, and finally a systems perspective (Swuste et al., 2021; Aven, 2022). The understandings derived from theoretical frameworks, such as NAT, HRT, and especially RE nowadays, could be or are partly embedded in the way investigators analyse aviation accidents and incidents.

A popular example from the past is the Dryden accident – Air Ontario flight 1363 in 1989. This fatal accident due to a failure in de-icing resulted from a number of systematic, organisation, and human factors issues, such as pressure at individual and organisational level, lack of resources, and a lack of procedures and oversight. This accident resulted in a number of changes at national and international level, not only for refuelling and de-icing procedures, but also with regards to human factor situational awareness. (Minister of Supply and Services Canada, 1992; Bennett, 2015). Thus, system thinking and an increased understanding of the subsystem and influencing factors, such as competitive pressure, while analysing this accident resulted in changes beyond simply addressing the de-icing issues (Bennett, 2015). A first well-known similar application of the system-thinking in around secondary subsystems could be observed in the accident analysis and following industry changes of the National Airlines flight 102 in 2013. The accident was mainly caused by “inadequate procedures for restraining special cargo loads, which resulted in the loadmaster’s improper restraint of the cargo, which moved aft and damaged hydraulic systems …, rendering the airplane uncontrollable” (NTSB, 2015, p.74). In addition, a lack of certification, deficient aircraft load training, procedures, and oversight also contributed to the accident. Thus, the recommendations, as well as industry actions also go beyond simply addressing the root cause, but analysing the various system components including the regulator’s role, the airline’s role, the ground handler’s role, and human factors issues in the particular subsystems involved. (NTSB, 2015; FAA, 2015). For both accident examples, the theoretical frameworks of HRT for the Dryden accident and RE for the national airlines flight potentially informed how the accident analysis and discussion has been approached.

The aviation system is indeed a high reliable tightly coupled system, tightly coupled meaning that all its subsystems function simultaneously, and any error from one subsystem will affect total system performance. As HRT is predominantly based on HRO principles, it would be interesting in the future whether all the aviation subsystems follow all these principles in their operations and, if so, whether they all place the same importance on them or different subsystems assign different weights to them.

The HRT principles still apply in all aviation subsystems. In addition, RE allows some space for adaptation, reflection and improvement which can provide, in combination with HRT, a coherent and comprehensive approach to address safety challenges in complex systems operating in dynamic and volatile environments. The interplay between stringent safety processes and procedures, and dynamic adaptations within the various aviation subsystems would be an interesting direction for future research with researchers emancipated from dogmatic theses but sensitive for controversies can develop new knowledge and theoretical frameworks in aviation safety. The very concept of resilience in aviation can trigger more integrated and progressive approaches to aviation safety science, notwithstanding the learnings of NAT and HRT.

In addition to a detailed analysis of aviation accident reports, a more practical perspective can be reached by reviewing aviation industry sources (e.g. from ICAO or IATA), rules and regulations (such as national, supra-national, and international regulations), and applied organisational approaches (e.g. from airlines, airports, or air navigation service providers) must for these theories potentially embedded in their aviation safety and risk management systems and manuals. For this, mainly qualitative research approaches, such as thematic content analysis is recommended, but might be complemented by quantitative research such as various modelling techniques.

5.3. Discussion of the thematic analysis

The third part of the assessment details the results of the thematic analysis and discussed the themes identified in more detail. The results and discussion thereof address 'What are the key findings of these studies and what are potential areas needing further research?' to identify gaps in the system with the application of the theories.

5.3.1. Research discussing the three theories in general

In the area of **general theory discussion** main research was performed around controlling safety or disruptive events, or disasters (Karanikas and Nederend, 2018; Agwu, Labib and Hadleigh-Dunn, 2019; Wong *et al.*, 2020) with the framework that is provided by one or more theories. Karanikas and Nederend (2018) state that controllability is dependent on the level of intervention potential, the familiarity of the end-user with the situation or event, and the effect of the end-user intervention. To manage disasters, Agwu *et al.* (2019), state that learnings from HRO can be applied to a wider range of organisations, and a more harmonised approach is developed to apply learnings from different areas. But not only do severe safety events or disasters in different subsystems influence the reliability of a system but also events that lead to system disruptions do, such as delays (Wong *et al.*, 2020). By combining the learnings of simple and complex disruptive events, safety events, and even disasters the total system understanding increases, as well as the general ability to act in any of these situations. Hence, the guiding aim seems to be to understand the system and its challenges (Hollnagel, 2014; O'Neil and Kriz, 2013; LaPorte and Consolini, 1991), measure the performance of the approaches (Peñaloza *et al.* 2017; Zhou and Chen, 2020) and develop management principles (Weick, 1987; Antunes and Mourão 2011), including training and educational measures (Teperi and Leppänen, 2010; Vieira, Santos and Kubo, 2014). Preceding this analysis of safety events is the analysis of the theories themselves. Therefore, some authors dealt with the characteristics of the theories and their applicability in different socio-technical environments, such as in aviation (O'Neil and Krane, 2012; O'Neil and Kriz, 2013).

Nevertheless, combining these findings and exploiting the lessons learned would allow for a more harmonised and advanced approach across the three theories and systems and subsystems. Hence, future research could investigate the theories in an applied operation context and in combination with existing frameworks, such as safety, risk and human error management or accident analysis. Therefore, it is recommended to analyse the general theory discussion in different businesses and explore major disasters and disruptions, as well as challenges that multiple high-reliability systems face.

5.3.2. Research discussing the theories in the context of risk management

The dominant focus in the **theoretical discussion of risk management** was risk governance (Tjørhom, 2010), hazard and risk assessment (Brooker, 2011; Brown, 1995), and the management of risks (Gander *et al.*, 2011). Tjørhom (2010) identified the importance of harmonised national and supranational risk governance in aviation, providing the framework for hazard and risk management on an organisational level. Improved hazard and risk management are considered when researchers and practitioners not only look at what went wrong or what could go wrong but also at analysing what went right and for what reasons (Brown, 1995). Based on the framework and the analysis of operations, safety improvements and management approaches, such as fatigue risk management can be derived (Brooker, 2011; Gander *et al.*, 2011). Nevertheless, risk management-related analysis was often conducted in the context of the primary subsystems (Gravio and Patriarca, 2016).

5.3.3. Research discussing the theories in the context of human factors and the management of human error

Linking with the theme on risk management**, human factors in the system, and the management of human error** could be identified as a key for achieving safety, reliability, and resilience of a system. While Batteau (2001) describes the human role and historic development in the aviation system, Heese *et al.* (2013) and Holbrook et al., (2019) discussed the influence of human behaviour and human performance in the system. Heese *et al.* (2013) use a similar approach to Brown (1995) in the risk management theme: not only observing what went wrong but also what went right and for what reasons. In this approach, human behaviour was observed, and the main influencing factors were identified: goal-directed behaviour, proactive solutions, flexibility, improvisation, and the availability of resources Heese *et al.* (2013). Although it is important to identify these factors, it is also crucial to manage human error when it occurs. The management of error is evaluated by Wiegmann and Shappell (2001) and identifies the need for decision support with objective criteria in organisations when choosing the error analysis and prevention approach. A major application area is Crew Resource Management in Aviation (Flin, O'Connor and Mearns, 2002; Gross, 2014). The current research analyses different characteristics and gaps in the application, nevertheless a conceptual framework and guidance for practitioners are only available for specific subsystems, also not being standardised to date.

Future research in the areas of risk, human factors and human error management may provide a more harmonised and holistic system view, based on system and subsystem characteristics. Along the same lines, a detailed assessment of the different human factor characteristics in the various subsystems is important. Naturally, those characteristics must be acknowledged in the development and execution of risk, human factor, human error, and safety management.

5.3.4. Research discussing the theories in the context of safety management

Theory discussion in the context of safety management includes various components that are also relevant for risk, human factors, and human error management. Nevertheless, in this identified theme, the focus lies on the concept of Safety Management Systems (SMS) (Adjekum and Tous, 2020; Lofquist, 2017; Weiland, Law and Sunjka, 2020; Pariès *et al.*, 2019), safety culture (Akselsson *et al.*, 2009), and safety performance indicators (Herrera and Hovden, 2008; Herrera, 2012). It follows, then, applying RE principles in SMS, Lofquist (2017) and Weiland, Law and Sunjka (2020) identified the need to adapt current SMS concepts caused by modern system dynamics and complexity. For similar reasons, Herrera and Hovden (2008) and Herrera (2012) identified the need for new proactive or leading safety and reliability performance indicators. As a result, the concept of RE, which is predominantly discussed in this theme, may change the current SMS framework. Outcomes of a variety of aviation, but also interdisciplinary research might be analysed. Those are also recommended to include the 'future research' recommendations in the areas of general theory discussion, subsystem characteristics, risk management, human factors and human error management, as well as accident analysis.

Lessons learned from the past are an important component of a potential conceptual framework and can be derived from **theory discussion in the context of accident analysis**. Essentially, accident causation analysis (Saleh et al., 2010; Hudson, 2012) and the assessment of high-risk operations using accident analysis (Fraher, 2015) provide insights on potential weaknesses in the current safety and risk management approaches. Thus, the understanding of causes and contributing factors in accidents have been and will be important for continuous system improvements.

As a result, future research could conduct a more in-depth analysis of past accidents and incidents to reveal hazards and risks in different subsystems. By understanding gaps in considering the different subsystem characteristics, and especially the influence of secondary subsystem in aviation accidents and incidents, system understanding can be increased, and future management approaches can be adapted. This might be done by an extension of the research and application of resilience engineering tools, based on the learnings and components of NAT and HRT, for more integrated, progressive, and dynamic approaches to aviation safety science.

5.4. Limitations

This systematic scoping review is not a holistic assessment of system reliability theory application to aviation subsystems, but rather an assessment of academic literature on NAT, HRO, and RE theory application to aviation. The aim was to identify focus areas of theory application in aviation subsystems and gaps therein. Further review and analyses on these gaps are needed to identify, assess, analyse and measure the difference between aviation subsystems and the resulting impact on the aviation system.

Even though, a SSR was conducted using five different databases, there is a probability that not all relevant articles were found within these databases or that other databases have additional relevant records. This could be for example caused by the keywords selected or the screening conducted. Nevertheless, the number of databases and the thick description of the methodology is expected to be beneficial for the overall reliability of this SSR.

With regards to the classification and focus on primary and secondary subsystems, it must be noted that no additional analysis was conducted on the reasons of researchers to believe that a given subsystem is less relevant for their own theory at a given time. This focus on primary subsystems might have emerged because the secondary systems have been or still are less complex, less dynamic, less exposed to the vagaries of real time, or less frequently involved in accidents as compared to primary subsystem. Additionally, it is not solely the writings of safety theorists that determine safety management practices, but rather the current visions and developments within the system. The influence of safety theories on actual safety management, and even more on actual safety performance cannot be taken for granted.

In this context, it is also important to note that only academic resources have been reviewed in this study, and that there is potentially more discussion and application of NAT, HRT and RE components within the industry or individual organisations. In the aviation industry, rules, regulations, standards, best practices, and guidance material are developed by national and international rulemaking bodies, such as the International Civil Aviation Organisation (ICAO) or the European Union Aviation Safety Agency (EASA) or industry associations, as the International Air Transport Association (IATA). Material developed by these, and other organisations can potentially reveal that the theoretical frameworks might be embedded in the different subsystems to a different extent.

6. CONCLUSION

This systematic scoping review (SSR) aimed to review the application of three different approaches to discuss safety and in particular accidents in aviation, namely NAT, HRO, and RE. The objectives were to explore the three theoretical frameworks applied to aviation, to examine how and in which areas research is conducted in these fields, and to identify and discuss knowledge gaps within the academic assessment of these areas (Munn et al., 2018).

This SSR provides quantified insights on the application and discussion of three theories in the context of aviation subsystems and qualitative analysis of themes. The first part of the quantitative assessment aimed at identifying ‘Which sub-systems have received most attention when applying these theories?’, while the second part aimed at addressing the questions: ‘Which theoretical approaches are more prominent within the aviation safety literature?’ and ‘Which methodological approaches are primarily used to apply NAT/HRT/RE in aviation?’. It could be concluded that neither all theories nor all aviation sub-systems received similar attention from researchers. In particular, high-reliability theory and resilience engineering were used by scholars in several studies and within different aviation subsystems. The review confirmed that air traffic management and flight operations are the most investigated subsystems in aviation safety studies underpinned by NAT, HRT and RE followed by organisational/policymaking/rulemaking subsystems, airport operations/ground operations, and aircraft maintenance (Table 2).

In addition, the SSR revealed that NAT, HRT, and RE are well-known theories to aviation but are mainly applied to air traffic control (ATC) and flight operations. Even though it is acknowledged that these theories have their roots in these high-risk areas of the aviation system, the findings indicate that the subsystem ground operations and aircraft maintenance receive significantly less attention in academic research. In addition, an increase of theory application within the last 12 years could be identified, with a majority of articles in the area of resilience engineering and applied to the aviation sub-system ATC/ANS/ATM. Nevertheless, this lower implication frequency, as well as the nature of the associated risk, may explain that scholars have not been interested in the secondary subsystems with the same frequency as for other subsystems.

In a third step, a thematic analysis and discussed the themes identified in more detail. The results and discussion thereof address 'What are the key findings of these studies and what are potential areas needing further research?' to identify gaps in the system with the application of the theories. As a result, five main themes were identified: general theory discussion, theory discussion in the context of risk management, human factors/human error management, safety management and assessment, or accident analysis (Table 3).

The main research proposals presented in the discussion above are to:

- increase the focus and understanding of the secondary subsystem and assess if and how this can improve the total system safety (Section 5.1),
- further explore the concept of resilience in aviation and the role of the three theories in aviation safety developments (Section 5.1)
- review and analyse industry resources and applied organisational approaches for a potential inclusion of the three theoretical frameworks (Section 5.2),
- analyse the general theory discussion in different businesses and explore major disasters and disruptions, as well as challenges that multiple high-reliability systems face (Section 5.3),
- a more in-depth analysis of past accidents and incidents to reveal hazards and risks in different subsystems (Section 5.3),
- examine the relevance and potential benefits of an extension of the research and application of resilience engineering tools, based on the learnings and components of NAT and HRT, for more integrated, progressive, and dynamic approaches to aviation safety science. (Section 5.2 and 5.3)
- conduct a more in-depth analysis of past accidents and incidents to reveal hazards and risks in different subsystems, with the aim to increase the understanding of the subsystems and system as a whole (Section 5.3).

As a result of these proposals, it is generally recommended to analyse whether a comprehensive theoretical framework including valuable components of all the theories can be developed to provide a set of tools suitable for primary and secondary subsystems. To achieve a clearer picture of the theory application in an operational context, not only academic literature but also industry rules, standards and guidelines must be evaluated. In addition, an increased understanding of the subsystems, especially secondary subsystems, and their role in system safety could be thoroughly assessed. Ultimately, those findings may be used for a more comprehensive safety, risk, human factors, and human error management approach in aviation.

The overall aim of the analysed records can be described as improving the safety, efficiency and resilience of a system. Even though most records selected for this paper are focused on applying or assessing theories in an aviation context and are therefore application-focused, practical implications for the operator are rare. Hence, NAT, HRT and RE are extensively discussed in the context of one or more aviation subsystems, however, its application in the operational context is missing. As a result, this indicates a need for the increased usage of case studies and other practical assessments to not only benefit the body of knowledge and other researchers but also to make the theories understandable and usable for practitioners and more transferable within their operational context.

Nevertheless, the limitations in section 5.4 must be considered in the context of these recommendations and can be considered and reduced in further studies, such as analysing aviation accidents or, industry regulations and standards to assess in how far the three theoretical frameworks are embedded in the aviation industry already.

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7. Appendix

Table 4: Overview of the records included in the SSR

Ref #	Article Name	Author	Journal	Year of Publication
1	Assessing the relationship between organizational management factors and a resilient safety culture in a collegiate aviation program with Safety Management Systems (SMS)	Daniel Kwasi Adjekum; Marcos Fernandez Tous	Safety Science	2020
2	The controllability classification of safety events and its application to aviation investigation reports	Nektarios Karanikas; Jeffrey Nederend	Safety Science	2018
3	Resilience engineering: Current status of the research and future challenges	Riccardo Patriarca; Johan Bergström; Giulio Di Gravio; Francesco Costantino	Safety Science	2018
4	Agent-based modelling and mental simulation for resilience engineering in air transport	Sybert H. Stroeve; Mariken H.C.Everdij	Safety Science	2017
5	A systematic literature review of resilience engineering: Research areas and a research agenda proposal	Angela Weber Righi; Tarcisio Abreu Saurin; Priscila Wachs	Reliability Engineering & System Safety	2015
6	Resilient Business Process Management: Framework and services	Pedro Antunes; Hernâni Mourão	Expert Systems with Applications	2011
7	Resilience in the Aviation System	Chialastri, Antonio; Pozzi, Simone	Conference Paper	2008
8	Do High-Reliability Systems Have Lower Error Rates? Evidence from Commercial Aircraft Accidents	Patrick D. O'Neil; Kenneth A. Kriz,	Public Administration Review	2013
9	Disaster prevention through a harmonized framework for high reliability organisations	Agwu Emele Agwu; Ashraf Labib; Sara Hadleigh-Dunn	Safety Science	2019
10	Resilience Safety Culture in Aviation Organisations	Akselsson, R.; Koornneef, F.; Stewart, S.; Ward, M.	Draft Book Chapter	2009
11	The Anthropology of Aviation and Flight Safety	Allen W. Batteau	Human Organization	2001
12	Risk governance within aviation	Tjørhom, Berit Berg	Risk Management	2010
13	Learning from incidents: from normal accidents to high reliability	David L. Cooke, Thomas R. Rohleder,	System Dynamics Review	2006
14	The Aviation Paradox: Why We Can 'Know' Jetliners But Not Reactors	John Downer	Springer - Minerva	2017
15	Crew resource management: improving team work in high reliability industries	Rhona Flin, Paul O'Connor, Kathryn Mearns	Team Performance Management	2002
16	Technology-push, market-demand and the missing safety-pull: a case study of American Airlines Flight 587	Amy L. Fraher	New technology, work, and employment	2015
17	Airport Security, High Reliability, and the Problem of Rationality	H. George Frederickson; Todd R. LaPorte	Public Administration Review	2002
18	Assessing Behaviour towards Organizational Resilience in Aviation	Michaela Heese; Wolfgang Kallus; Christa Kolodej	Resilience Engineering Association	2013
19	Leading indicators applied to maintenance in the framework of	Ivonne A Herrera; Jan Hovden	Paper presented at The 3rd	2008

	resilience engineering: A conceptual approach		Resilience Engineering Symposium, 28 – 30 October 2008, Antibes Juan Les Pins, France.	
20	Proactive safety performance indicators	Herrera, Ivonne Andrade	PhD Dissertation	2012
21	Resilience engineering and the built environment	Erik Hollnagel	Building Research & Information	2014
22	Modeling resilience of the ATC (Air Traffic Control) sectors	Zoran Jakšića; Milan Janić	Journal of Air Transport Management	2020
23	The art of measuring nothing: The paradox of measuring safety in a changing civil aviation industry using traditional safety metrics	Eric Arne Lofquist	Safety Science	2010
24	High-Reliability Uncaged: Safety Lessons From Army Aviation	Richard Malish; Patrick D Sargent	Military Medicine	2019
25	Operations safety: an assessment of a commercial aviation safety program	Kathleen L. McFadden; Balakrishna S.Hosmane	Journal of Operations Management	2001
26	'The 'Wheel of Misfortune': a taxonomic approach to human factors in accident investigation and analysis in aviation and other complex systems	David O'Hare	Ergonomics	2000
27	Policy and Organizational Change in the Federal Aviation Administration: The Ontogenesis of a High-Reliability Organization	Patrick O'Neil; Dale Krane	Public Administration Review	2012
28	Do High-Reliability Systems Have Lower Error Rates? Evidence from Commercial Aircraft Accidents	Patrick D. O'Neil, Kenneth A. Kriz,	Public Administration Review	2013
29	Normal Accidents	Charles Perrow	Book	1984
30	Theoretical and operational challenges of "high-reliability organizations": air-traffic control and aircraft carriers	Todd La Porte; Paula Consolini	International Journal Of Public Administration	2007
31	Transferring Aviation Practices into Clinical Medicine for the Promotion of High Reliability	Powell-Dunford, Nicole; McPherson, Mark K.; Pina, Joseph S.; Gaydos, Steven J.	Aerospace Medicine and Human Performance	2017
32	From Deadlock to Dead End: The Normal Accidents- High Reliability Debate Revisited Managing Major Hazards.	Jos A. Rijpma	Journal of contingencies and crisis management	1999
33	Complexity, Tight–Coupling and Reliability: Connecting Normal Accidents Theory and High Reliability Theory	Jos A. Rijpma	Journal of contingencies and crisis management	1997
34	Normal Accident Theory versus High Reliability Theory: A resolution and call for an open systems view of accidents	Samir Shrivastava; Karan Sonpar; Federica Pazzaglia	Human Relations	2009
35	Characterisation of the Variation in Safety Beliefs across the Aviation Industry	K. Steele Jean Pariès	Project Publication: not peer-reviewed	2008
36	High reliability organizations (HROs)	Kathleen M Sutcliffe	Best Practice & Research Clinical Anaesthesiology	2011
37	Organizational Culture as a Source of High Reliability	Karl H. Weick	California Management Review	1987

38	Human Error Perspectives in Aviation	Douglas A Wiegmann; Scott Shappell	The International Journal Of Aviation Psychology	2001
39	Creating Foresight: How Resilience Engineering Can Transform NASA's Approach to Risky Decision Making	David D Woods	Testimony on The Future of NASA for Committee on Commerce, Science and Transportation, John McCain, Chair October 29, 2003	2003
40	Application of reliability technologies in civil aviation: Lessons learnt and perspectives	Enrico ZIO; Mengfei FAN; Zhiguo ZENG; Rui KANGc	Chinese Journal Of Aeronautics	2019
41	Data-driven analysis of resilience in airline networks	Allen Wong; Sijian Tan; Keshav Ram Chandramouleeswaran; Huy T. Tran	Logistics and Transportation Review	2020
42	Network Hub Structure and Resilience	Morton E. O'Kelly	Networks and Spatial Economics	2015
43	Highlights from the literature on accident causation and system safety: Review of major ideas, recent contributions, and challenges	J.H. Saleh; K.B. Marais; E.Bakolas; R.V.Cowlagi	Reliability Engineering & System Safety	2010
44	Technological Peripheralization	Allen W. Batteu	Science, technology and human values	2010
45	Generation and recovery of airborne delays in air transport	Seddik Belkoura; José Maria Peña; Massimiliano Zanin	Transportation Research Part C: Emerging Technologies	2016
46	Formal and computational modeling of anticipation mechanisms of resilience in the complex sociotechnical air transport system	Anne-Nynke Blok; Alexei Sharpanskykh; Matthieu Vert	Reliability Engineering & System Safety	2018
47	Assessing NASA's Safety Culture: The Limits and Possibilities of High-Reliability Theory	Arjen Boin; Paul Schulman	Accident Analysis of Prevention	2008
48	Experts, Bayesian Belief Networks, rare events and aviation risk estimates	Peter Brooker	Safety Science	2011
49	Community, technology, and risk: Collective well-being in the aviation industry	Gary Brown	Technological Forecasting & Social Change	1995
50	Critical Airport Infrastructure Disaster Resilience: A Framework and Simulation Model for Rapid Adaptation	T. Comes; Martijn Warnier; Wouter Feil; Bartel Van de Walle	Transportation Research	2020
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53	Simulation Approach to the Resilience Engineering Assessment of the ATM System in Crisis Scenarios	Angela Errico; Edoardo Filippone; Roberto Palumbo; Domenico Pascarella; Francesco Gargiulo	AIAA Modeling and Simulation Technologies Conference	2016
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57	Resilience Modeling Method of Airport Network Affected by Global Public Health Events	Jiuxia Guo; Xinping Zhu; Chenxi Liu; ShuzhiSam Ge	Mathematical Problems in Engineering	2021
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63	“Old” and “new” safety thinking: Perspectives of aviation safety investigators	Nektarios Karanikas; Dimitrios Chionis; Anastasios Plioutsias	Safety Science	2020
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66	Working in Practice but Not in Theory: Theoretical Challenges of "High-Reliability Organizations"	Todd R. Laporte; Paula Consolini	Journal of Public Administration Research and theory	1991
67	Jousting with Dragons: A Resilience Engineering approach to managing SMS in the transport sector	Eric Arne Lofquist	International Transport Forum Discussion Papers	2017

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