CRANFIELD UNIVERSITY

Fabian Steinmann

Identifying resilience principles in the UK air transportation industry and developing an integrated conceptual resilience framework

School of Aerospace, Transport, and Manufacturing

Doctor of Philosophy

Academic Year: 2019 - 2022

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This thesis is submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy

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ABSTRACT

Organisations across the aviation sector strive to become more resilient, and there is a great desire to integrate resilience into the operation. However, there is no clear definition of resilience, and people in academia and industry have interpreted the concept differently.

The research aims to integrate different conceptualisations of resilience and develop a framework that holistically explains how resilience can be developed in the UK air transportation industry context. The development of the framework is achieved through an integration of the literature and empirical refinement of the subsequent preliminary framework.

A systematic, multi-sector and cross-disciplinary literature review was conducted to determine four main themes of resilience: *System Design, System Preparedness*, *System Response*, and *System Changes*. A total of 26 high-level resilience principles were identified in the literature and grouped into different (sub-)themes, building the foundation for a Preliminary Resilience Framework (PRF).

The empirical work of the thesis investigated five cases in the UK air transportation system. The qualitative research aimed to identify empirical evidence through thematic analysis of how the UK air transportation industry operationalised the identified high-level principles. The analysis of the cases found evidence for 19 of the 26 principles. Furthermore, the case study findings determined ten new connections between the various identified (sub-)themes and refined the PRF.

The five case study findings were synthesised to develop an Integrated Conceptual Resilience Framework (ICRF). The ICRF combines findings from all five case studies and provides a holistic resilience framework, outlining the principles and features of a resilient UK air transportation system.

Keywords: Resilience Engineering, IRG, System, Setup, Checks, Preparedness, Robustness, Rebound, Extensibility, Changes

ACKNOWLEDGEMENTS

A PhD journey is sometimes described as climbing a mountain. Writing a PhD during COVID-19 has added some additional rockfalls and patches of fog. Despite some setbacks along the way, I shared some amazing moments and climbing the PhD mountain has been an incredibly rewarding experience. I acknowledge that I could not have reached the summit on my own. Thanking everyone individually would be challenging, so I will just mention a few and send out my sincere thank you to all the people that joined me along the journey and shared their experience, passion, and friendship:

Thank you to my wonderful and loving family for supporting me throughout my PhD. For constantly encouraging me to do what I am passionate about and giving me the confidence to go to the UK for my PhD climbing expedition. To my fantastic supervision team for building such a strong rope team that helped me plot a route through the COVID-19 scree and caught me whenever I slipped. Thank you Graham for having the faith to offer me a PhD position at Cranfield, your guidance and providing the necessary climbing gear. Thank you Colin for your constant feedback, patiently reading my draft versions, and making sure I put sufficient bolts in the wall. Thanks to Professor David Denyer and Dr Mehdi Yasaee for watching me from the base camp and checking I am on track. To all the people at the CSAIC and CATM for creating such a fantastic work environment. Thanks to all the colleagues who became good friends over the years and brightened up even the greyest of all British days. To all my friends around the world for the great moments and for making the PhD such a fun time. Special thanks to Jon Proudlove for inviting me to become a member of the IRG, which proved invaluable for the research. Thanks to all the IRG members for sharing their insights and to all the contributing interviewees. Thank you to the CAA, DfT, and Border Force for allowing me to participate in the weekly resilience meetings. Thanks to Professor Hugo Marynissen for introducing me to the maritime industry and guest lecturing opportunities. Thanks to Professor Stephen Flynn and his team for hosting me for five months at the GRI in Boston.

“*The summit is what drives us, but the climb itself is what matters*” (Conrad Anker) and I had the privilege to climb with some amazing people – Thank you everyone!

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LIST OF ABBREVIATIONS

ACL	Airport Coordination Limited
ACOG	Airspace Change Organising Group
AMS	Airspace Modernisation Strategy
ANSP	Air Navigation Service Provider
ATC	Air Traffic Control
ATCO	Air Traffic Control Officer
ATM	Air Traffic Management
BDL	Bundesverband der Luftverkehrswirtschaft e.V.
CAA	Civil Aviation Authority
CCG	Clinical Commissioning Group
CPHMO	Chief Port Health Medical Officer
DfT	Department for Transport
DIM	Duty Incident Manager
EACCC	European Aviation Crisis Coordination Cell
EFPS	Electronic Flight Progress Strip
ESG	Expert Steering Group
ETTO	Efficiency-Thoroughness Trade-Off
EU	European Union
FAA	Federal Aviation Authority
FCO	Foreign and Commonwealth Office
FIR	Flight Information Region
FIS	Flight Information Service
FISO	Flight Information Service Officer
FRAM	Functional Resonance Analysis Method
HRO	High Reliability Organisation
IFISA	International Flight Information Service Association
IATA	International Air Transport Association
IAPH	International Association of Ports and Harbors
ICF	Informed Consent Form
ICRF	Integrated Conceptual Resilience Framework
IMC	Incident Management Centre
IRE	Integrated Resilience Framework

IRG	Industry Resilience Group
LACC	London Area Control Centre
LAG	Local Area Group
LOGN	Lead Organisation-Governed Network
LRF	Local Resilience Forum
LTCC	London Terminal Control Centre
LTMA	London Terminal Manoeuvring Area
MedEvac	Medical Evacuation
NACME	National Crisis Management Executive
NASA	National Aeronautics and Space Administration
NATS	National Air Traffic Services
NAO	Network Administrative Organisations
NHS	National Health Service
NOP2020RP	European Network Operations Plan – 2020 Recovery Plan
NOTAM	Notice to Airmen
OACC	Oceanic Area Control Centre
ODLG	Operations Director Liaison Group
OG	Oversight Group
OIR	Oceanic Information Region
PERL	Plan, Execute, Review, and Learn
PHE	Public Health England
PM	Prime Minister
PPE	Personal Protective Equipment
PRF	Preliminary Resilience Framework
RAG	Resilience Analysis Grid
RE	Resilience Engineering
REA	Resilience Engineering Association
RRU	Restart and Recovery Unit
SARS	Severe Acute Respiratory Syndrome
SARS-CoV-2	Severe Acute Respiratory Syndrome Coronavirus-2
SFP	State Focal Point
SLR	Systematic Literature Review
SPGN	Shared Participant-Governed Network

SPWG	Service Provision Working Group
STAMP	Systems-Theoretic Accident Model and Processes
TC	Terminal Control
VIRG	Voluntary Industry Resilience Group
WAD	Work-As-Done
WAI	Work-As-Imagined
WHO	World Health Organization
WSG	Worldwide Slot Guidelines

1 INTRODUCTION

1.1 Research Background

In order to illustrate how topical this research is, the document starts with a story that was unfolding just as the last words of the thesis were written.

After more than two years of COVID-19-affected air travel, most border entry restrictions were abandoned, and customer confidence to travel returned at the beginning of the summer season in 2022. People were streaming to the UK airports, hoping to go on vacation again since the COVID-19 pandemic hit the country in early 2020. Airlines and airports were looking forward to a strong summer season and recovering some of the severe financial losses of the past two years. The return to some pre-pandemic normality should have been a blessing for the UK air transportation industry, and yet, the industry entered another crisis after the COVID-19 crisis. The situation at the airports was chaotic, with queues at the check-in counters and security so long that passengers sometimes missed their long-awaited flights. Airlines had to cancel flights on short notice, leaving passengers stuck at the airport or abroad (Dollimore, 2022). In fact, the situation has been so dramatic that the government summoned the CEOs of several UK air transportation stakeholders to tackle the current challenges and plan for the rest of the summer (Buckley, 2022).

Several reports (e.g. Bryant, 2022; Dollimore, 2022; Topham, 2022) by the media concluded that there is a lack of resilience or the air transportation industry is not resilient enough to handle the situation – but what does it mean to be resilient in the air transportation system context?

Although it may be expected that multiple factors led to the chaotic situation at the airports, some reports indicated that a significant part of the problem was a lack of resources at various parts of the operation (e.g. Reuters, 2022; Yeginsu, 2022). During the COVID-19 pandemic, the air transportation industry laid off staff to save costs, especially after supporting government retention schemes expired in September 2021 (Harper, 2022). The decision to make staff redundant created an environment where there was not enough workforce in the system to accommodate the rapid increase in air travel after the pandemic. This situation is amplified by the high fragmentation of the air transportation system, which requires a seamless integration of airports, airlines and Air Traffic Control (ATC). Additional supporting actors, such as ground handlers and border force create a complex system and any disruptions within a single stakeholder could have an impact on the overall performance.

The current situation and the claims that resilience is missing in the air transportation industry raise the question of whether resilience is only about having sufficient resources available.

However, it is not the first-time resilience has been used when the air transportation industry was faced with a disruptive event. Andrew Herdman, Director General at the Association of Asia Pacific Airlines, was asked during an interview with Bloomberg Markets and Finance on 9th February 2020 (beginning of the COVID-19 pandemic) about airlines in the Asia Pacific region. He replied with the following: "…*This, of course, is an entirely unpredictable shock to the industry, but we've had similar shocks before, in the past with SARS and so on or other natural disasters. So the industry has a definite strength and resilience and, you know, will recover and recover quickly as and when the circumstances allow…"* (Bloomberg Markets and Finance, 2020). Andrew Herdman used the term resilience in this context as a bouncing back behaviour and that the industry would grow back to pre-pandemic figures. As we have witnessed in the UK air transportation industry, the recovery was hampered. Although circumstances allowed the industry to recover, the industry was not able to fully capitalize on the suspension of border restrictions and the resurgence of passengers' desire to travel.

There have also been other cases where the term resilience was used in the context of the air transportation industry. Following the devastating drone attack at Gatwick airport in December 2018 (BBC, 2018), people also used the term resilience in the context of robustness (CBC, 2018). According to the European Union Aviation Safety Agency (EASA, 2021), the Gatwick event was not the first infringement of a drone at an airport. However, the attack over multiple days had a devastating effect and highlighted how fragile the air transportation system could be to external threats. A sustained attack over multiple days was identified as a new threat. Superintendent James Collies mentioned that "*our activities at the airport continue to build resilience to detect and mitigate further incursions from drones*" (CBC, 2018).

As these examples show, resilience seems to be a term used more frequently in aviation. The academic literature indicates that publications in the Scopus database containing the words "*resilience*" and "*aviation*" significantly increased in the 21st century, as shown in Figure 1-1. This trend raises the question: Why has resilience seen such an increase in attention?

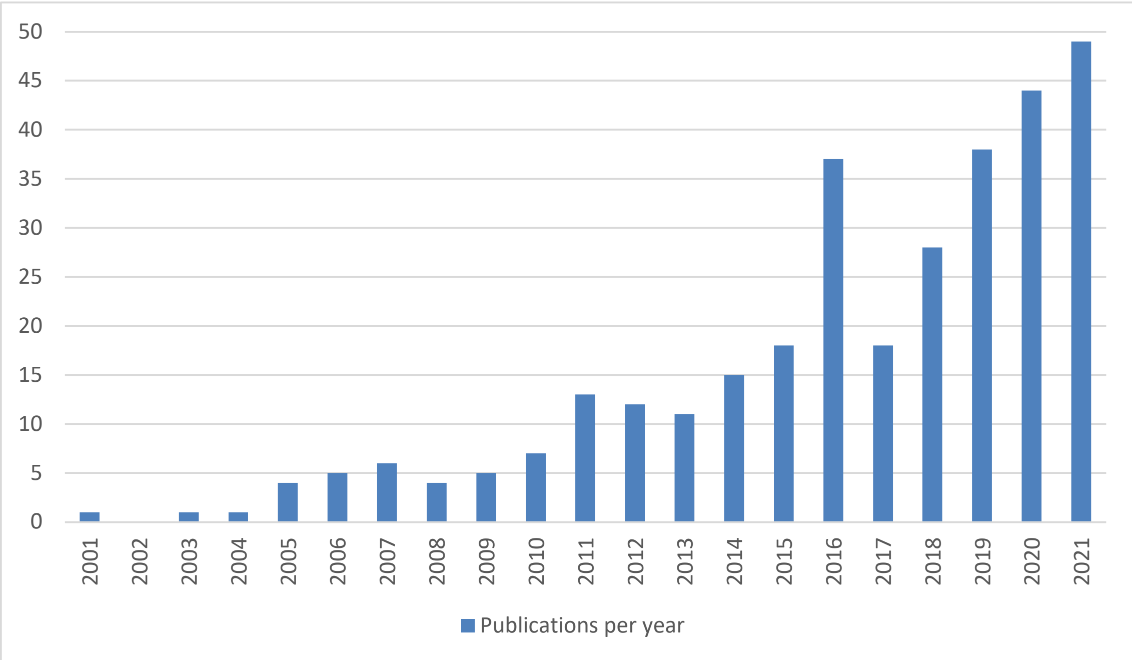


Figure 1-1 Publications with "*resilience*" & "*aviation*" from 2001 to 2021

There may be multiple answers to this question. The following paragraph may be one possible explanation for one of the contributing factors to the increase in popularity of the term resilience in air transportation.

Over decades, humans have built complex, highly sophisticated, and optimized systems. Some key drivers included the desire for higher efficiency, safety, and reliability. However, it appears that the drive for more performance output sometimes compromises the safety element. Professor David Denyer provided one of the pictures that capture this phenomenon. Based on the narrative of his presentation, the researcher made up a photo of the described situation using a raster graphics editor (see Figure 1-2). It shows two rowers paddling at high speed towards the edge of a waterfall. The story is that the two people get so obsessed with performance that they only look back and check how well they are doing with a retrospective view. Just as they think they are doing well (e.g. their speed increases), there is a significant disruption (e.g. they go over the cliff) and conclude in hindsight that they were not resilient enough and therefore had an accident. This example stresses the need to balance multiple system goals (e.g. efficiency vs safety) and identify and mitigate expected disruptions.

Figure 1-2 Performance-driven view

The air transportation industry has had multiple significant, large-scale disruptions in the 21st century that impacted the air transportation market. Examples include the 9/11 attacks in the USA in 2001, the Severe Acute Respiratory Syndrome (SARS) outbreak in Asia in 2003, the Icelandic volcanic ash eruption in 2010, the Gatwick drone attack in 2018, the 737 MAX crisis in 2019, and the latest disruption being the global COVID-19 pandemic. The number of large-scale disruptions in recent times may be one of the drivers for why resilience is more frequently discussed in the air transportation context.

However, resilience in the air transportation industry is not always related to mitigating disruptions and used as a reactive term. In 2017, the UK Civil Aviation Authority (CAA) (2017a, p.8) described resilience in a more proactive way as *“the ability of the UK South East air transport system to operate broadly to plan despite variances that arise during the operational day, to effectively handle disruptive forces when they arise, and to recover rapidly and robustly in the event of disruption”*.

Using the word resilience for different disruptions and as a concept that helps with day-to-day operations shows that the term has been understood differently, and this may be where the problem lies.

1.2 Research problem

Resilience means different things to people. Even though the CAA defined resilience in their report (CAA, 2017a), people in the UK air transportation have different perceptions of how the concept can be operationalised.

At the start of this work, the researcher spoke with several UK air transportation stakeholders’ representatives. During those informal discussions, one interviewee talked about a project that was going on at their airport. This particular organisation realized that its performance would significantly suffer if they were to lose its primary air traffic control system. The person concluded that their organisation was not resilient as it would experience a significant performance reduction in the unlikely event of losing its primary air traffic control system. In another discussion, a different person explained that their organisation was trying to increase their resilience by minimizing the frequency of operational breakdowns. In the first example, resilience was used as a synonym for redundancies, whereas in the second case, it was referred to in the context of reliability.

Throughout this research, the list of synonyms grew. In order to visualize how different the people’s perceptions of resilience were, the researcher summarized all of the synonyms and combined them in Figure 1-3 to build the word *Resilience*. At the end of the research, the list contained 18 synonyms.

Figure 1-3 Experienced synonyms for the term "*resilience*"

Therefore, the research problem was identified as follows. UK air transportation stakeholders saw resilience as a valuable concept for the air transportation industry. However, there was no universal understanding of what resilience meant, how the different views could be integrated and how the concept could be operationalised.

1.3 Definition of the UK air transportation system

The air transportation industry is often referred to as a complex system (e.g. Kumar and Singh, 2020; Rocha, 2017), *“made of people, technology and environment, each of them complex in itself”* (Chialastri, 2009, p.265). The Free Dictionary (2022) defined the air transportation system as “*a transportation system for moving passengers or goods by air*”. According to Teodorović and Janić (2022, p.16), *“the air transport system generally includes airports, ATC (air traffic control) system, and airlines”*.

This research considers the UK air transportation system as the system made up of all the UK stakeholders involved with the end-to-end journey of passengers and goods. This selection includes airlines based in the UK, commercial UK airports, the leading UK Air Navigation Service Provider (ANSP), supporting agencies such as the slot coordinator and ground handlers, and the UK aviation regulator, the CAA. A detailed description of the UK airspace management system and how the main UK ANSP runs it is provided in case study 1.

1.4 Research question and objectives

Based on the previous discussion, this research aims to answer the following research question: *How is the UK air transport industry resilient?*

The research aims to develop a framework that outlines how the concept of resilience can be applied to the UK air transportation industry. The framework aims to represent and suggest a pathway for the UK air transportation industry, to grow and maintain the system's resilience.

Based on this goal, the following four objectives for answering the research question were developed:

- Understand what resilience means. Therefore, a literature review needs to be conducted to identify the elements of a resilient system and clarify the meaning of resilience.
- Use the elements of the literature review to integrate the disparate perspectives on resilience into a PRF.
- Conduct case studies and capture empirical evidence to illustrate ways of resilience in the UK air transportation industry context. Five case studies will be used to collate evidence that generates an empirical application of the basic framework of the literature review.
- Conduct a cross-case analysis. A synthesis across multiple case studies should refine the basic framework and develop an ICRF in the UK air transportation system context.

1.5 Research approach

The primary motivation for the research was to bridge novel academic insight with the air transportation industry and provide practical use to practitioners. The initial screening of the literature and first impression from the air transportation industry indicated that there was no consensus in academia and practice on what resilience is.

Therefore, it was decided to conduct a rigorous literature review to conceptualise the concept of resilience. In order to ensure that the research was not done in isolation without capturing practical insight, it was decided to engage as early as possible with the UK air transportation stakeholders. The UK air transportation industry was already collaboratively working on the system's resilience and set up the Industry Resilience Group (IRG) before the research started. The history and objectives of this working group are explained in a later section of the research (see subchapter 4.2). Immediately after hearing about IRG, the researcher reached out to the working group chair. The researcher was invited to join the IRG and had the first introduction to senior members of the UK air transportation industry one month after the start of the research. The early engagement brought several benefits.

- The regular contact and meetings with the working group and industry stakeholders helped build relationships and trust, which especially became helpful during the data collection phase of the research.
- The relationships allowed the researcher to conduct site visits early on and attend workshops, which helped the researcher become familiar with the UK air transportation industry. The air transportation industry is highly safety conscious. According to Gilberto Lopez Meyer, Senior-Vice President of Safety and Flight Operations at the International Air Transport Association (IATA) (2020, p.1), *"Safety is our [air transport] industry's top priority"*. Also, the Federal Aviation Authority (FAA) (2019) published a statement that "*Safety is the top priority for the FAA*". Visiting several operation centres of UK air transportation stakeholders re-emphasized the desire of the aviation stakeholders to achieve the highest safety standard possible. Those visits helped the researcher understand how resilience was used in this safety-driven context. It also highlighted the expectation of the practitioners towards the concept.
- The insights and experiences from engaging closely with the industry also supported the selection process for the most appropriate literature, as shown in the literature review (see section 2.1.5).
- The constant engagement with industry also ensured that the research captured the resilience challenges discussed by industry, which ensured

the practical application of the outputs and gave unrivalled access to data for the case studies.

1.5.1 Conducting research during COVID-19

Writing a PhD thesis about resilience in the air transportation industry during a global pandemic was both a curse and a blessing.

Needless to say, the outbreak of COVID-19 at the beginning of the second PhD year severely disrupted the research. Due to the lockdown measures and the devastating impact of the pandemic on the air transportation industry, the original data collection was no longer possible, and the research design had to be revised. Restructuring the research added additional pressure to an already stressful environment, in which lockdown measures put people in isolation, and the global situation created general uncertainty and anxiety. However, the research was inspired by a quote from Albert Einstein: *"In the middle of every difficulty lies opportunity"*.

The impact of COVID-19 caused the biggest crisis in commercial air traffic (Brzeska, Borowski and Kozuba, 2020). The researcher had to be adaptive and create a new research design to accommodate the global pandemic's changes. Those adjustments caused some limitations, as listed in the discussion subchapter (see subchapter 5.7). On the other hand, collecting data during this unique time generated fascinating insight, as shown in case studies 4 and 5. The researcher had the opportunity to witness how the UK commercial air transportation industry responded to a large-scale disruption it had never experienced before. Although living and working through the pandemic created some additional challenges, it provided some unique and rare insight.

1.6 Research structure

In order to structure the reporting of the research, the thesis is divided into six chapters.

Chapter One lays out the background of the research and outlines some of the resilience challenges observed in the air transportation industry. It also shows the motivation for the research and introduces the research goal and objectives. Furthermore, the first chapter describes the approach taken to meet the objectives and points out some challenges encountered due to the COVID-19 pandemic.

Chapter Two investigates the academic literature on resilience and establishes a focus area of the resilience literature for this research. The Resilience Engineering (RE) literature was reviewed systematically to understand the concept of resilience. Reviewing the literature showed that the blurred vision of the concept of resilience is not just a phenomenon in the air transportation industry but also exists in the academic literature. The literature was analysed to identify high-level principles of a resilient system. In order to structure the literature and conceptualise resilience, a PRF was proposed and used to categorise the various contributions.

Chapter Three outlines the methodology adopted to conceptualise resilience in the UK air transportation industry context. It explains how exploratory qualitative research was used to build detailed narratives for five cases in the UK air transportation industry. The cases were then analysed using thematic analyses to bridge the empirical data with the outputs of the literature review. The third chapter also includes two practical examples of how the methodology was used in each case study.

Chapter Four contains the five case studies and their findings. The chapter is divided into five major sections, and each of the sections represents a separate case study. Each case study is introduced separately with background information and individual objectives. The sections also explain the design of each case study. This explanation includes which methods were deployed to collect the data and achieve triangulation of multiple data sources.

Each section contains an extensive description of the individual case, followed by a discussion sub-section. These discussions cover what elements of the resilience themes proposed at the end of the literature review could be observed. They also outline how the findings of the individual case study were used to add details to the PRF as a first step towards building an ICRF.

Chapter Five includes the overall discussion of the research. The chapter re-emphasises the rationale for the ICRF. The discussion chapter uses the outputs of all the individual discussion sub-sections in chapter four to propose the ICRF. The ICRF is a synthesis of all the outputs from the case studies used to refine the basic framework from the literature review. It is shown how the PRF evolved based on the findings of the case studies. Each of the resilience-generating themes is briefly explained again, and the connections that link the themes are highlighted.

The discussion chapter also describes the research view of resilience and how resilience is defined based on the ICRF. It ends with recommendations for practice and suggestions for further research based on the researcher's identified limitations.

Chapter Six concludes the thesis by giving some final remarks. It also highlights the main contributions of the research.

2 SYSTEMATIC LITERATURE REVIEW

The objectives of the thesis were to conceptualise resilience and identify properties of a resilient system, generate empirical evidence by conducting case studies in the UK air transportation industry, and use the outputs of the case studies to develop an ICRF.

The goal of reviewing the literature was to outline the concept of resilience, propose a PRF to define resilience themes, categorize existing literature according to the proposed framework and identify the principles of each theme.

The initial search for "*resilience*" in the Scopus database, the largest abstract and citation database for peer-reviewed literature, returned over 125,000 results. Hence, it was pivotal to construct a methodology allowing an efficient and sufficiently thorough review of the literature for the thesis. Tranfield, Denyer and Smart (2003) highlighted the importance of reviewing the literature for any kind of research. The literature review should meet the criteria of transparency, inclusivity, explanatory and heuristic nature (Denyer and Tranfield, 2009). In order to meet Denyer's and Tranfield's (2009) criteria, a two-stage systematic literature review (SLR) was applied.

2.1 Stage 1: Establishing a focus area of resilience literature

The goal of the first stage of this SLR is to obtain an overview of the resilience literature and understand how the concept was applied in various disciplines and domains. The outputs from stage one were used to establish a focus area of the resilience literature for the second stage.

2.1.1 Methodology

In the first stage, the database of Scopus was searched using the search criteria "*resilience* AND *literature review*" for title, abstract and keywords for any contributions before 2020. Literature reviews establish an understanding of research in a particular domain and "*provide a reference point for mapping a field of study and form the baseline for developing theoretical contributions*" (Patriotta, 2020, p.1272). Therefore, the string "*Literature review*" was included in the search criteria. Furthermore, only journal articles and reviews were included in the data set to focus on peer-reviewed literature. The initial data set contained 842 contributions. Figure 2-1 outlines the process used for Stage 1 of the SLR methodology.

After a title screening, 563 items were removed. An abstract screen of the remaining 279 papers excluded a further 253 documents.

Papers were excluded if:

- Their main focus was not on the concept of resilience.
- The paper did not define how the concept was applied in a specific discipline(s).

The remaining 26 papers were studied in full. A list of all 26 included papers is provided in Appendix A.

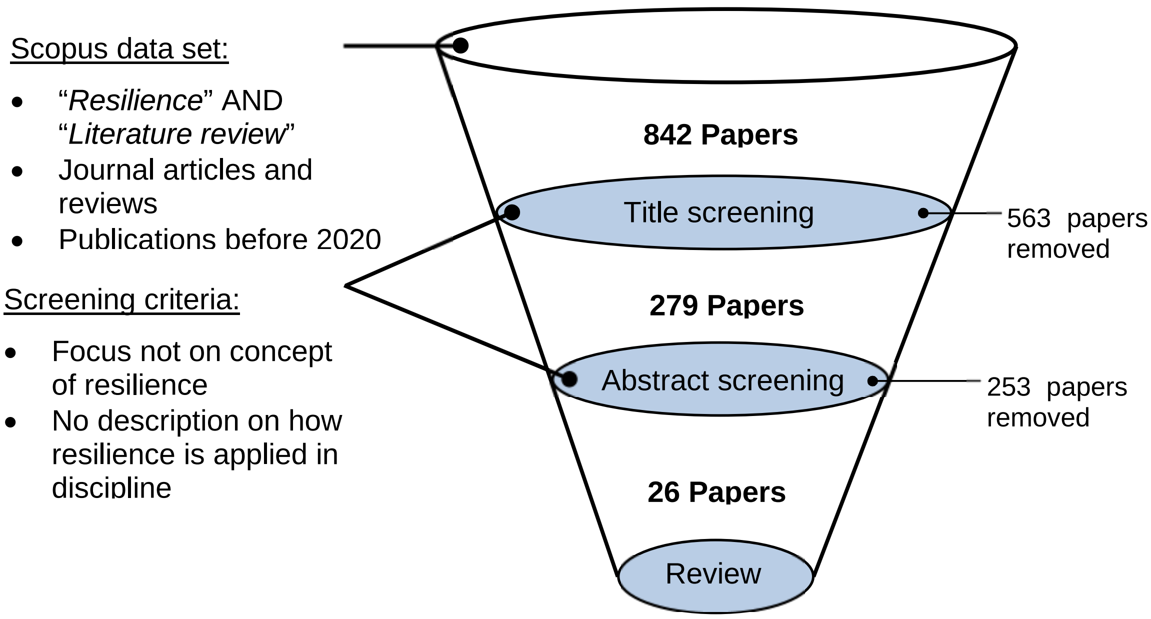


Figure 2-1 Methodology of Stage 1 of Systematic Literature Review

2.1.2 Overview of the concept of resilience

Over the last three decades, contributions containing the word "*resilience*" in title, abstract and keywords have seen a steep increase from 111 published contributions in 1990 to over 16,000 in 2020, as seen in Figure 2-2.

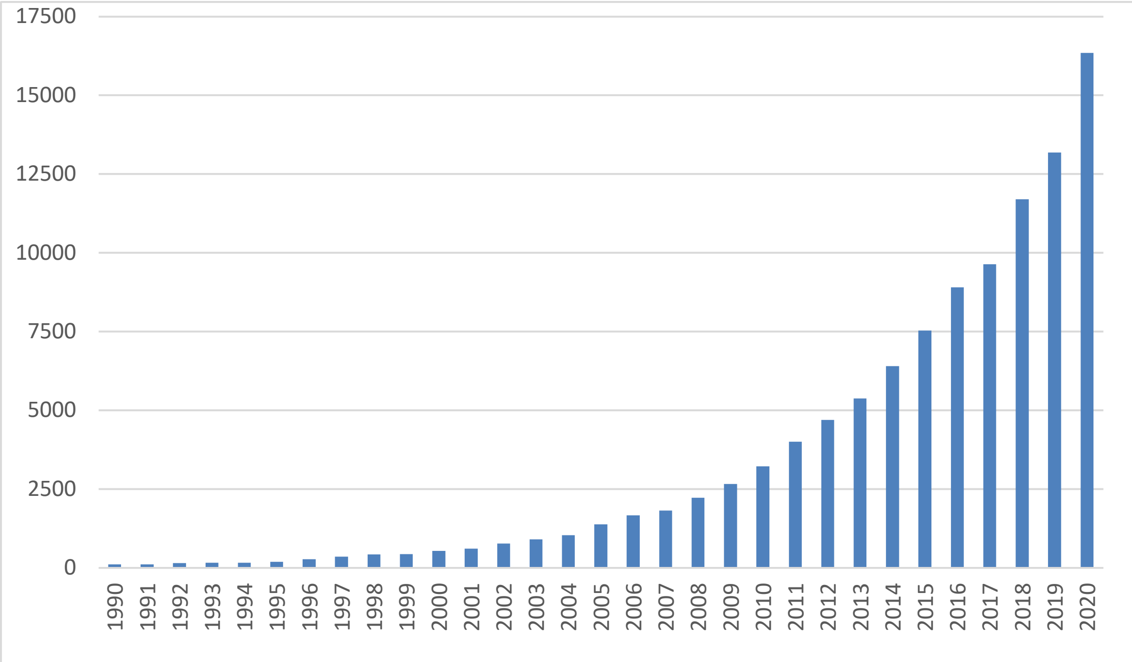


Figure 2-2 Publications with "*resilience*" from 1990 to 2020

Even though the interest in resilience is exponentially growing and the concept is considered promising, it has also been disapproved for its lack of a consistent definition. According to Burnard and Bhamra (2011), the lack of consistent definition has limited the use of the concept for research and practice. Several authors questioned even the novelty of the concept and see resilience as a reiteration of existing schools of thought in the safety literature (Hale and Heijer, 2006a; Hopkins, 2014). Some authors, on the other hand, acknowledged that resilience shares many similarities with several existing concepts (Azadeh et al., 2015; Cai et al., 2018) but saw resilience as more of a *"family of related ideas"* (Westrum, 2006, p.65). Righi, Saurin and Wachs (2015) reiterated the need for clarity on the resilience theory and positioning of the concept within existing theories. With reference to Rose's (2007) work, Davoudi, Books, and Mehmood (2013, p.307) argued that "*resilience is a contested* *concept, which is in danger of becoming a vacuous buzzword as a result of its overuse and ambiguity*". Podsakoff, MacKenzie, and Podsakoff (2016, p.166) disputed that "*a lack of conceptual clarity causes a number of problems – both at the conceptual and the operational levels*". Therefore, it is of great importance to integrate different conceptualisations of resilience to provide the required conceptual clarity.

The following SLR analyses the resilience literature, provides an overview, showed overlaps with existing concepts, and defines the concept of resilience for this thesis. Looking at the history of the word resilience and how the word has evolved may help to explain the lack of consistency in definitions and the multifaceted nature of the concept.

2.1.3 History of the word resilience

The word resilience has been in our vocabulary for a long time and has developed and been used in several different ways, which explains the diversity in definitions.

Resilience has its root in Latin, and "*resilire*" and "*resilio*" mean "*bounce*" and "*jump back*" (Alexander, 2013b). It was first used by Seneca the Elder in the sense of "*leaping*". Moving on to the mid-1500s, the meaning of the word changed to "*retract*" or "*cancel*", translated from the French word "*résiler*". When the term travelled across the channel to England (resile), the meaning changed back to the original use of "*returning to a former position*" (Alexander, 2013b).

Sir Francis Bacon was the first person who used the term in a scientific context in the 17th century for the strength of echoes (Alexander, 2013b). The word "*resilement*" can be found in Thomas Blount's dictionary in 1656, where it was described as "*rebound*" and "*go back on one's work*" (Alexander, 2013b). Tredgold (1818) used the term resilience to analyse the characteristics of timber and explain why some woods could cope with sudden and significant stress without breaking.

While resilience was mainly used for rebounding in the first half of the nineteenth century, Bell extended the meaning in 1839 when using "*resiliency*" as a synonym for "*fortitude*" in response to adversity and withstanding challenges (Bell, 1839). After a series of seismic events, resilience was used to cope with the effects of earthquakes (Tomes, 1857). Tomes (1857) highlighted the Japanese people's adaptive capacity as displaying resilience following the earthquake and tsunami sequence in Shimoda in 1854. In the construction industry, the meaning from material science was adopted, and the first serious use was in 1858 by Rankine when he described the strength and ductility of steel beams (Rankine, 1867). The main attributes of a resilient steel beam were rigidity and ductility.

The meaning of resilience was then further expanded to ecology (Holling, 1973; Walker et al., 2004) and health science (Almedom and Glandon, 2007). Organisational science also integrated the term (Linnenluecke, 2017). Today, the concept of resilience has gained popularity in a number of disciplines where it was even adopted by societal security (Hornborg, 2013), climate change adaptation (Schmidt, 2013), political theory (Evans and Reid, 2016), healthcare (Allmark, Bhanbhro and Chrisp, 2014) and organisational management (Duchek, 2020).

Depending on the context, the concept of resilience can also have different meanings, attributes, and goals (Holling, 1996). Its original meaning of jumping back is still frequently used when people discuss how systems need to be able to rebound after events (e.g. Cedergren, 2013; Hale and Heijer, 2006a; Henry and Ramirez-Marquez, 2012). In contrast to this is the word's meaning in the context of overcoming the risk of adversity and the ability to handle sudden shocks (Kolar, 2011) and fortitude (Bell, 1839). Definitions by Tredgold (1818) and Holling (1973) added the characteristics of flexibility and adaptability to the term.

2.1.4 Resilience as a versatile concept

The concept of resilience is interdisciplinary (Xu and Kajikawa, 2018) and can be applied at different levels (Korber and McNaughton, 2017; Ma, Xiao and Yin, 2018). The interdisciplinary nature of the concept is shown by the number of domains adopting the term resilience and investigating different aspects of resilience. Therefore, the literature on resilience is fragmented, and multiple, sometimes contrasting definitions of resilience were given (Bhamra, Dani and Burnard, 2011). "*There is no universal definition of resilience adopted in the research literature"* (Aburn, Gott and Hoare, 2016, p.980) as resilience is a *"multi-faceted concept that is adaptable to various uses and contexts but in different ways"* (Alexander, 2013b, p.2714). Table 2-1 summarizes some of the definitions of resilience.

Table 2-1 Sample of definitions for resilience

Domain	Definition of resilience
Resilience Engineering	Resilience is the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions (Hollnagel, 2011a)
Social-ecological system Resilience	Ability of the system to maintain its identity in the face of change and external shocks and disturbances. (Cumming et al., 2005, p.976)
Critical infrastructure Resilience	Vital societal functions, and thus infrastructures, must be restored or adapted as quickly as possible. This capacity refers to the concept of resilience. (Curt and Tacnet, 2018, p.2442)
Psychological Resilience	It is a dynamic process evolving over time that implies a type of adaptive functioning that specifically allows us to face difficulties by recovering an initial balance or bouncing back as an opportunity for growth. (Sisto et al., 2019, p.14)
Supply chain Resilience	The adaptive capability of a supply chain to prepare for and/or respond to disruptions, to make a timely and cost effective recovery, and therefore progress to a post-disruption state of operations – ideally, a better state than prior to the disruption. (Tukamuhabwa et al., 2015, p.5599)
Material Resilience	Resilience is used as synonym of robustness for a part or a material that can withstand with high loads without fracturing…material resilience in engineering represents its capability of absorbing energy elastically. (Negrello et al., 2019, p.8374)
Food system Resilience	Resilience is a characteristic of complex and interrelated social–ecological systems that provides the system with the ability to absorb perturbations and also with the capacity to benefit from change through generating opportunities for development and innovation (Prosperi et al., 2016, p.7)
Transport System Resilience	Resilience is the ability of a transportation system to absorb disturbances, maintain its basic structure and function, and recover to a required level of service within an acceptable time and costs after being affected by disruptions. (Wan et al., 2018, p.489).
Urban Resilience	Urban resilience refers to the ability of an urban system-and all its constituent socio-ecological and socio-technical networks across temporal and spatial scales-to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity. (Meerow, Newell and Stults, 2016, p.39)
Community disaster Resilience	Resilience is acceptably defined as the ability of social units, e.g. organisations, communities to mitigate hazards, contain the effects of disasters when they occur and carry out recovery activities in ways that minimise social disruption, and mitigate the effects of future disasters (Adeyeye and Emmitt, 2017, p.495)

According to Bhamra, Dani and Burnard (2011), the term resilience was first popularised in ecology by the Canadian ecologist Crawford Stanley Holling in 1973 with his publication *“Resilience and Stability of Ecological Systems”* (Holling, 1973). His definition of resilience greatly influenced the use of resilience in ecology as the ability to *“absorb change without dramatically altering”* (Holling, 1973, p.7). He further described the sudden collapse of the systems when being pushed beyond their boundaries. He saw resilience as “*a measure of the persistence of systems and the ability to absorb change and disturbance and still maintain the same relationships between populations or state variables*.” (Holling, 1973, p.14). Resilience in this context points to the existence of one or more stable states and the basin of attraction and size of the valley around a stable state as shown in Figure 2-3.

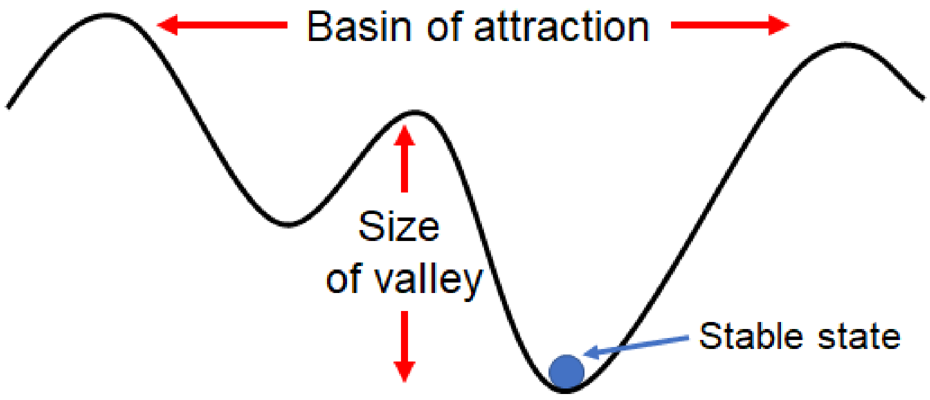


Figure 2-3 Ecological Resilience

The size of the valley resembles the maximum perturbation that can be absorbed before causing a shift to an alternative stable state (Scheffer et al., 2001). A loss of resilience results in a more fragile system where perturbations can easily cause the system to move into a catastrophic state. Holling’s (1973) work formed the foundation for the concept of ecological resilience.

Holling (1973) emphasised that resilience describes maintaining a stable state and acknowledged that they might be more than one equilibrium. On the other hand, resilience was sometimes seen as the ability to return to the original function (e.g. Schack and van den Essen, 2014). Seeing resilience as the rebound and return to the previous state relates to the stress-stain model. In material science, resilience is defined as *“the ability of a material to absorb energy under elastic deformation and to recover this energy at removal of load”* (Vegas and Del Yerro, 2013, p.923). Resilience in material science is used as one of the mechanical properties of all structural materials alongside material strength, ductility, creep resistance, and fracture toughness (Yvon and Carré, 2009).

A milestone for resilience in the context of social science was set by Luthar, Ciccetti and Becker (2000) with their critical appraisal of resilience to understand better the processes affecting at-risk individuals and how children overcome unfavourable circumstances. They defined resilience as a *“dynamic process encompassing positive adaptation within the context of significant adversity”* (Luthar, Cicchetti and Becker, 2000, p.543). With 4,015 citations in Scopus, it is one of the most frequently cited papers in the entire resilience literature. Therefore, the developmental literature commonly discusses resilience as a factor that promotes the development of healthy personality characteristics of children exposed to unfavourable or aversive life circumstances (Masten, 2001). Resilience in psychology was also used to describe the ability of adults to deal with an isolated and disruptive event, such as a life-threatening situation or the death of a close relative and maintain a stable equilibrium (Bonanno, 2004). However, resilience was not only applied to individuals but also small groups (Zemba et al., 2019) and communities (Oliveira and de Morais, 2018). Adger (2000, p.347) described social resilience *“as the ability of groups or communities to cope with external stresses and disturbances as a result of social, political and environmental change”*.

Another use of resilience in sociology was the ability of a social unit to contain the impact of a disruption, conduct recovery activities to minimise social disruptions and prepare for future earthquakes (Bruneau et al., 2003). Furthermore, there is an increasing tendency to investigate how work teams contribute to the overall performance of an organisation and how better collaboration strengthens the organisation’s resilience (Rodriguez-Sanchez and Vera, 2015). Urban Science has also adopted the term for complex socio-technical systems and their management to investigate resilience in an urban context (Bozza, Asprone and Fabbrocino, 2017; Meerow, Newell and Stults, 2016). Resilience in an urban science context was described as the ability to absorb and recover from shocks and restore equilibrium.

Resilience was also used in computer science when describing the operation of large networks such as the internet (Cohen et al., 2000) but also for designing hardware using an error-resilient system architecture that ensures a reliable operation despite faults (Cho, Leem and Mitra, 2012). In the network literature, resilience was further used for transportation networks (Ilbeigi, 2019; Ta, Goodchild and Pitera, 2009; Wan et al., 2018), supply chains (Hohenstein et al., 2015; Kochan and Nowicki, 2018), critical infrastructure (Curt and Tacnet, 2018), such as electricity, gas and roads (Rehak, Senovsky and Slivkova, 2018) and water distribution (Prasad and Park, 2004). Network resilience was commonly referred to as the ability to understand the impact of external influences, maintain functionality despite shocks (Whitson and Ramirez-Marquez, 2009) and recover to a desired level of performance (Barker, Ramirez-Marquez and Rocco, 2013). On the other hand, the civil infrastructure literature highlighted that resilience is used for addressing *"both sudden onset and slow onset disruptive events"* (Gay and Sinha, 2013, p.332), implying that resilience is both a continuous, dynamic process and a rapid response (Datta, 2017).

Nowadays, resilience is also frequently used in the management literature in various settings. Vogus and Sutcliffe (2007) defined resilience as positive adjustments during both disruptions and ongoing risks so that the organisation is stronger and more resourceful. Ma, Xiao and Yin (2018, p.255) highlighted that organisational resilience *"emphasizes on survival, adaptability, the ability to bounce back and improvement under disruptive situations"*. The term resilience has been used for all sorts of organisations, including enterprises (Branzei and Abdelnour, 2010), start-ups (Aldianto et al., 2021) and family businesses (Amann and Jaussaud, 2012). Some studies focussed on the operational aspect of resilience (Essuman, Boso and Annan, 2020). In contrast, others investigated the financial aspect and referred to financial resilience as *"the ability to access and* *draw on internal capabilities and appropriate, acceptable and accessible external resources and supports in times of financial adversity"* (Muir et al., 2016, p.5). Furthermore, the term resilience is also famous in the safety domain for adapting to emerging risks and keeping a system safe (Bergström, van Winsen and Henriqson, 2015) and in risk, emergency and disaster management (Demiroz and Haase, 2019; Manyena, Machingura and O'Keefe, 2019). In 2003, Woods (2003) introduced the term RE for managing the safety of complex socio-technical systems and as a way to engineer resilience into systems. The core of RE was dealing with a system's complexity and managing production goals and safety (Patriarca et al., 2018a), adding yet another element to the concept of resilience. Madni and Jackson (2009, p.187) summarized the variety in the conceptualisation as follows: "*Resilience is a semantically overloaded term in the sense that it means somewhat different things in different fields*".

2.1.5 Focus of literature review

As outlined in the previous sections, resilience is a context-dependent term used in various domains. Son et al. (2020, page not identified) argued that *"existing reviews focused mostly on summarizing various definitions ('what is resilience?') and application areas ('how is resilience used?') with limited attention to documenting constituent dimensions of resilience ('what makes a system resilient?')"*.

Therefore, the thesis aims to generate a holistic view of resilience for the air transportation industry and define what a resilient air transportation system looks like. The idea for the literature review was to focus on a specific section of the resilience literature and conduct an in-depth review to build the foundation for conceptualising resilience in the UK air transportation industry context. Focussing the literature review on results for either "*Critical Infrastructure Resilience*", "*Network Resilience*", or "*Supply Chain Resilience*" seemed appropriate. The air transportation system is a critical infrastructure and forms a network of multiple interconnected organisations. Looking at the passenger journey and how airports, ground handlers, airlines and ATC services interconnect, the air transportation system could also be considered a supply chain.

However, during site visits and discussions with multiple people from air transportation stakeholders, it became apparent that there was a great interest in understanding how resilience applies to a system that is heavily driven by achieving the highest level of safety. As shown in the previous section, RE was the only resilience literature that explicitly mentioned the connection between the concept of resilience and safety. Furthermore, contributions also discussed how safety could be balanced with other system properties (Tian, Lin and Wang, 2020). Therefore, RE seemed to be a highly suitable term for several reasons.

First and foremost, safety is crucial to the air transportation industry, as emphasised in the introduction (see subchapter 1.3). In addition, the air transportation industry was referred to as a complex system (Kumar and Singh, 2020; Rocha, 2017), *"made of people, technology and environment, each of them complex in itself"* (Chialastri, 2009, p.265) and the environment of air transportation was described as a high-risk environment (Brady and Goldenhar, 2014). Hale and Heijer (2006b, p.125) argued that in RE, resilience is also *"discussed as a desirable attribute of organisations in managing safety in complex, high-risk environments"*. This view on resilience appeared to be a promising term which shows how the concept of resilience can be applied to the operation of complex systems, such as the air transportation industry.

Moreover, RE applies the concept of resilience to different levels in operation (Righi, Saurin and Wachs, 2015) and investigates how these levels interrelate (Bergström and Dekker, 2014). With RE also being *"a paradigm for safety management that focuses on how to help people cope with complexity under pressure to achieve success"* (Woods and Hollnagel, 2006, p.6), it includes not only the focus on how individuals in an organisation can be supported but also how the concept applies to organisations to achieve a more resilient operation (Pillay, 2016) and how a resilient organisation contributes to the overall resilience of a system (Mendonça and Wallace, 2015). Furthermore, contributions to RE include aspects of supply chains (Bukowski and Feliks, 2012), online retailing (Azadeh et al., 2018), networks (Amodeo and Francis, 2019), emergency management (Borell, 2015) and critical infrastructure resilience (Curt and Tacnet, 2018). Therefore, focussing on the RE literature seemed to be the most promising choice for this research. The decision was taken to limit the literature to contributions containing the term “*resilience engineering*”.

2.2 Stage 2: Analysing the Resilience Engineering literature

The term Resilience Engineering was first introduced in 2003 by Woods (2003) for managing the safety of complex socio-technical systems. RE is still “*a relatively new paradigm for safety management that focuses on how to cope with complexity under pressure or disturbance to achieve success, addressing the limitations of existing safety analysis measures*” (Kim et al., 2018).

One core of RE is dealing with a system's complexity and simultaneously managing production goals and safety (Patriarca et al., 2018a). Hence, RE is concerned with helping people cope with the complexity of a system while being under pressure to achieve success (Woods and Hollnagel, 2006). RE can also bring a higher level of safety and success to a system (Havinga, Dekker and Rae, 2018).

However, RE also includes reactive elements and describes how systems deal with disruption and enhance performance (Salehi and Veitch, 2020). It is essential to mention that RE is not just a concept for ultra-safe sectors but also applies to non-safety-critical but hazardous occupations such as construction, fishery or agriculture (Harvey, Waterson and Dainty, 2019). The concept provides a holistic view of complex adaptive systems and explains how interacting elements adapt, adjust and reinforce each other when responding to emerging forces (Ray-Sannerud, Leyshon and Vallevik, 2015).

In conclusion, RE building resilience into complex systems. A system is considered resilient when it can *“adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions”* (Hollnagel, 2011a, p.xxxvi). Therefore, the literature review focused on how systems can integrate the concept of resilience to achieve a resilient operation.

Upon screening the RE literature, it became apparent that the concept of resilience is blurred even in the context of RE. Some authors saw the concept as a continuous and proactive strategy to keep the system within its safe boundaries (Hale and Heijer, 2006a) or used it to identify or anticipate dangerous developments (Dolif et al., 2013). Other contributions focused on the reactive side and used the concept of recovering the operation and bouncing back from disruptions (Grabowski and Roberts, 2019). Some contributions linked the sustainability element with resilience and used the concept for adjusting the operation to meet expected future demands or challenges (Davoudi, Brooks and Mehmood, 2013). This variety of ideas shows that people view the concept of resilience differently and various, sometimes contradicting, perspectives of resilience exist (Madni and Jackson, 2009).

2.2.1 General characteristics of a resilient system

Describing key characteristics of a resilient system has drawn a high interest in the RE literature (Patriarca et al., 2018a). Costella, Saurin and de Macedo Guimarães (2009, p.1057) argued that "*there is no one set of RE principles which is widely accepted in the academic circles*". Their study identified top management commitment, flexibility, learning, and awareness as RE principles.

Even though there is not a set of universally agreed indicators or characteristics (Ranasinghe et al., 2020), Wreathall (2006) and Azadeh et al. (2014b) defined lists of items frequently referred to by other researchers. Although other authors use slightly different lists (e.g. Jain et al., 2018; Penaloza, Saurin and Formoso, 2020; Thomas et al., 2019; de Vries, 2017; Wahl, Kongsvik and Antonsen, 2020), these two contributions appeared to be used frequently by other studies (see Table 2-2).

Table 2-2 Sample of characteristics of a resilient system

	Top-level commitment	Just culture	Learning culture	Awareness	Preparedness	Flexibility	Opacity	Self-organisation	Teamwork	Redundancy	Fault tolerance
(Wreathall, 2006)	✓	✓	✓	✓	✓	✓	✓				
(Azadeh et al., 2014b)	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓
(Asadzadeh, Maleki and Tanhaeean, 2020)	✓	✓	✓	✓	✓	✓					
(Pillay and Morel, 2020)	✓	✓	✓	✓	✓	✓					
(Salehi and Veitch, 2020)	✓	✓	✓	✓	✓	✓					
(Salehi, Veitch and Musharraf, 2020)	✓	✓	✓	✓	✓	✓			✓	✓	
(Taghi-Molla et al., 2020)	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓
(Shirali and Nematpour, 2019)	✓	✓	✓	✓	✓	✓	✓				
(Zarrin and Azadeh, 2019)	✓	✓	✓	✓	✓	✓				✓	
(Azadeh, Yazdanparast and Zadeh, 2018)	✓	✓	✓	✓	✓	✓				✓	
(Rubio-Romero et al., 2018)	✓	✓	✓	✓	✓	✓	✓				
(Azadeh, Salmanzadeh-Meydani and Motevali-Haghighi, 2017)	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓
(Fernandes, Hurtado and Batiz, 2015)	✓	✓	✓	✓	✓	✓					
(Azadeh and Salehi, 2014)	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓
(Shirali, Mohammadfam and Ebrahimipour, 2013)	✓	✓	✓	✓	✓	✓	✓				
(Grecco et al., 2012)	✓	✓	✓	✓	✓	✓					
(Saurin and Carim Júnior, 2011)	✓		✓	✓		✓					
(Costella, Saurin and de Macedo Guimarães, 2009)	✓		✓	✓		✓					

Wreathall (2006) was one of the first to start a list of resilience principles. He described top-level commitment, just culture, learning culture, awareness, preparedness, flexibility, and opacity as the seven capabilities of a highly resilient system.

Top-level commitment is achieved when senior managers recognize and address the challenges and problems of people. This attitude for proactive, timely and continuous investigation of safety and resource allocation values human performance and its significance to the system.

Just culture supports the workers' willingness to report problems and issues. Without a just culture, the system's ability to learn from weaknesses in its defences is limited.

Learning culture describes the ability of a system to implement lesson learning and not respond to events with denial. Learning opportunities can also be created by investigating and reporting everyday work.

Awareness of the human performance quality, its implication on the system and the current defensive state are generated for management by data gathering.

Preparedness is a system's feature to actively anticipate challenges and problems arising from human performance and safety issues and prepares a response to mitigate them.

Flexibility allows a system to adapt to and self-organise when faced with new and complex issues, and the system is trying to solve them without disrupting its overall functionality. This approach requires a structure where people at the operational level can make judgements and decisions without waiting for the managers' instructions.

Opacity describes the awareness of a system to know its boundaries and how close the operation is to them when defences and barriers degrade.

Azadeh et al. (2014b) suggested adding four items and expanding Wreathall's (2006) list by including self-organisation, teamwork, redundancy, and fault-tolerance. However, they did not include opacity as a separate resilient capability of a system and combined opacity with awareness.

They labelled their list as an Integrated Resilience Engineering (IRE) framework. The IRE aims to improve the performance of human resources and safety in a system, and RE plays a vital role in the performance of a system (Azadeh, Salehi and Kianpour, 2018). Furthermore, it was shown that IRE could positively impact the system's efficiency (Azadeh, Roudi and Salehi, 2017).

Self-organisation refers to the ability of a system to create order by actions taken by interdependent agents instead of an overall plan imposed by a central authority. Interdependent agents exchange information, take actions and adapt to other agents' actions unceasingly.

Teamwork consists of communication, leadership, mutual support, and situation monitoring. A high workload of systems can increase the pressure on individuals, potentially leading to error and decreasing the system’s reliability. Teamwork can release this pressure through mutual support and assistance, leading to a higher level of safety, and good workplace relationships can positively impact resilience (Novak et al., 2017).

Redundancy supports a system in achieving its intended performance by ensuring an alternative pathway when components become unavailable.

Fault tolerance describes the capability of a system to maintain a specified performance when errors occur. Systems must therefore have the ability to adapt and compensate when a failure occurs in a part of a system.

However, Table 2-2 also highlights that none of the studies takes a holistic view and combines all of the characteristics in their studies. Shirali, Shekari and Angali (2016) extended the list even further and defined a total of thirteen resilience factors: just culture, management of change, learning culture, risk assessment/management, preparedness, flexibility, reporting culture, management commitment, awareness, safety management system, accident investigation, involvement of staff, competency.

As mentioned in section 2.1.3, Woods (2003) was the person who introduced the term RE in his analysis of the National Aeronautics and Space Administration’s (NASA)’s Columbia accident. The initial literature screen also looked at the resilience characteristics he defined. Woods (2003) identified five patterns that contributed to the fatal accident and loss of the space shuttle. He concluded the analysis with three basics of RE that a resilient system needs to have.

Firstly, it must be able to detect indicators of increasing organisational risk. Secondly, it must have the authority and resources to issue extra investments in safety in times when this seems to be the least affordable. The last essential characteristic is that the system can recognize where and when to invest in a targeted manner to re-balance the production and safety trade-offs and counteract the leading indication of organisational risk.

Hollnagel (2009a) attempted to include Woods' (2003) findings in broader terms when he defined resilience with four cornerstones. These four cornerstones are monitoring, anticipating, responding, and learning. According to Hollnagel (2009a), the four cornerstones are essential to growing and maintaining resilience. Each cornerstone must capture what happens in the environment and in the system itself (Hollnagel, 2014a), and a system needs all four resilience abilities (Apneseth, Wahl and Hollnagel, 2013).

> **Monitoring** describes the ability to monitor what is going on. It includes tracking the system's performance, monitoring what happens outside the system's boundaries in the environment and handling early warning signs and leading indicators. It should enable the system to detect the emergence of unwanted developments and react quickly to changes. Monitoring is part of the regular operation and during the response phase.
>
> **Anticipation** is related to foresight and the ability to anticipate risky events. It uses the information from the monitoring to foresee how they might develop into an unsafe state, which can prevent deviations from turning into accidents. Anticipation allows a system to prepare for future events, mainly supporting entities with limited resources to identify bottlenecks ahead and reallocate their resources or prepare the system for disruption.
>
> **Responding** describes the reaction to disturbances, changes but also opportunities. In order to achieve the best possible outcome, the response must be timely and effective. A system can either have prepared resources or responses available or is flexible enough to reconfigure its structure in the event of a surprise.
>
> **Learning** is the ability of a system to analyse how it performed during an event and take away the appropriate lessons. Identifying what went wrong and what went right strengthens a business's performance and prepares it for future disruptions. The ability to learn also includes updating the risk

assessment, which helps systems anticipate how environmental changes may affect the response to events (Vogus and Sutcliffe, 2007).

The four cornerstones build the foundation for Hollnagel's (2011b) Resilience Analysis Grid (RAG). The RAG is a questionnaire that can measure the potential for resilience in a system and to what extent the four cornerstones are present. Examples of domains in which the RAG has been used included the oil and gas industry (Apneseth, Wahl and Hollnagel, 2013), maritime industry (Praetorius, Hollnagel and Dahlman, 2015; Praetorius and Hollnagel, 2014), construction industry (Penaloza, Saurin and Formoso, 2020) and the work of an emergency department (Chuang et al., 2020). Mentes and Turan (2019) showed how the four cornerstones apply to Offshore Wind Turbine maintenance operations.

Some scholars also referred to the cornerstones in sensing, anticipating, adapting and learning (Thomas et al., 2019). In addition, authors added characteristics to the four cornerstones, such as self-monitoring and recovery (Lundberg and Johansson, 2015) or communication and coordination (Hegde et al., 2020), to highlight specific objectives of their research.

When describing the concept of community resilience, Becker et al. (2011) took a similar approach to Hollnagel by stating that a system needs to have enough capacity to anticipate, recognise, adapt and learn. Their specific description includes risk assessment and forecasting for anticipation, monitoring and impact assessment for recognition, prevention and mitigation, preparedness, response and recovery for adaptation and evaluation for the learning category, respectively.

This short description of the characteristics of a resilient system in the previous paragraphs shows that people think different about resilience. As seen with Hollnagel's (2009a) list of abilities, the resilience enabling characteristics occur at different times during the operation and describe actions taken prior to, during and following disruption (Hollnagel, 2011a). The question is how a system can operationalize the cornerstones and the other described characteristics of a resilient system.

Instead of listing all the characteristics of a resilient system mentioned in the RE literature, this SLR attempts to analyse the literature in a structured way and conceptualise resilience. Therefore, the following methodology was developed.

2.2.2 Methodology

Having narrowed down the scope for the in-depth literature review to the RE literature, it was essential to determine which contributions were relevant for the analysis. In order to be as inclusive as possible and avoid any limitations, all of the peer-reviewed RE literature published up to December 2020 was included. Limiting the search to peer-reviewed literature brought the benefit that all contributions had undergone an external review process to assess the publications' quality, validity and originality. Like in stage 1, the Scopus database was searched using the "*resilience engineering*" search criteria for title, abstract, and keywords for any contributions before the end of 2020. The type of document was limited to peer-reviewed literature, including articles, reviews, and editorials, but excluding all of the conference papers and book chapters. A total of 309 documents were considered for the second stage of the SLR. A breakdown of the contributions per year is shown in Figure 2-4.

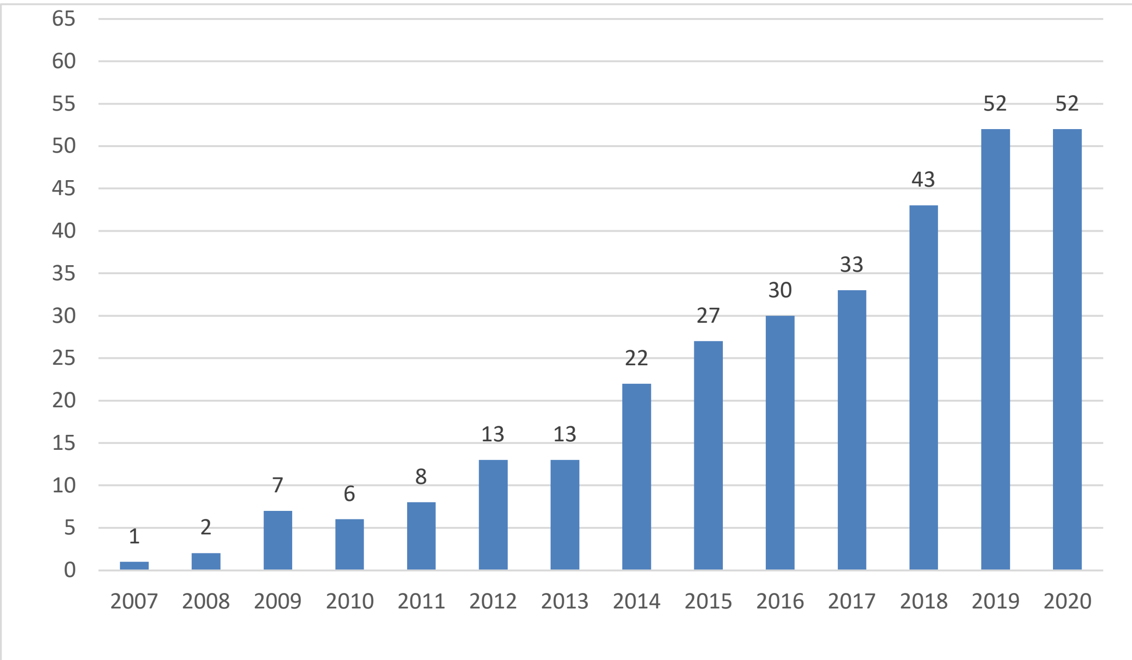


Figure 2-4 Breakdown of the included contributions per year

The first Resilience Engineering Association (REA) Symposium was held in Sweden in 2004, making the term RE widely known to the academic safety science community (Righi, Saurin and Wachs, 2015). The REA comprises over 600 people from academia and industry who come together to learn, collaborate, and co-create in the field of RE (REA, 2022). Based on the first symposium, the book *Resilience Engineering: Concepts and Precepts* was published in 2006 (Hollnagel, Woods and Leveson, 2006). The REA held further symposia in 2006, 2008, 2011, 2013, 2015, 2017, 2019 and 2021. Four additional books were published based on outputs from the first four symposia (Hollnagel et al., 2011; Hollnagel, Nemeth and Dekker, 2008; Nemeth, Hollnagel and Dekker, 2009; Nemeth and Hollnagel, 2014). Table 2-3 provides an overview of all the books that have been published as part of the REA symposia.

Table 2-3 Correspondence between REA symposia and books

REA symposium	Book published on outputs
2004 (Söderköping, Sweden)	Resilience Engineering: Concepts and Precepts (2006)
2006 (Sophia Antipolis, France)	Resilience Engineering Perspective Volume 1 – Remaining sensitive to the possibility of failure (2008) Resilience Engineering Perspective Volume 2 – Preparation and restoration (2009)
2008 (Antibes Juans Les Pins, France)	Resilience Engineering in Practice: A guidebook (2011)
2011 (Sophia Antipolis, France)	Resilience in Engineering in Practice Volume 2: Becoming resilient (2014)
2013 (Soesterberg, Netherlands)	-
2015 (Lisbon, Portugal)	-
2017 (Liege, Belgium)	-
2019 (Kalmar, Sweden)	-
2021 (Toulouse, France)	-

Some of the books from the REA symposia are highly cited sources. According to the Scopus database, *Resilience Engineering: Concepts and Precepts* and *Resilience Engineering in Practice: A guidebook* have 1,415 and 301 citations, respectively. Therefore, the books from the 1st, 2nd, 3rd, and 4th symposia were included in the data set. Each book chapter was considered a separate document, bringing up the number of contributions to a total of 411.

Figure 2-5 outlines the methodology that was used for the second stage of the SLR.

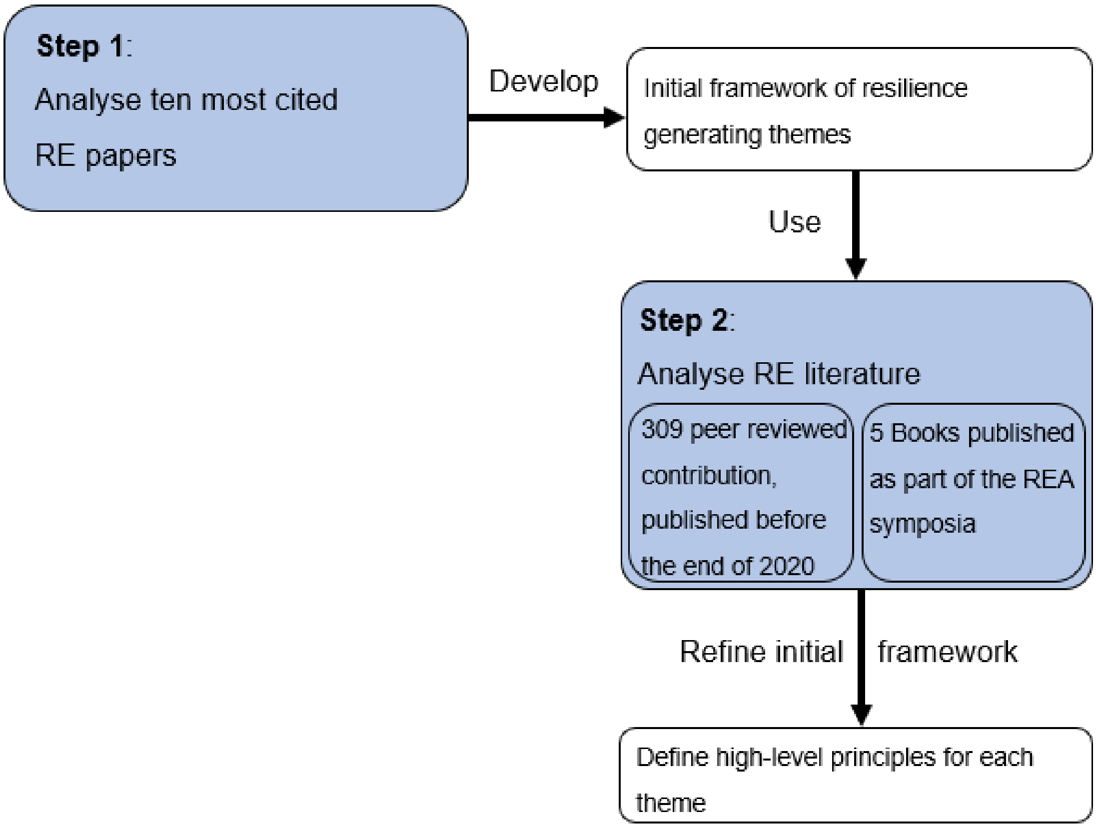


Figure 2-5 Methodology for Stage 2 of the Systematic Literature Review

The ten most cited RE papers were used to develop a preliminary framework. The framework outlines themes that generate resilience during the operation. This framework was then utilized to categorise the peer-reviewed RE literature and used a synthesis of the findings to refine the preliminary framework.

The next section of the PhD thesis addresses the objectives in the following order:

- Analyse the ten most cited papers in the RE literature. Conceptualise resilience by defining resilience-generating themes and building a preliminary framework based on themes.
- Categorise the existing RE literature with the preliminary framework that was developed based on the ten most cited papers
- Define high-level principles for each theme

2.2.3 Analysis of the ten most cited papers

This literature review defined resilience as the outcome of conditions or actions taken by a system. Based on the different views in the literature, the view of the PhD thesis is that resilience can be generated during various stages by using various high-level principles. This view follows the work of Pettersen and Schulman (2019), who defined three forms of resilience. Precursor resilience is about staying within a bandwidth of conditions and acting quickly to manage risks. The second form of resilience is called restoration resilience. This form describes rapid actions that help a system recommence operations after a temporary disturbance. On the other hand, recovery resilience deals with restoring a damaged system. Unlike restoration resilience, recovery resilience focuses on establishing a so-called "*new normal" that is "at least as reliable and robust as before, if not improved*" (Pettersen and Schulman, 2019, p.461).

The initial screening of the RE literature confirmed that the concept of resilience includes a temporal element, and resilience can be generated during different stages of the operation. Resilience is generated in these stages via actions or conditions. In order to gain an overview of the RE literature and understand the different forms of resilience, the ten most cited peer-reviewed papers were analysed. The citation count (as of 10th February 2022) for the highest cited documents in the RE literature ranged from 128 citations for the contribution from Bergström, van Winsen and Henriqson (2015) to 324 citations for Woods' (2015) paper that defined four concepts of resilience. The ten most-cited papers used for the initial analysis are listed in Table 2-4.

Analysing the ten most cited RE papers concluded that the literature can be divided into four main themes that create resilience: *System Design*, *System Preparedness*, *System Response*, and *System Changes*. *System Design* is further split into the subtheme of *System Setup* and *System Checks*. *System Response* also consists of the subthemes of *System Robustness*, *System Rebound* and *System Extensibility*.

Table 2-4 Analysis of ten most-cited papers in RE literature

	Citations	System Design		System Preparedness	System Response			System Changes
		System Setup	System Checks		System Robustness	System Rebound	System Extensibility	
(Woods, 2015)	324				✓	✓	✓	✓
(Madni and Jackson, 2009)	305	✓	✓	✓	✓	✓	✓	✓
(Righi, Saurin and Wachs, 2015)	171	✓		✓	✓	✓		✓
(Davoudi, Brooks and Mehmood, 2013)	165				✓	✓		✓
(Patriarca et al., 2018a)	157	✓		✓	✓	✓		✓
(Dinh et al., 2012)	147	✓		✓	✓	✓	✓	
(Zhang and Lin, 2010)	140	✓				✓		
(Ip and Wang, 2011)	139	✓				✓		
(Bergström, van Winsen and Henriqson, 2015)	128	✓		✓	✓	✓		✓
(Costella, Saurin and de Macedo Guimarães, 2009)	124	✓		✓		✓		✓

2.2.3.1 Categorization of resilience

Three of the ten documents (Bergström, van Winsen and Henriqson, 2015; Patriarca et al., 2018a; Righi, Saurin and Wachs, 2015) were extensive literature reviews that summarized outputs from the existing RE literature. All of the literature reviews covered all four forms of resilience. However, all specific subthemes were not mentioned in all three literature reviews (see Table 2-4). This fact underlines the need to investigate the concept of resilience further and capture all angles to gain a holistic view of the topic of resilience.

The identified themes and subthemes were combined into a preliminary framework shown in Figure 2-6.

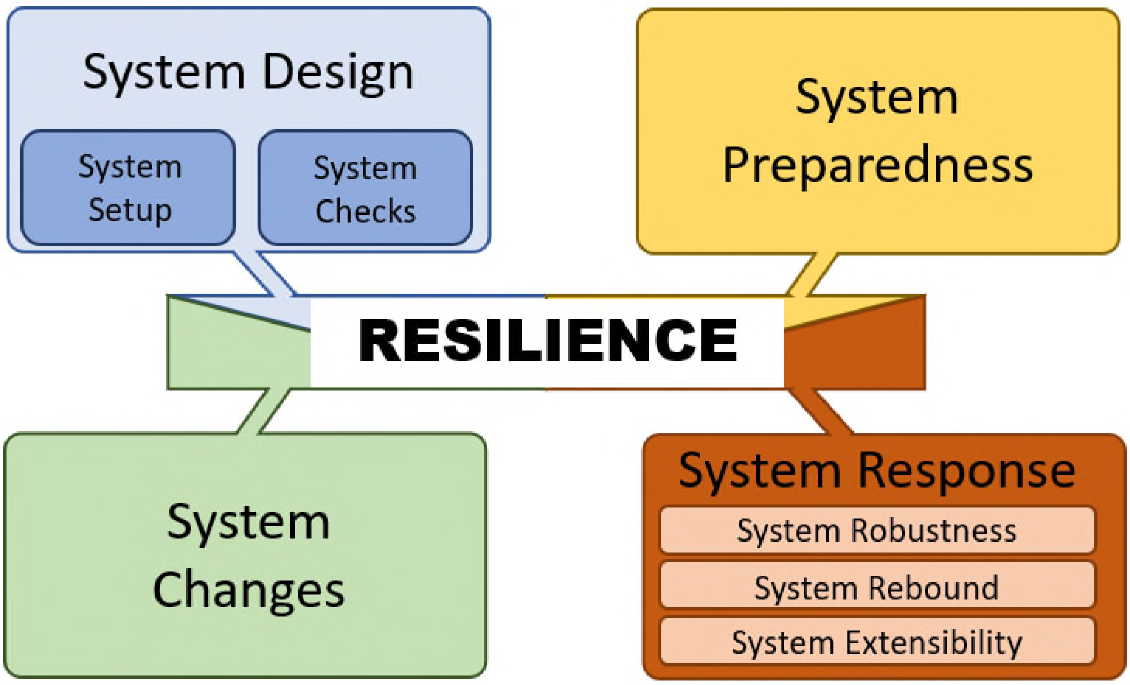


Figure 2-6 Proposed conceptualisation of resilience

The framework is based on the idea that resilience results from actions taken before, during, and following disruptions (Hollnagel, 2011a). This idea implies two things:

- resilience is seen as an outcome, meaning abilities and processes are enablers for resilience and
- resilience occurs at different stages, which means resilience is dependent on time.

2.2.3.2 System Design

The *System Design* consists of *System Setup* and *System Checks*.

2.2.3.2.1 System Setup

The *System Setup* investigates how organisations opt to set up their operation and deal with production/safety trade-offs (Madni and Jackson, 2009). According to Madni and Jackson (2009), trade-offs in operation arise due to finite resources, and they investigated how resilience can be sourced in operation.

Furthermore, the complexity of systems also drives the need for resilience (Bergström, van Winsen and Henriqson, 2015).

Zhang and Lin (2010, p.100) added another dimension to the *System Setup* by referring to resilience as a post-damage property that can be engineered into a system design so that "*the system can still function to a desired level when the system suffers from a partial damage*". For achieving such a design, a system needs to be able to reconfigure the operation in case of a disruption. Redundant resources, distributed supplies and reliable delivery lines play a crucial part in transport networks' resilience (Ip and Wang, 2011). Ip and Wang (2011) assessed the resilience of a railway network in China using these three criteria. Although one primary focus in the resilience literature has been the response to disruptions, "*how fast and effective this recovery is will depend not only on recovery plans but also on the system design itself*" (Dinh et al., 2012, p.233), six principles must be considered in the *System Setup*: flexibility, controllability, early detection, minimization of failure, limitation of effects, and administrative controls/procedures (Dinh et al., 2012). On the other hand, Costella, Saurin and de Macedo Guimarães (2009) listed integrating flexibility, learning, awareness, and top-level commitment as design principles.

2.2.3.2.2 System Checks

System Checks describe a "*dynamic assessment and update of risk models that enhance an organization's ability to effectively prioritize safety investments*" (Madni and Jackson, 2009, p.183). The goal is to constantly check whether the system stays within the limits and safety boundaries defined in the *System Setup*.

System Checks are a vital part of achieving a resilient operation. "*The difficulty in performing these tradeoffs has long been recognized as the major contributor to the slow, but sure erosion of safety margins, and subsequent drift towards failure (e.g. the Kemira chemical discharge in Hälsingborg) in complex, socio-technical systems*" (Madni and Jackson, 2009, p.185). Costella, Saurin and de Macedo Guimarães (2009) argued that this auditing goes beyond standard safety measurements. It helps to highlight gaps between the current standard and the desired performance and identify problems. This information can develop action plans that help improve performance (Costella, Saurin and de Macedo Guimarães, 2009).

2.2.3.3 System Preparedness

System Preparedness is concerned with the creation of foresight and taking proactive actions. The goal is to put the system in a state of alertness and increase the buffer capacity. Costella, Saurin and de Macedo Guimarães (2009, p.1058) described this as "*proactiveness which refers to anticipating problems, needs or changes, and which leads to actions being drawn up*".

Bergström, van Winsen and Henriqson (2015) referred to Hollnagel's (2011a) definition, which includes adjusting functioning prior to disturbance. This form of preparation requires commitment from management (Madni and Jackson, 2009). Dinh et al. (2012) highlighted that preparedness might lead to a rapid and proper response.

2.2.3.4 System Response

One of the ten papers' central focuses has been investigating how systems respond to disruptions. Dinh et al. (2012) argued that even good risk management reaches its limit, so resilience is needed when responding to disruption. They distinguished between three different system states: normal, upset, and catastrophic (Dinh et al., 2012). The actions and objectives of each of the three states describe a different form of resilience.

Woods (2015) also tried categorising different resilience concepts, and his categorisation has been adopted to define the *System Response* form sub-categories. Woods' (2015, p.5) concepts described "*different technical approaches to the question of what is resilience and how to engineer it in complex adaptive systems*". Woods' labels of *System Robustness*, *System Rebound* and *System Extensibility* are adopted in the framework built from reviewing the top most-cited papers.

2.2.3.4.1 System Robustness

This form of resilience is achieved by increasing the ability to dampen perturbations (Woods, 2015). "*Robustness is achieved by having "shock* *absorbers" in the form of, for example, resource buffers that enable the system to withstand a disruption without having to reconfigure itself to respond to the disruption*" (Madni and Jackson, 2009, p.187). According to Dinh et al. (2012), the system must be able to detect perturbations and adjust operating variables to keep the operation within the normal state.

2.2.3.4.2 System Rebound

One frequently used definition of resilience is the ability to bounce back. The goal of generating resilience through the *System Rebound* is the ability to recover regular operations after a disruption. Ip and Wang also adopted this perspective (2011). They saw resilience as "*the ability of a system to return to a stable state following a strong perturbation caused by failure, disaster or attack*" (Ip and Wang, 2011, p.189). This view coincides with the definition of resilience as "*the ability to recover quickly after an upset*" (Dinh et al., 2012, p.233).

2.2.3.4.3 System Extensibility

Whereas *System Rebound* focuses on the recovery of the operation, the main objective of the *System Extensibility* category is the ability not to lose control. Woods (2015, p.7) defined this concept as "*the opposite of brittleness, or, how to extend adaptive capacity in the face of surprises*". This view on resilience is also linked with survivability (Madni and Jackson, 2009). Resilience in the *System Extensibility* category could be needed after a significant disruption. Alternatively, it may also be needed if an "*upset system is not managed properly and is not able to recover to its normal state, then larger events…may follow and the system may cross over into a catastrophic state*" (Dinh et al., 2012, p.233).

2.2.3.5 System Changes

This form of resilience is concerned with ensuring the long-term sustainability of a system. *System Changes* also refers to Woods' (2015) fourth concept of resilience: Sustained Adaptability. The system needs to have the ability to adapt to changing circumstances via a dynamic re-optimization or reconfiguration of the resources and capacity that are available (Madni and Jackson, 2009). Madni and Jackson (2009) defined a framework that helps organisations maintain and grow resilience through avoiding accidents, surviving disruptions and integrating lessons learned. Therefore, failures represent an "*inability of the system to adequately adapt to perturbations and changes in the real world given finite resources and time*" (Madni and Jackson, 2009, p.181). Davoudi, Brooks and Mehmood (2013) combined engineering, ecological and evolutionary resilience perspectives and examined how systems adapt to climate change. The study results concluded that resilience could also be fostered through transformative opportunities that arise through change, which goes beyond simply viewing the concept as a capacity to bounce back (Davoudi, Brooks and Mehmood, 2013). Therefore, adaptability and transformability are critical factors for achieving resilience (Davoudi, Brooks and Mehmood, 2013).

As Table 2-4 shows, Madni and Jackson (2009) covered all of the described themes of resilience, even though they only mentioned subthemes like *System Changes* and *System Extensibility* briefly.

Their work was aimed at proposing a conceptual framework for RE. Figure 2-7 shows Madni's and Jackson's (2009) conceptual framework. Their framework links the variables of *System Attributes*, *Methods*, *Disruptions*, and *Metrics* with *System Resilience*.

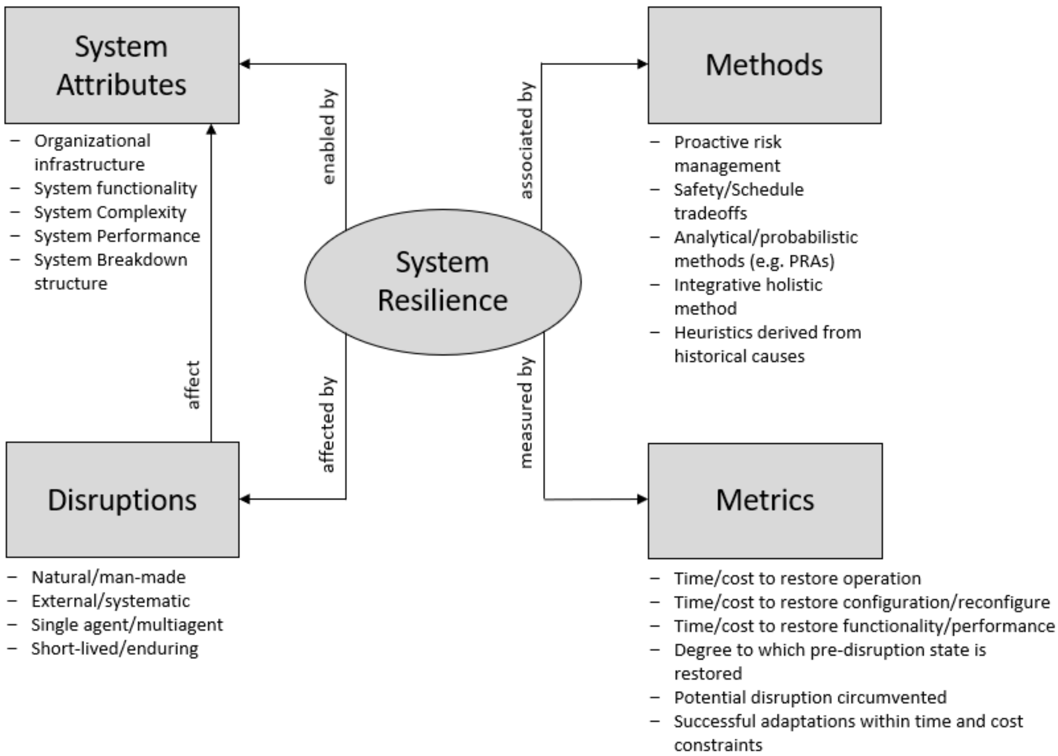


Figure 2-7 Framework for RE proposed by Madni and Jackson (2009)

The framework operates at a high level and shows some connections between the variables. For example, Madni and Jackson (2009) argued that *System Attributes*, such as organisational infrastructure, system performance, or system breakdown structure, enable *System Resilience*. *System Resilience* is also associated with *Methods* that include proactive risk management and safety/schedule trade-offs. *Metrics* can be used to measure *System Resilience*. *Metrics* examples are time/cost to restore operation, potential disruptions circumvented, or successful adaptations within time and cost constraints. In their framework, *System Resilience* is affected by disruptions (e.g. natural/man-made or short-lived/enduring), and disruptions again affect the *System Attributes*.

However, one major limitation is that the framework does not show how the concept of resilience can be operationalised during various stages of the operation. Although Madni's and Jackson's (2009) work recognised that resilience has four faces, it lacked the integration of these faces into their conceptual framework. The four faces were avoid (Anticipation), withstand (Absorption), adapt to (Reconfiguration), and recover from (Restoration). The four faces share some overlaps with the four themes of resilience identified in this literature review. Madni's and Jackson's (2009) four faces are much more general, and their work only mentioned all of this work's themes and subthemes without providing specific principles for each theme. The lack of integration is another justification for the thesis' work, as it is essential to define principles for each theme to show how resilience can be operationalised during various stages.

In order to achieve this goal, the categorisation from Figure 2-6 was used in section 2.2.4 to analyse all of the peer-reviewed literature. The purpose of section 2.2.4 is to conceptualise resilience by using the identified themes and subthemes to define high-level principles for each proposed theme. Therefore, elements such as metrics and disruptions from Madni's and Jackson's (2009) model were not included in the conceptualisation of resilience for this work.

2.2.4 Categorisation of the RE literature

This literature review sees resilience as a result of processes that occur at different times during the operation. Various resources, abilities and behaviours influence these processes. Based on the analysis of the ten most cited papers, a framework was developed in section 2.2.3 that defined four primary resilience-generating themes: *System Design*, *System Preparedness*, *System Response*, and *System Changes*. Results from the review of the RE literature were used to define and outline the characteristics of each theme and subtheme that lead to resilience.

Each theme is described separately, and at the end of each section, a table summarizes the purpose of each theme and subtheme, respectively.

2.2.4.1 System Design

The way a system is designed heavily influences the system's resilience. Furthermore, the performance during a disruption depends on the resources and structure put in place before the disruption. Therefore, the resilience of a system can be enhanced by how a system is set up. It is also influenced by the mechanisms used to monitor and constantly check whether the internal processes or surrounding environment have changed or whether they still match the original assumptions and definitions. Two main subthemes help achieve a resilience *System Design*. Therefore the *System Design* theme is split into the following two subthemes: *System Setup* and *System Checks*.

2.2.4.1.1 System Setup

According to Dinh et al. (2012), achieving resilience depends on how the operation is set up and resources are distributed. During the operation setup, the desire to achieve a higher level of resilience may compete with other targets, such as minimising costs (Matrosov et al., 2015). The *System Setup* category deals with trade-offs generated by constantly enhancing and broadening existing capabilities and improving how to incorporate and exploit current and new technologies while meeting the criteria for safe operation.

The ontology behind this concept is that every system has limited resources available. Hoffman and Woods (2011) identified several fundamental trade-offs which define the boundary conditions for all macro-cognitive work systems. It is about designing and maintaining the operation, and the underlying theory is how the system manages the different trade-offs (Hoffman and Woods, 2011).

One trade-off argues that multiple goals cannot be improved simultaneously, and the improvement of one goal might result in the brittleness of another target. The search for the so-called "*Silver Bullets*" (Woods, 2006b, p.27) is the desire to improve multiple goals simultaneously without any goal conflict. In his analysis of NASA's *Faster, Better, Cheaper* approach Woods (2006b) outlined how NASA tried to combine conflicting goals in one policy, which resulted in a deterioration of the safety measures. Woods (2006b) concluded that the Silver Bullet strategy is an illusion and a system needs to have a mechanism to balance multiple goals and make the trade-offs (Woods et al., 1994).

Another compromise is described by the Efficiency-Thoroughness Trade-Off (ETTO) principle (Hollnagel, 2009b). As mentioned earlier, a system has limited resources available. It must decide how to set up the operation and how much safety margin to leave as an overhead during normal operations to adapt to changing situations. The ETTO principle refers to the trade-off between a system's efficiency and safety assurance and how the system is dealing with the high-risk environment. Both of the mentioned trade-offs can be traced back to Rasmussen's (1997) Stretched Dynamics model.

Stretched Dynamics model

With this model, terms like *Safety margin* and *Working near capacity* can be explained and illustrated. Rasmussen (1997) defined the system's performance envelope with the boundaries of unacceptable workload, economic failure and unacceptable operation. Figure 2-8 shows how Rasmussen's (1997) model was adapted by Son et al. (2013) to represent resilience. The three boundaries define an area in which the operation of a system can be set up.

The marginal operating boundary builds a space between the boundary of unacceptable operation and the buffer capacity inside the system builds the so-called safety margin. Multiple opposing forces such as economic pressure, workload release and safety create a dynamic interplay that acts on the system's operating capacity. The forces which act on the system can push the operation near and over boundaries. Normal functioning describes minor differences caused by the various forces, which can sometimes move the system close to its boundaries. As soon as the system is pushed over the marginal operating boundary into the safety margin, mishaps and disruptions can occur. The system can even suffer accidents when breaching the unacceptable operating boundary.

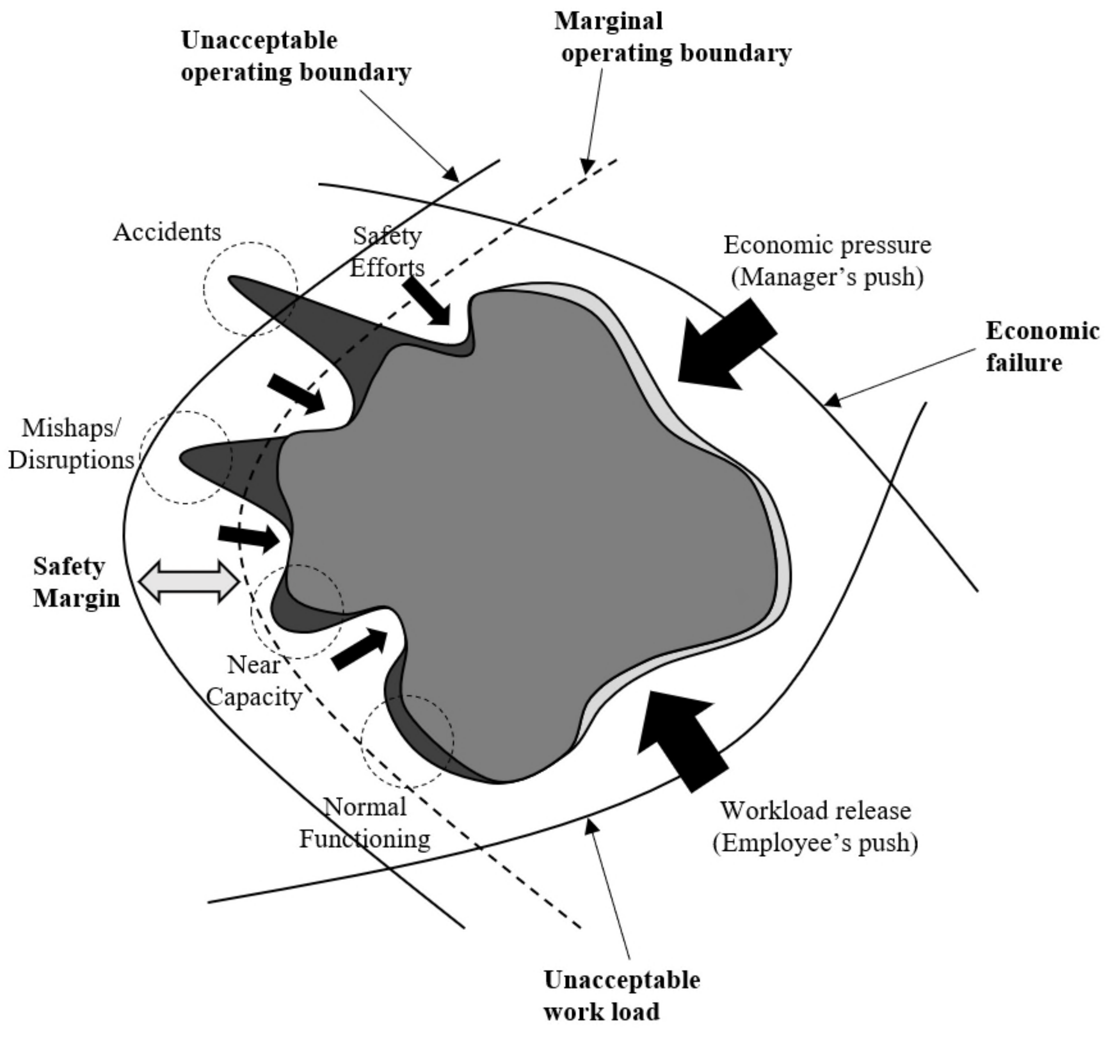


Figure 2-8 Rasmussen Stretched Dynamics model (adapted from Son, Bernat and Sasangohar (2013))

The model is a good representation of how the system's operation can be set up and how much buffer capacity should be left to create the safety margin. The safety margin compensates for variances in the internal operation, or external environment and RE considers internal and external factors (Engler, Göge and Brusch, 2018).

An entity working in a hostile environment might want to trade efficiency for a higher safety margin to cushion minor disruptions without compromising its regular operation. Hale and Heijer (2006a) used the Rasmussen (1997) model to describe resilience as "*the ability to steer the activities of the organisation so that it may sail close to the area where accidents will happen, but always stays out of that dangerous area*" (Hale and Heijer, 2006a, p.36). This ability implies that the system operates close to the safety margin without accidents. Patterson and Deutsch (2015) used the Rasmussen model to investigate the danger of brittleness and miscalibration in the health care domain. They discovered that "*the combination of practice, performance and debriefing activities incorporate the primary resilience engineering activities, which include the ability to respond, monitor, learn and anticipate*" (Patterson and Deutsch, 2015, p.387)

Dermot Williams and Smart (2010) adapted Rasmussen's (1997) model. They used the boundaries of financial failure, target failure, unacceptable working conditions and failure of safety to define the safe working envelope for their case study about the resilience of the National Health Service (NHS) hospitals in the UK (see Figure 2-9).

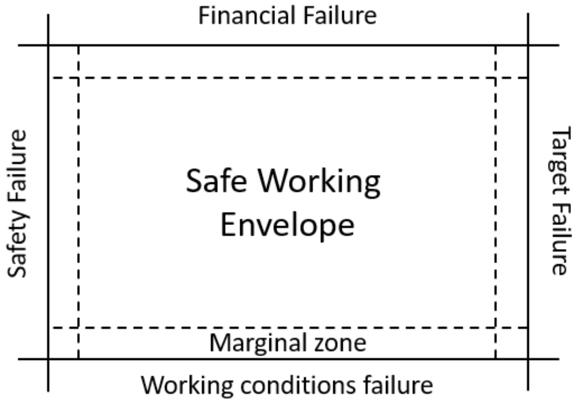


Figure 2-9 Safe Working Zone model (adapted from Dermot Williams and Smart (2010))

The most significant difference between Rasmussen (1997) and Dermot Williams and Smart (2010) is that the latter split Rasmussen’s boundary of economic failure down into financial failure and target failure. Target failure describes the failure to meet targets set by the system. Failure to meet the targets could destabilize the system as the set performance would not be met. For example, Dermot Williams and Smart (2010) mentioned how an increased waiting time could affect passenger safety and the financial balance.

The third trade-off that a system must manage describes the conflict between short-term and long-term goals. Woods (2006b) referred to this as the tension between acute and chronic goals. Acute goals are production targets that can be assessed in the short term, whereas chronic goals such as safety and equity can only be analysed in the long run (Hoffman and Woods, 2011). Safety goals need to remain predominant to production goals to prevent a deterioration of the system’s safety level (Tjorhom and Aase, 2011), which would also decrease the level of resilience in a system as there is a trade-off between safety and productivity (Tian, Lin and Wang, 2020).

There is a drive to utilise every available resource, increasing the system's efficiency and sacrificing chronic goals to achieve acute goals (Patterson and Wears, 2015). Even during the design of a system, the desire to achieve a level of resilience may compete with other targets, such as minimising costs (Matrosov et al., 2015). Another significant influence on resilience is power within a system and how the power is governed. Cedergren (2013) discovered in his study about decision-making in tunnel projects that power relations between stakeholders could also adversely affect decision-making and to what extent the system's resilience is considered. He further demonstrated that decisions taken on a local level impact the global railway system’s resilience. The conclusion was that for achieving system resilience, other system properties, for example, cost and schedule need to be traded off for achieving a resilient operation (Wheaton and Madni, 2019). Therefore, one characteristic of a resilient system is that it takes safety as a core value (Woods and Hollnagel, 2006) which requires top-level commitment (Wreathall, 2006).

The fourth trade-off describes the balance between standardising the system and ensuring the system's flexibility. The flexibility ensures adaptability to unanticipated events and avoids brittleness. Broadening the scope of routine actions can increase a system's efficiency and the likelihood of surprises at the system’s boundaries (Hoffman and Woods, 2011). Sujan, Spurgeon and Cooke (2015) concluded that practitioners must constantly make dynamic trade-offs to overcome the inevitable tensions and ensure safe practices. Resilience in this form is about maintaining the balance of the trade-offs and keeping the operation within the boundaries. It also needs to ensure there is sufficient safety margin to deal with variances within the operation and changes in the environment.

Besides dealing with trade-offs, another core element of resilience is the challenge associated with the complexity of a system. Many of the contributions in the RE literature are concerned with providing solutions for managing the complexity and how to design systems to achieve this best. Socio-technical systems include multiple components and interrelated players and are considered System-of-systems (Checkland, 1999). Due to the complexity, accidents may not always have a direct cause and effect (Hasan, Chatwin and Sayed, 2020; Hirose and Sawaragi, 2020). This complexity could mean that disturbances can have unforeseen impacts on the entire system, and “*it is difficult to pre-identify or gauge the cascading effects of interactions and failures across networks*” (Grabowski and Roberts, 2019, p.518). Therefore, Madni and Jackson (2009) mentioned that the system’s resilience could be improved by avoiding unnecessary complexity, such as including safety barriers to compensate for a poor system design.

In addition, with new technology being introduced and systems becoming more and more complex, traditional safety management approaches have reached their limits (Shirali et al., 2016). Grote (2012) raised the point that industries can also learn and adopt safety management systems from other industries to provide a meaningful knowledge transfer. However, traditional safety and risk management tools are no longer sufficient, and Adriaensen, Decre, and Pinelon (2019) reiterated the need for new tools to assess the safety of a system are required that go beyond traditional safety and risk management. Brooker (2011) highlighted that a risk assessment is only as good as the variables used. In his analysis of aviation risk estimates. He concluded that "*for life-critical risk assessment, it is vital to know where the numbers came from and if these numbers are used in the correct way*" (Brooker, 2011, p.1154).

Hassall, Sanderson and Cameron (2014) developed a technique called SAfER (Strategies Analysis for Enhancing Resilience). SAfER can complement other risk assessment methods and support systems to select the appropriate control strategies and assess their effectiveness. Another approach was taken by Steen and Aven (2011) by showing how Hollnagel's four cornerstones can be applied to the ACU framework, which describes the event (A), consequences (C) and related uncertainty (U). The results of the framework were used to develop proactive risk management. The idea behind it was to identify uncertainties and describe them. Quantifying the reliability of networks was also mentioned as an enabler in improving resilience (Paredes et al., 2019). Another enabler for a resilient response can be risk and vulnerability analyses. The analysis can identify critical parts of the operation and interdependencies, which is a sound basis for risk reduction and control (Johansson and Hassel, 2010). In order to understand the individual risk indices, one must be aware of and be able to model the underlying processes of the system (Luthar, Sawyer and Brown, 2006). Based on this, there is a need to understand the dependability between system-of-systems (Bukowski, 2016).

In order to visualise underlying processes, Hollnagel (2012) developed the Functional Resonance Analysis Method (FRAM). FRAM is a method to investigate how non-linear interactions and variables in a system can lead to various outcomes. In order to be truly effective, it is vital to spot interdependencies with FRAM to understand the internal and external context. FRAM can describe possible outcomes that arise from the variability of everyday performance. The method uses the principle of resonance and shows how coupled functions may produce unexpected and out-of-the-scale outcomes. The method is based on four principles: equivalence of failures and successes, approximate adjustments, emergence, and functional resonance. FRAM can be used for negative and positive resonances in a system that leads to failure or flourishment (Furniss, Curzon and Blandford, 2016). This analysis must happen on the strategic, tactical, and operational levels, as Louisot (2015) concluded in his enterprise-wide risk management analysis. By analysing the events during the Fukushima disaster with FRAM, Hollnagel and Fujita (2013) pointed out the importance of possessing all four cornerstones (Hollnagel, 2009a). They highlighted how shortcomings in anticipation and response contributed to the disaster. With an analytic hierarchy process, FRAM can identify out-of-control situations and therefore presents a good monitoring tool (Rosa et al., 2017). In another study, FRAM was used to understand the incident involving a hunting accident (Bridges, Corballis and Hollnagel, 2018).

De Carvalho (2011) reiterated the need to understand how a system functions. He applied FRAM to analyse a mid-air collision in Brazil and showed that systems operating with low buffer capacity, flexibility, and an operation near the margin of safety have a low tolerance for disturbances. He argued that some drift towards failure is caused by adjustment due to the ETTO (de Carvalho, 2011). In a study about drug administration, Kubra, Fahri and Ozturk (2019) showed how FRAM can be used to understand performance variability, how deviations influence the system, how to respond to the changes, what the deviations may lead to and to understand how to monitor the changes and learn from them. FRAM has been applied to multiple industries, including ATM (Patriarca, Gravio and Costantino, 2017) and healthcare (Raben et al., 2017).

Before FRAM, Leveson (2004) proposed the Systems-Theoretic Accident Model and Processes (STAMP) to capture the dynamics of a socio-technical system and define safety as a dynamic control problem. STAMP combined constraints, hierarchical levels of control and process loops (Pereira et al., 2015). Pereira et al. (2015) applied STAMP to the Deepwater Horizon accident. They concluded that *“many of the decisions that contributed to the accident were perfectly acceptable when isolated, but the fragmented view did not allow the understanding of the impacts of individual decisions may bring to the overall* *system, changing decision patterns over the time."* (Pereira et al., 2015, p.2310). Woltjer (2019) added that the interconnectedness and cross-scale interventions between micro, meso, and macro levels must be addressed and understood. In his study, he explored the resilience of Air Traffic Management (ATM). The micro-level is the controller, the meso level is the sector and tower/centre, and the macro level is the national and international systems. His conclusion was that *"by studying resilience at these diverse interconnected levels and establishing a vocabulary strongly connected to the operational vocabulary at different scales, resilience research may contribute to a better understanding of adaptive capacity and coping with our increasingly complex world"* (Woltjer, 2019, p.111).

However, there is a limit to identifying risks when assessing the system and its complexity, as complex systems are not fully knowable (Cilliers, 2002). Therefore it can be challenging to describe the system and define clear system boundaries (Lundberg and Johansson, 2015). Dekker et al. (2013) warned that it could be challenging to understand a system altogether. They differentiated between complicated and complex systems. Complicated systems follow a set of rules and afford a complete description. Order and stability are achieved by determining and complying with the best method and clear system boundaries. Instead of having a set of rules that describe the system's dynamics, Dekker et al. (2013) accepted the non-linear interaction between all components. However, STAMP and FRAM can help understand a complex socio-technical system better (Patriarca et al., 2020). Even though FRAM and STAMP are tools that make interdependencies and variables in a system more visible and determine which parameters are essential to monitoring (Madni and Jackson, 2009), not all potential hazards can be identified due to the complexity of a system (Taleb-Berrouane and Khan, 2019) and a risk assessment may not capture all potential threats. Therefore, it is vital to be aware of the critical functions of a system to be able to protect them or repair during a disruption (Falegnami et al., 2019).

One enabler for resilience is developing an error-tolerant design for the system (Jain et al., 2018). Error-tolerant design helps a system not to fail in a significant way due to experienced variations. When faced with undesired and unknown external influences, processes still work (Jain et al., 2018), which is also highlighted as fault-tolerant (Azadeh et al., 2014b). Palazzi et al. (2014) viewed resilience as a proactive defence against disturbances, and risk is managed through prevention, reduction and mitigation strategies. Systems must have a level of redundancy and safety margin in operation. Furthermore, it must be flexible to absorb unforeseen events (Pasman, Knegtering and Rogers, 2013). Using appropriate barriers can safeguard the operation by either preventing accidents or reducing the consequences of an action by stopping the spread (Bouloiz, 2020), which increases or maintains the level of resilience (Sperstad, Kjølle and Gjerde, 2020). Hollnagel (2014b) proposed four different categories of system barriers: material, functional, symbolic and immaterial barrier systems. Material barriers are physical barriers that should prevent an action from taking place or the outcomes from spreading. Examples of material barriers are walls, fences, and railings. Functional barriers have an impeding function by creating a logical or temporal interlock. Only if one or more pre-conditions are met an action can happen. Examples of functional barriers include locks, passwords, or any form of identification. Symbolic barriers only work in combination with the interpretation by the user. Unlike a material barrier, this barrier is insufficient to prevent an action from happening physically. Symbolic barriers can be either a visual barrier like a line on the ground, a sign, or an auditory signal. Barriers in the form of immaterial barriers are not present in a physical form and require the user's knowledge to fit their purpose. Examples of immaterial barriers are rules, restrictions, and laws. Hale's et al. (2006) list of barriers provided more details and described eleven barriers in total. However, the underlying theory is comparable with Hollnagel's (2014b) four categories of barrier systems. Hollnagel's (2014b) list can therefore be seen as a summary of Hale et al. (2006) work.

In order to ensure a flexible mode of operation, Hollnagel and Sundström (2006) argued that a system needs to have various defined states that it can switch in between to always remain in a stable state. The different states also help a system respond appropriately to various disturbances without losing control. The

Resilience State Space model describes various states a system can be in prior to, during, and following a disruption (Hollnagel and Sundström, 2006).

Resilience State Space model

Figure 2-10 is a graphical representation of the Resilience State Space model from Hollnagel and Sundström (2006). The Resilience State Space model extended the work of Sundström and Hollnagel (2006), who defined three states a system can pass through: healthy, unhealthy, and catastrophic. Every system has its normal functioning (healthy state), during which everything works as intended and reliably. Furthermore, there is a mode for regular reduced functioning, such as a system that is less busy during the night shift or holiday and has a scheduled transition into this state.

On the other hand, irregular reduced functioning occurs in response to a shortage of internal resources. The system is intended to work at a reduced performance to prevent loss of control.

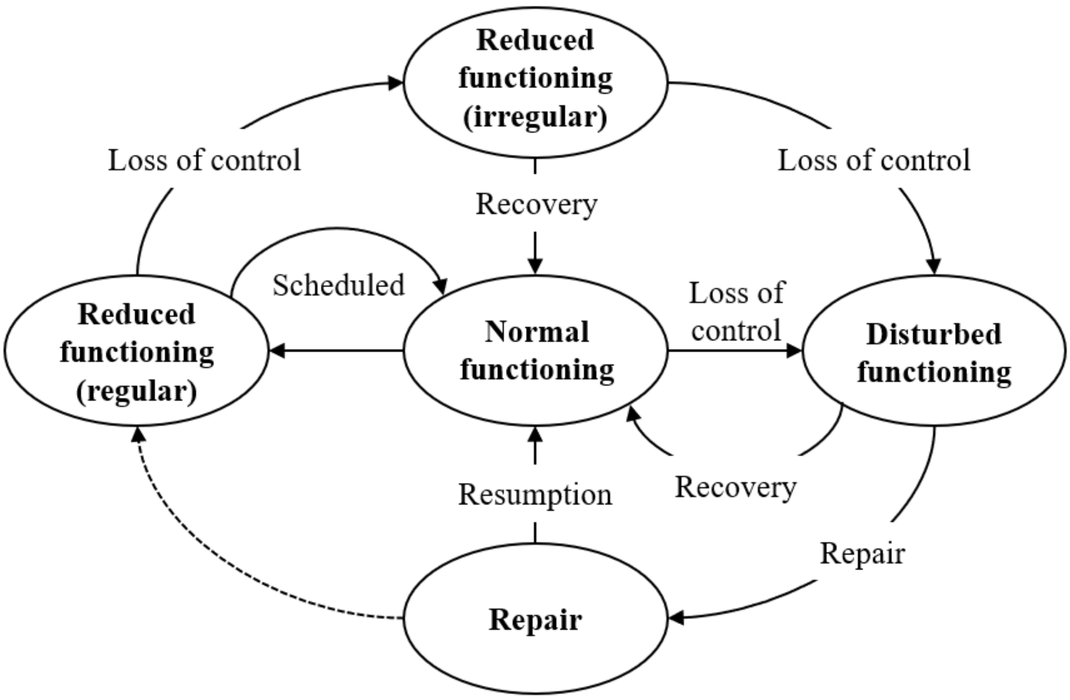


Figure 2-10 Resilience State Space model (adapted from Hollnagel and Sundström (2006))

Hollnagel and Sundström (2006) acknowledged that there will always be unforeseen disruptions and, therefore, there is a need for a state of disturbed functioning. This type of functioning is similar to the unhealthy state (Sundström and Hollnagel, 2006) or upset state (Dinh et al., 2012) of a system. A system can have multiple disturbed functioning modes, depending on the severity of the disruption. The difference between irregular reduced and disturbed functioning is a temporary loss of control. The authors argued that *"it may be the mark of a resilient organization that it has a number of different modes of functioning whenever a disturbance happens"* (Hollnagel and Sundström, 2006, p.341). In order to return to normal functioning, a system may pass through a state of repair or, for less severe disturbances, may recover directly.

In conclusion, the complexity of a system makes the system inherently risky, and resilience in this context is the ability to adapt to the emerging risk and keep the system safe (Bergström, van Winsen and Henriqson, 2015). Therefore, achieving resilience is linked to a proactive and continuous approach that seeks a robust yet flexible system (Azadeh et al., 2014a). This form of resilience deals with the changing nature of complex socio-technical systems, managing trade-offs, monitoring everyday variability, and providing feedback in real-time (Penaloza et al., 2020). Table 2-5 defines the purpose of the *System Setup* theme. Furthermore, the table is a high-level summary of this section and lists the main principles of the *System Setup* theme with illustrative contributions.

Table 2-5 Summary of the System Setup theme

System Setup
Purpose: Managing trade-offs and defining normal functioning with sufficient safety margin
High-level principles: • Buffer capacity is incorporated (e.g. Woods, 2006b) • Built-in redundancies (e.g. Madni and Jackson, 2009) • Sufficient resources are available to monitor operation (e.g. Hollnagel, 2009a) • System is aware of interfaces with other systems (e.g. Bukowski, 2016) • System is aware of bottlenecks and critical parts of the operation (e.g. Falegnami et al., 2019) • Error-tolerant design (e.g. Jain et al., 2018) • Flexible mode of operation (e.g. Hollnagel and Sundström, 2006)

2.2.4.1.2 System Checks

System Checks are concerned with monitoring developments in the environment and monitoring the work inside the system, which is linked to awareness and opacity (Wreathall, 2006). Resilience is also based on anticipating changing risks before harm and failure occur (Qureshi, Ashraf and Amer, 2007). Dekker (2006) stated that a crucial part of achieving resilience is that a system constantly checks if its perception of risk still matches with reality and then updates its risk model. The focus is on monitoring the process closely to identify upcoming issues before they occur, including their internal operation and the environment. Therefore, *System Checks* heavily rely on Hollnagel's (2009a) second cornerstone of resilience, monitoring, and support for the design and maintenance of work practices as it helps keep the operation within the safety boundaries. The purpose of the *System Checks* theme is to see if the environment and assumptions made when the system was designed still match the current conditions. The environment constantly changes, which demands a frequent update of the system's operation to avoid brittleness. Changes in the environment can be slow and may go unnoticed by the company. Regular audits of the environment can make the environment changes visible, and the system can use the outputs of the checks to adapt its operation and counteract outdated behaviours. Specific indicators can help identify the drift into these intolerable safety levels (Thieme and Utne, 2017). In their study, examples of safety indicators in the operation of autonomous marine systems are the percentage of faults related to critical subsystems detected by self-tests or the percentage of time-critical sensors that work without faults (Thieme and Utne, 2017).

Continuously monitoring and timely responding to arising threats can mitigate potentially hazardous challenges. Hollnagel and Woods (2006) mentioned that resilience is not a property of a system that will always be there once established but needs to be constantly monitored and maintained. Systems, especially socio-technical systems made of complex connections between sub-systems and consisting of humans engaging with technical equipment, need to be regularly examined and updated to match the changing conditions and evolve due to the changing nature of complex systems (Penaloza et al., 2020). Leading indicators, such as workload growth, can help spot weaknesses and support the system's resilience (de Regt, Siegel and Schraagen, 2016). It can also be helpful to inject faults into the system to constantly check for flaws and dependencies inside the system and update processes (Robbins et al., 2012). Moreover, Geraghty et al. (2020) discovered in the research within the healthcare sector that the introduction of checklists can increase reliability and minimise the likelihood of wrong-site surgery. Local knowledge of the operation, preparing and creating foresight to use information from various sources, and communication and trust between stakeholders influence the successful operation (de Vries, 2017). Furthermore, maintenance plays a vital role in improving the productivity and efficiency of a system as it limits the risk of failure (Azadeh et al., 2016). This perception of resilience is in line with the view that sees resilience more in the context of reliability (Salzano et al., 2014).

Some authors highlighted the similarities between the theory of High Reliability Organisation (HRO) and RE. Haavik et al. (2019) proposed a research agenda that combines HRO and RE methods. Both HRO and RE aim to understand how a high level of safety is achieved in a system (Macrae and Draycott, 2019). Paries et al. (2019) compared HRO and RE through the lens of safety management systems within the French ANSP. Whereas HRO stands for robustness against variability, RE goes one step further and promotes the balance of robustness and variability and uses compromise to achieve safety in light of variations and disturbances.

Hopkins (2014, p.13) described similarities between resilience and High-Reliability Theory by saying, "*Resilience Engineering purports something new, yet on examination it is hard to see where it goes beyond HRO theory*". However, other authors showed the differences between the concept of reliability and resilience (Zhang and Lin, 2010). A system is considered reliable if the probability of failure is acceptably low. On the other hand, resilience goes one step further and being resilient means that a system can recover from disruptions, degradation of working conditions, and irregular variations (Zhang and Lin, 2010). Pulley and Wakefield (2001) associated resilience with elasticity, buoyancy and adaptation. Zhang (2007) acknowledged the partial damage to the system and defined resilience as the ability of a system to function to some desired level even when suffering from partial damage. The emphasis on partial damage differentiates resilience from reliability and robustness (Zhang and Lin, 2010).

To summarize these ideas, being resilient allows for failures and mistakes because the system can recover from these events. This view argues that even complex and tightly coupled systems that produce failures can recover from these events. A resilient system detects the deviation, stops the failure from spreading and recovers from it. HROs are systems with highly reliable behaviour and practices, and it is an essential concept for crisis prevention and mitigation. Resilient organisations are reliable but might have more significant variability in performance. Those systems also show the ability to rebound from disruption or survive a crisis (Grabowski and Roberts, 2019). Grabowski and Roberts (2019) argued that both characteristics are desirable, and a system can be an HRO and resilient simultaneously. This PhD thesis follows this view and sees reliability as a part of the concept of resilience.

As mentioned in the *System Setup* section (see section 2.2.4.1.1), the concept of resilience highlights the issues with trade-offs and describes the challenges associated with the complexity of a system. Trade-offs may cause employees to deviate from standard procedures and define their work practices. These new work practices may appear more efficient and effective from an employee's perspective but could potentially have devastating side effects on the system, as argued by Scheytt et al. (2006). Exceeding any system boundaries may lead to brittleness, which the system tries to prevent. One marker of a resilient system is whether it knows how close it works to the system's boundaries (Woods and Cook, 2006). Hence, Sujan et al. (2015) argued that there is a need to go beyond the traditional interventions such as standardisation, safeguards and barriers. Adaptations by practitioners and dynamic trade-off decisions are needed to *"translate inevitable tensions in their everyday work into safe practices"* (Sujan, Spurgeon and Cooke, 2015, p.60).

Systems need to adapt to fluctuations and make dynamic trade-offs (Lindblad, Flink and Ekstedt, 2017). Practitioners must be supported to make the required trade-off decisions and consider how the system could facilitate flexibility (Sujan, Spurgeon and Cooke, 2015). Wahl, Kongsvik and Antonson (2020) investigated trade-off decision-making regarding maritime operation and identified three abilities that support workers in this process: recognising anomalies and flexibly solving problems, defining limits of action through shared knowledge with peers, and operating the system with confidence. Shirali, Mohammadfam and Ebrahimipour (2013) found out that creating a reporting system, improving training, moving from hindsight to foresight, changing blame culture on accident investigations as well as considering safety as a value, establishing feedback system and improving the safety culture are the foundation for achieving resilience in a system. Saurin et al. (2014) described how training could be designed which helps grid electricians to develop and improve Hollnagel's (2009a) four cornerstones of resilience: monitoring, anticipating, responding, and learning. Their study highlighted the importance of training in more challenging scenarios and debriefing and evaluation (Saurin et al., 2014).

The drive for more efficiency in the system generates a drift towards the system's boundaries. The Law of Stretched Systems states that all systems are stretched to work at their competency envelope (Hoffman and Woods, 2011; Patterson and Deutsch, 2015). Hale and Heijer (2006b) analysed the Dutch and European railways to identify explanations for why systems become brittle. One of the contributing factors was that "*defences erode under production pressure*" (Hale and Heijer, 2006b, p.137). There is a drive to use every available opportunity to achieve higher intensity and efficiency of the operation. New technology or improvement in the processes create new resources which are exploited, and as soon as they become available, the system moves towards its maximum capacity. For resilient systems, it is crucial to balance the need for constant exploitation of these opportunities and safety by leaving enough buffer capacity in the system to compensate for internal and external variations in performance to avoid becoming brittle.

Another critical aspect is understanding the work of a system, which is supported by Havinga et al. (2018), who argued that there is value in investigating accidents and everyday work. Understanding how a system behaves as it works close to its safety margin and within the bandwidth of conditions can help discover sources of brittleness and resilience (Rankin et al., 2014). Saurin and Carim Junior (2011) identified 47 sources of brittleness in the work environment when examining an electricity distributor's health and safety management system with a framework based on the four RE principles: top management commitment, learning, flexibility and awareness. The study aimed to identify sources of brittleness and resilience in a system and proposed an improved method for assessing health and safety management systems. In another study, Saurin and Carim Junior (2012) used a different framework to identify and analyse brittleness and resilience sources for two Brazilian air taxi carriers. Being resilient was mainly used in the sense of adaptability to counteract some of the shortcomings in the design. The authors could identify a system's brittleness and resilience sources in both cases (Saurin and Carim Junior, 2012). Saurin and Carim Junior (2012) study linked the sources of brittleness directly with a corresponding source of resilience which allows an assessment of the severity of the sources of brittleness and the effectiveness of the sources of resilience. Therefore, the system needs to understand how work is conducted in a system (Lay, Branlat and Woods, 2015).

Shirali et al. (2012a) showed how a short survey could identify sources of brittleness in a system, such as poor safety training, poor management of change and poor attitude. Achieving this understanding means investigating if the processes work in practice as defined in theory. This difference is referred to as the deviation between Work-as-done (WAD) and Work-as-imagined (WAI) (Dekker, 2006). In order to be resilient, systems need to reflect on their work and understand the deviation between WAI and WAD (de Carvalho et al., 2018). The deviation between WAI and WAD is another area of resilience discussed by the academic literature. However, the deviation is described in two opposing views.

The first one sees the deviation as something negative that must be prevented, and closing the gap between the manager's perception of how the work is conducted (WAI) and the actual work (WAD) is a sign of resilience (Azadeh and Salehi, 2014). They argued that one cause of accidents is "*Practical drift*" (Snook, 2000, p.24) or "*Drifting into failure*" (Dekker, 2006, p.82). Practical drift *"is the slow steady uncoupling of local practice from written procedure"* (Snook, 2000, p.24) and Dekker, later on, described this phenomenon as the *"slow, incremental movement of system's operation towards and eventually across the boundaries of their safety envelope"* (Dekker, 2006, p.82). It happens as an endless chain of slight, gradual deviations from the original norm and is accepted and adopted by everyone inside a system. Literature often uses the 1994 shootdown of two US Army helicopters by two US Air Force fighter jets for practical drift. Two Black Hawk helicopters were part of a humanitarian aid mission in northern Iraq and were brought down in friendly fire, killing all 26 peacekeepers on board the two aircraft. According to Snook (2000), a major contributing factor to the accidental shootdown was the constant decoupling of practice from procedure over time, which he describes as practical drift. Dekker (2006) argued that a vital part of achieving resilience is detecting deviations from written procedures in seemingly safe systems before breakdowns occur. Dekker (2006) suggested broadening checks to see if the manager's perception of risks matches the one received by the front-line workers, and scenario-based auditing can be one way to conduct these tests.

Turner (1978) described the incubation period, which is the time when latent errors accumulate. According to Dekker and Pruchnicki (Dekker and Pruchnicki, 2014), incubation occurs due to reconciling differential pressures on a system combined with imperfect knowledge and uncertain technology. RE supports the system to stop this incubation by recognising the margins of safe operation and when the boundaries are skirted or crossed (Dekker and Pruchnicki, 2014). Deviation from procedures can lead to unsafe conditions, and McDonald and Durso (2015) showed how an intervention improves the workers' behaviour, not forgetting a step of the procedure. Their study in the rail sector concluded that breaking assignments down into smaller tasks minimises the likelihood of errors.

Pasman et al. (2013) argued that resilience depends on early warnings, and a gradual decline in the safety level can be detected by auditing the system. FRAM can help uncover deviations between procedural and actual practices and increase the safety and productivity of a system (Patriarca et al., 2018b). Once a signal is detected, it is crucial to translate it into a safety hazard to mitigate it (Axelsson, 2006). This transfer can significantly reduce the probability of incidents and major impacts on the system. According to the view, which sees the deviation between WAI and WAD as something negative, systems become brittle as the difference between WAI and WAD builds up. Local adaptation can have negative side-effects on the system as coordinated processes no longer match their definitions and the rising potential for accidents is caused by this gap. Therefore, one marker of resilience is the deviation between the processes and how the management assumes how they are carried out and how they are actually executed as it minimizes the chances for accidents caused by the deviation. Another marker is whether the system encourages discussions about risk as it maintains the awareness that local adaptation needs to be detected and prevented.

While some see the difference between WAI and WAD as the reason for accidents, others argue that fluctuations in work are unavoidable and necessary to maintain production and avoid failure (Patriarca and Bergström, 2017). Unlike the first approach, which sees compliance as a source of resilience, the other paradigm sees rule violation as a necessary adaption of rules. This adaptation is required to cope with the complexity of a system and the environment. Not every potential event can be foreseen, and mitigation procedures must be developed, making adaptation necessary. The complexity of a system or variations in the operation and changes in the built environment means that adaptation in the work processes is necessary to continue with the operation and mitigate arising threats (Watt, Jun and Waterson, 2019). It is argued that just having a set of procedures does not mean any incident can be prevented. When the incident occurs, the procedures may not be applicable or practical to deal with this uncertainty. This adaptation makes human variability an asset of safety (Borys, Else and Leggett, 2009). Humans are no longer considered the weak part of industrial systems and can be a critical component that makes socio-technical systems work (Re and Macchi, 2010). When seeing resilience as improvisation and adaptation, principles of Safety-II are used (Lundberg and Johansson, 2015). This form of resilience sees the human and its adaptability as the enabler to cope with challenging situations (Hegde et al., 2013). Carthey (2019) defined twelve regulatory, organisation, team and individual factors that help foster Safety II by studying resilience in the operating theatre. Factors include collaborative cross-checks and learning from incidents. These factors support teams and individuals to respond in a resilient manner (Carthey, 2019).

These two views show a contradiction in the literature as there are two ways of looking at the deviation between WAI and WAD. One sees deviation as a source of weakening resilience, while the other sees rule adaptation as a necessary action and source of resilience. The question arises, how can these two opposing views be combined in the concept of resilience as the first paradigm drives standardisation while the second calls for more flexibility (Johansson and Lundberg, 2010). The challenge is balancing the principles of Safety I with the properties of Safety-II (Johansson and Lundberg, 2010). Grøtan and Størseth (2012) looked at how the concept of RE can be an additional feature of the principles and practices of safety management and how to strike a balance between compliance and adaptability. New tools are needed to understand the difference between WAI and WAD (Cuvelier, Bencheckroun and Morel, 2017). Anderson et al. (2016) developed a Concept for Applying Resilience Engineering, CARE, to translate the concept of resilience into operational use. This model is based on the principle of WAI vs WAD and how adaptations and adjustments can help align demand and capacity to improve healthcare quality.

Rankin et al. (2014) saw the adaptive performance as a source of resilience but acknowledged that these adaptations could negatively influence a different part of the system. Others may not see changes in the operation, and opportunities are missed to identify and learn from these adaptations. However, more importantly, it makes the system unstable as other stakeholders may not be aware of the changes. Hence, a system needs to understand its adaptive performance and how its capabilities have changed concerning the system boundaries to avoid becoming brittle in the long term (Rankin et al., 2014). Wahl, Kongsvik and Antonson (2020) investigated this topic regarding maritime operation and identified three abilities supporting workers in this process: recognising anomalies and flexibly solving problems, defining limits of action through shared knowledge with peers and operating the system with confidence. RE is about making adaptation safe and guiding these adaptations (Provan et al., 2020). Grote et al. (2009) offered one option to achieve this, who suggested the concept of flexible routines to get the right balance between flexibility and standardization. These routines are achieved by flexible rules, namely, goal, process, and action rules.

According to Shirali et al. (2012b), challenges to building RE in companies were, prioritising production goals over safety, the difference between WAI and WAD, lack of reporting system, poor feedback loops and economic challenges. To counteract these challenges, Shirali et al. (2012b) suggested that safety should be a value, not a priority, change perspective from hindsight to foresight, enhance instruction systems, create an open and fair reporting system, improve feedback loops, and create a culture of learning and management of change. Owen, Healey and Benn (2013) indicated that communication, teamwork and operational feedback systems are among the factors that improve the safety of decommissioning operations. Yu et al. (2020) attempted to define a list of eight general principles for RE by merging principles identified in the RE literature with socio-ecological system principles. Their list included recognizing that system context matters, fostering social capital, maintaining diversity, managing connectivity, encouraging learning-by-doing, embracing polycentric control, addressing the problem of fit and managing complexity to help systems grow and maintain their level of resilience. In addition, Woltjer et al. (2013) used eight principles to assess the resilience of the ATM. The principles are work-as-done, varying conditions, signals, and cues (anticipation, monitoring, response), goal trade-offs, adaptive capacity, coupling and interactions, timing, pacing, synchronization, under-specification, and approximate adjustments. These principles are intended to guide the resilient design of various roles within ATM

(Woltjer et al., 2015). Maintenance also plays an essential role in improving the productivity and efficiency of a system. Furthermore, it limits the risk of failure (Azadeh et al., 2016).

To summarize the *System Checks* theme, a system needs to constantly monitor its operation and assess whether the operation or environment has changed. These regular audits help the system to ensure that a sufficient safety margin is kept over time. Table 2-6 lists the purpose of the *System Checks* theme and summarises the high-level principles required for this theme. For each principle, an illustrative source is given.

Table 2-6 Summary of the System Checks theme

System Checks
Purpose: Reviewing operation and environment to ensure that safety margin does not erode over time
High-level principles: • Recognizing adaptations in operation and drift correction (e.g. Dekker, 2006) • Identifying changes in environment (e.g. Hollnagel, 2014a) • Recognizing changing risks to operation (e.g. Wreathall, 2006)

2.2.4.2 System Preparedness

This theme is closely linked to anticipation, one of Hollnagel’s (2009a) four cornerstones, and is used for expected, short-term disruptions. Bottlenecks and future disruptions may be temporary and do not require a permanent change in the structure. The *System Preparedness* theme can help to temporarily increase the buffer capacity by adding additional resources or reducing its performance output to allow safe operation during the anticipated event.

Hemond and Robert (2012) explained how the concept of preparedness evolved into the state of resilience. Their work highlighted how crucial preparation for future disruptions is. The preparedness concept can be expanded to include the capacity to anticipate, maintain and adapt activities. Therefore, the creation of foresight is a vital feature of a resilient system. Hollnagel (2009a) pointed out that anticipation is key to a resilient operation, which is in line with Nemeth (2019), who concluded that anticipating and adapting to expected demands increased resilience in his examples from paediatric care. One conclusion was that resilience was achieved by "*anticipated change in demand volume*" (Nemeth, 2019, p.109). It is essential to shift from a retrospective perspective of disruptions to a proactive approach and actively anticipate and alleviate weaknesses in the system, as argued by Benn, Healey and Hollnagel (2008) in their study about improving performance reliability in the surgical system. Gomes et al. (2009) saw the creation of foresight and escaping from the hindsight bias as essential to achieving resilience in the helicopter transportation system. Anticipating future challenges and bottlenecks gives systems enough time to prepare for these challenges and puts the system into a state of alertness. The system counteracts the drift caused by the different forces and identifies when the operation is pushed near or across boundaries before hazardous situations occur.

Dolif et al. (2013) analysed the effectiveness of the ALTERTA RIO system, a weather forecast information system used to evacuate risk areas prior to severe weather. The analysis found an urgent demand for easier and faster access to correct and accurate meteorological information during these events to allow the forecasters to integrate better support tools. The analysis also highlighted essential sources of resilience and brittleness, which can be addressed in the design and system of a weather forecasting system, such as mixing experienced forecasters with new members to preserve knowledge.

Besides adding additional resources, a deliberate reduction of the system's performance to increase the buffer capacity is also a mitigation strategy for the system for identified and anticipated bottlenecks (Woods, 2011). Decreasing the system's performance can be seen in Hollnagel's and Sundström's (2006) state of regular reduced functioning. Reducing the performance frees up resources to counteract the impact on the remaining operation during the predicted disruption. The increase in safety margin is noticeable in Rasmussen's (1997) model when the gap between unacceptable and marginal operating boundaries widens. This form of foresight or anticipation is required to achieve chronic goals, such as safety and compromise acute goals (e.g. high utilisation of the system). Hence, a resilient system must create foresight (Woods and Hollnagel, 2006).

It is crucial for the system to respond to an early indication of errors (Øien et al., 2010), expected disruptions or predicted higher demand and make sacrifice decisions if necessary. This sacrifice is necessary to ensure safe operation and protect the rest of the operation from ripple effects and avoid a significant performance reduction. Appropriate sacrifice judgement can be challenging, especially as the hindsight view might show that the reduction of the operation may not have been needed as the normal operation would have been possible. However, systems need to make these sacrifices to avoid people taking higher risks than they want to achieve the potential for resilience (Woods, 2006b). Sacrifice decision-making highlighted the need for top-level commitment (Wreathall, 2006). It is vital to stop working in unsafe conditions, but doing that may be challenging in practice, as Weber et al. (2018) highlighted by studying the work in the liquefied petroleum gas industry. Workers may fear negative consequences and therefore do not make the sacrifice decision (Weber et al., 2018). Woods (2006a) tried to support people to make relaxation or sacrifice decisions with explicit guidance, but this topic remains a significant challenge in achieving resilience.

RE is aimed support companies to develop a preventative focus and anticipate undesirable events, supporting systems to be more resilient and sustainable (Fernandes, Hurtado and Batiz, 2015). The purpose of the *System Preparedness* theme and the mentioned principles that support generating resilience in this theme are summarized in Table 2-7 with illustrative sources.

Table 2-7 Summary of the System Preparedness theme

System Preparedness
Purpose: Creation of foresight and achieving state of alertness
High-level principles: • Ability to anticipate bottlenecks (e.g. Hollnagel, 2009a) • Preparing operation for expected disturbance (e.g. Dolif et al., 2013) • Temporarily increasing buffer capacity (e.g. Woods, 2011)

2.2.4.3 System Response

The previously discussed forms of resilience describe a process which should help minimise the risk of disruptions and ensure the system is in the best possible shape to cope with disruptive events. Resilience in a reactive context describes the ability of systems to respond and cope with large and small disruptions (Fairbanks et al., 2014). Shirali et al. (2013) argued that the growing complexity increases the potential for disastrous failures and new safety issues in highly technological systems. As mentioned earlier, disruptions are unavoidable due to the system's complexity and interrelation between the sub-systems (Bergström, van Winsen and Henriqson, 2015). Nan and Sansavini (2017) focussed on the reactive side of resilience and listed three essential resilience capabilities for interdependent infrastructures. The ability to cope with disruption or change by minimising the initial negative impacts is called absorptive. The ability to adapt itself to changes and disruptions is called adaptive. A system's restorative capability describes the system's ability to recover from these events. Therefore, reacting to events is another critical feature of resilience. This differentiation shows that a system needs to have multiple forms of disturbed functioning in order to respond to various events (Hollnagel and Sundström, 2006).

Woods (2011) defined five essential resilience characteristics that enhance resilience's reactive form: buffer capacity, flexibility, margin, tolerance and cross-scale interaction. The buffering capacity is the type of event the system can absorb or, if necessary, adapt to without a collapse in the performance or structure of the system. Restructuring the system in response to external pressures or changes is described as flexibility. The system's margin indicates how close the system is to the performance boundaries, and tolerance is the system's behaviour when operating near these boundaries. Cross-scale interaction relates to the complexity of a system and the links within a system. RE principles also include the efficient use of resources during emergencies (Xu et al., 2018). Bruneau et al. (2003) and Filippone et al. (2016) referred to resilience with the 4R, robustness, redundancy, resourcefulness and rapidity, giving a system absorptive, adaptive and restorative capacity. Cimellaro et al. (2010) used these four characteristics when assessing how the disaster resilience of a hospital and hospital network can be improved. Their study concluded that the recovery process after an event usually depends on human and technical resources, public policies and societal preparedness and their availability influence the recovery. Tang and Heinimann (2018) utilized the 4R approach to search for solutions to minimise road congestion.

In order to take it apart and define what for kind of response these properties are required, the *System Response* was divided into three subthemes, *System Robustness*, *System Rebound*, and *System Extensibility*. The subsequent three subthemes describe the reactive side of a resilient system once a disruption has happened. The subthemes that are part of the *System Response* theme represent the required response to cope with regular threats, irregular threats, and unexampled events (Westrum, 2006).

Each form of resilience shows another escalation level, with *System Robustness* being the response to the least and *System Extensibility* the response to the most severe disruptive event. These three forms correlate with Dinh et al. (2012) categorisation of normal, upset, and catastrophic states, which is similar to the normal, degraded, and critical modes used by Bouloiz (2020). For handling a disturbance in the *System Robustness* theme, the system stays in the normal state, in the *System Rebound* theme in the upset state and in the *System Extensibility* theme in the catastrophic state.

The difference between *System Robustness*, *System Rebound* and *System Extensibility* can be explained and visualised in the Stress-Strain model. Woods and Wreathall (2008) used the model to represent the resilience of systems when faced with disruption.

Stress-Strain model

The stress-strain model was initially used in material science to describe the characteristics of a material and show how it performs under increasing loads. There are two regions, an elastic region in which the material elongates uniformly when the load increases and returns to its original lengths once it is released. The second region, called the plastic or non-uniform region, describes the phase when increasing loads cause the material to strain non-uniformly until a failure point is reached.

Woods and Wreathall (2008) used the model to represent the system's resilience when faced with disruption, as shown in Figure 2-11. Like in the original stress-strain model, their representation consists of a uniform and non-uniform region. In Woods' and Wreathall's (2008) analogy, the straight line stands for occasions where the system stretches uniformly to compensate for increased demands. This ability means that the system uses pre-developed procedures, plans, training, personnel, and related operational resources to compensate for the additional demand and stretches uniformly. This on-plan performance area correlates with Woods' (2006b) idea of a competence envelope.

As the demand increases and using all the pre-planned resources, the system's ability to adapt within the competence envelope is exceeded. In order to counteract the accumulation of gaps, active steps are needed to avoid system failure, and the system begins to stretch non-uniformly. People and groups actively adjust strategies or may recruit new resources to provide the system with enough flexibility to stretch. The additional region of the curve represents sources of resilience that compensate for the additional demand and enable non-uniform stretching. However, once the sources of resilience are exhausted, the system can no longer stretch, and decompensation patterns occur. The Stress-Strain model is a good way to visualise the adaptive capacity of a system (Fung et al., 2020). The stress-strain model in material science only consists of the uniform region and the hump in the non-uniform regions. The additional segments in the non-uniform region in Figure 2-11 were added to explain the additional adaptations required to avoid failure in the *System Extensibility* theme.

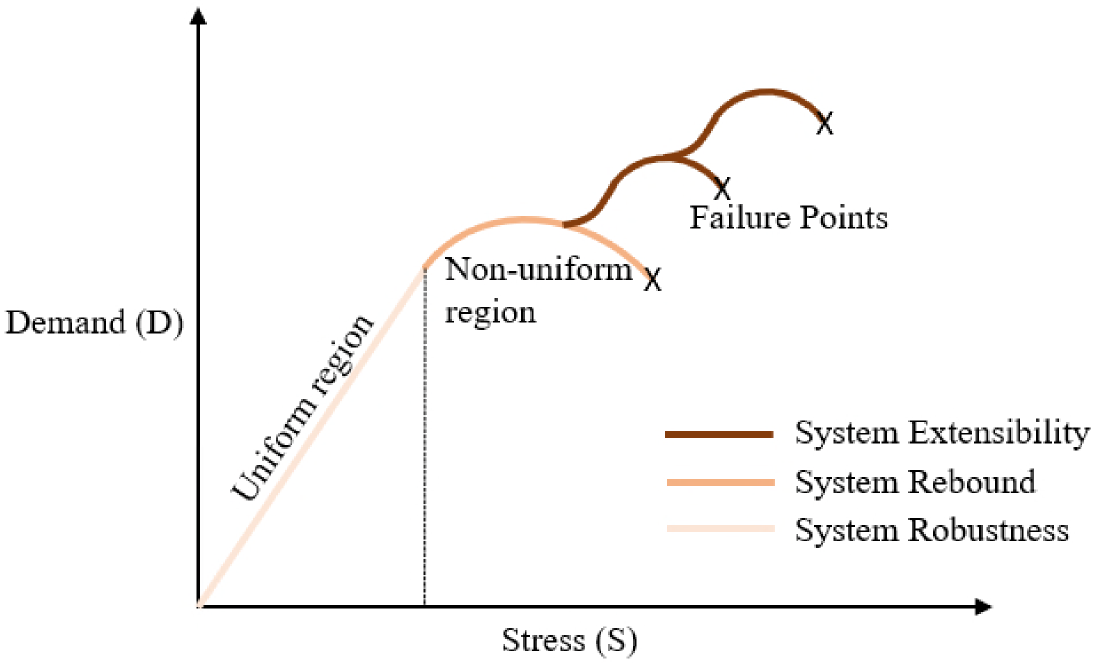


Figure 2-11 Stress-Strain model

One crucial difference between using the Stress-Strain model in material science and RE is the view of what part of the graph represents resilience. In material science, only the uniform region is labelled resilience, and the non-uniform region is called ductility (Negrello et al., 2019). However, Woods (2006b) argued that calling the performance in the uniform region resilience is wrong (Woods and Wreathall, 2008). For Woods (2006b), resilience starts in the non-uniform region, which is different from material science and other RE authors' perspectives (e.g. Barker, Ramirez-Marquez and Rocco, 2013), who see resilience as a combination of both behaviours. This PhD thesis follows the latter view and sees resilience as a combination of uniform and non-uniform regions.

Resilience Dynamics model

As shown in Figure 2-12, Cook (2006) presented a model that sees resilience as temporal patterns (see Figure 2-12). The performance to cope with various demands, changing over time, is called resilience. Cook (2006) defined three temporal patterns of resilience. The first one illustrates elastic performance, which always meets the demand. This ability corresponds with the uniform region of the Stress-Strain model or the normal functioning in Hollnagel and Sundström's

(2006) resilience model. The second pattern shows the principle of deformation or adaptation. The adaptation allows the system to compensate for a spike in demand, allowing a response to the increased demand. Again, there are parallels between the Stress-Strain model and the adaptation region or the disturbed functions in the Resilience State model. Cook's (2006) third temporal resilience pattern illustrates that the system's capacity to adapt to higher demand is limited. Once exceeded, the systems fail to respond to the demand, and collapse occurs.

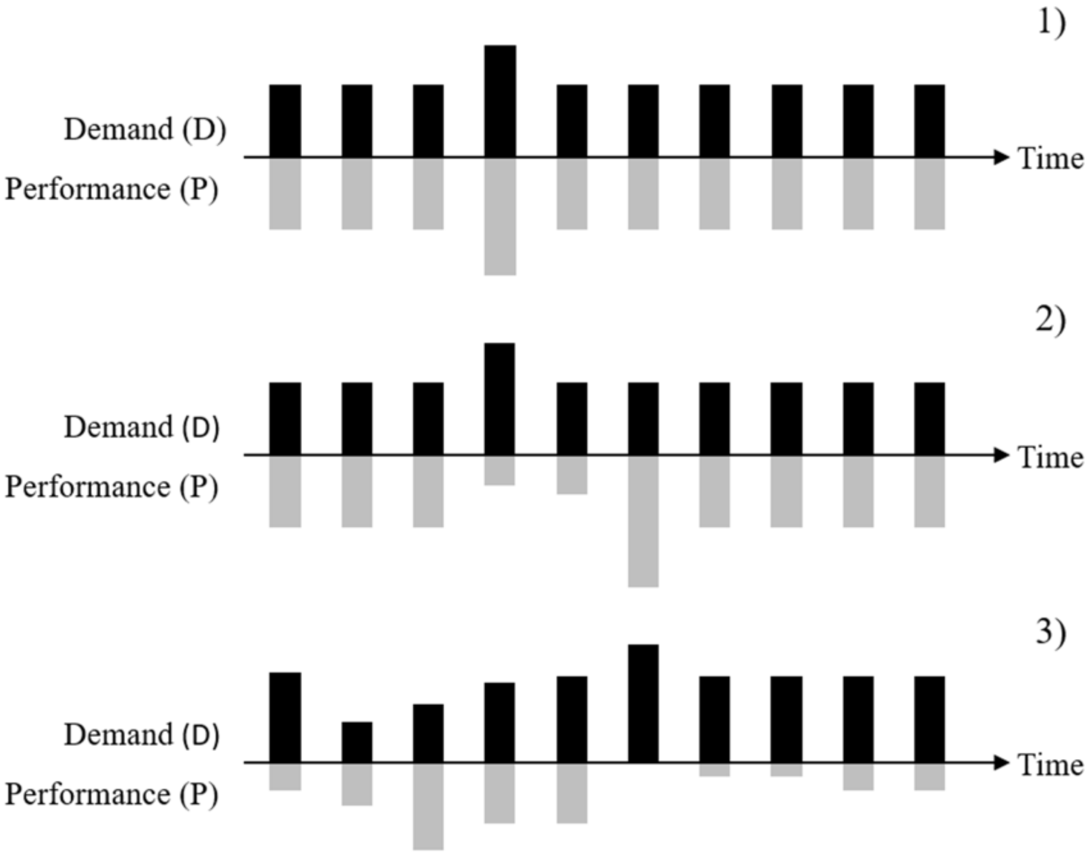


Figure 2-12 Resilience Dynamics model (adapted from Cook (2006))

According to Woods and Wreathall (2008), more resilient systems can foresee the decline and recognize that a strategy shift or additional resources are needed to avoid decompensation. Decompensation describes the state in which the system can no longer adapt and reaches its failure point (Woods and Wreathall, 2008). The following three sections summarize the purpose and properties of the *System Robustness*, *System Response*, and *System Extensibility* subthemes.

2.2.4.3.1 System Robustness

One way to define resilience is to see the concept as a synonym for robustness (Woods, 2015), and the concept of robustness works well for regular threats. Those events happen often enough, so the systems develop a standard response (Westrum, 2006). This form of threat has similar features to the actual and related threat described by Hällgren, Rouleau and de Rond (2018). Actual and related events are scenarios directly related to a system's core activities that happened in the past and are somehow expected to happen again. These events fall in the competence envelope (Woods, 2006b), which helps the system match the required demand with its performance. The goal of the concept of robustness is to increase the capability to absorb perturbations and keep the operation within the system's functional limits (Miller and Xiao, 2007). Miller and Xiao (2007) investigated the work at a trauma centre and analysed how mitigation strategies such as overlapping shifts and role redundancies keep the operation within Rasmussen's (1997) described safe operation envelope. Furthermore, identifying potential risks and developing procedures for these events expands the set of disruptions the system can respond to effectively.

The *System Robustness* theme helps the system *"after incidents happen rather than prevent incidents from occurring"* (Dinh et al., 2012, p.233). According to Dinh et al. (2012), resilience is achieved by minimization of failure, early detection, higher flexibility, higher controllability, minimization and limitation of effects and better administrative controls and procedures(Dinh et al., 2012). Early detection "*refers to the recognition of a system's 'weak' signals that could be precursors of an undesired abnormal event*" (Jain et al., 2018, p.69), and early detection provides the maximum time for an appropriate response (Jain et al., 2018). Furthermore, redundant resources, multiple sources and more than one delivery line can enhance the infrastructure of a system and improve its resilience, as shown by Wang and Ip (2009) in their study about logistic networks for aircraft servicing. Furthermore, multiple redundant communication channels can significantly enhance the overall network resilience as the system can maintain the performance of the whole network communication with at least one radio station in operation (Kabashkin, 2016).

However, seeing resilience as a label for robustness and reliability only works for well-modelled disruptive events (Alderson and Doyle, 2010). Hence, as soon as a perturbation falls outside the scope and the system cannot continue to respond to the demand, it will experience a sudden failure (Woods, 2015). The form of resilience as *System Robustness* reaches its limit as the disruption is beyond the standard competence, and the pre-planned adaptive capabilities of the system are exhausted. This category can either be an unexpected event or the event's severity, which requires a temporary shift in the operation. Looking at the Stress-Strain model, the difference between *System Robustness* and *System Rebound* is apparent in the transition from the uniform into the non-uniform area. De Carvalho (2011, p.1483) definition of resilience as *“the ability of a system to recognize and act accordingly (shift of processes, strategies, and coordination) when variability in its performance is unanticipated and falls beyond the usual competence and adaptations”* draws a good line between *System Robustness* and *System Rebound*. Tokadli et al. (2016) gave an example where the *System Robustness* principle reached its limits. Their study of the fire in the Chicago ATC centre showed how the system's performance rapidly declines once an event exceeds the system boundaries. Furthermore, due to limited resources, increasing the system’s capability to deal with some additional perturbations at one end increases the vulnerability of the systems to other types of disruptive events.

Table 2-8 summarizes the purpose of the *System Robustness* theme. It also lists the high-level principles that are relevant to this theme. An illustrative contribution supports each high-level principle.

Table 2-8 Summary of the System Robustness theme

System Robustness
Purpose: Absorbing failure while continuing with Normal Operation
High-level principles: • Early detection of disturbance (e.g. Dinh et al., 2012) • Ability to minimise and contain failure (e.g. Westrum, 2006) • Use of internal buffer capacity (e.g. Woods, 2006b) • Use of redundancies (e.g. Madni and Jackson, 2009)

2.2.4.3.2 System Rebound

In the *System Rebound* theme, the system is confronted with an event for which no exact pre-planned response is available. It needs to adjust existing procedures, develop other solutions to handle the perturbation, or adjust general, high-level principles to the specific scenario (Hollnagel, 2014a). Being faced with a disruption that falls outside the design envelope, the system is trying to recover from it and return to normal or previous function and state (Francis and Bekera, 2014). Westrum (2006) described these events as irregular threats, which are more challenging for a system. These can be events with low probability but catastrophic effects. Due to the number of possible events, a system cannot prepare for all of them. This principle also applies to past events, where information and environments change in the future, or new kinds of scenarios occur. Furthermore, Boring (2009) concluded that not all risks could be estimated. Morel et al. (2009) used this approach to look at resilience when analysing how the concept of resilience is used in sea fishing. They referred to it as the two visions of resilience; one focuses on trade-offs between safety and production as described in section 2.2.4.1. The other view is the ability to recover after a significant accident.

Westrum (2006) made an interesting point by differentiating in which circumstances an event takes place and whether an event would fall into a regular or irregular threat. For example, a bus bombing would be considered an irregular threat in most cases. However, during the Second Intifada in Israel, many bombings occurred, which led to the development of a coordinated response of the emergency services to mass casualty events, such as a suicide bombing on a bus (Cook and Nemeth, 2006). This example shows that the form of resilience is context specific. A scenario that falls into *System Rebound* for one system may still be in the category of *System Robustness* for another system. Therefore, the response to disruptions depends on the risk perception and the system's environment.

The principle of *System Rebound* is demonstrated in the Stress-Strain model with the first non-uniform curve when additional resources are freed-up to cope with the additional demand (Woods and Wreathall, 2008). Adaptability and adaptive behaviour are essential as they allow systems to cope with the variability of the environment without collapsing or losing control. When *System Rebound* is required, the situations challenge the boundaries of a system and demand the potential for adaptive capacity (Cook and Rasmussen, 2005). Adaptive capacity means reconfiguring the operation or using available additional resources (Madni and Jackson, 2009) and continuing the operation after a severe mishap (Hollnagel, 2006). In addition, Reniers et al. (2014) identified in their study of the chemical industry that stopping the spread of failures inside a system is vital for achieving resilience. *System Rebound* is represented in Hemond's and Robert's (2012, p.404) definition of resilience as *"the ability of a system to maintain or restore an acceptable level of functioning despite disruptions and failures".* The goal is to maintain adequate performance during the disruption, as shown by Wang et al. (2019) when studying the evacuation capability of infrastructure in emergencies. Resilience in this context is about restoring the operation (Shiraki et al., 2017).

A reoccurring and common slogan when seeing resilience as the response to an event is the ability to "*bounce back"* (Macleod, 2015, page not identified). Instead of using the vocabulary of rebounding, other authors describe this phenomenon as the ability to return to equilibrium (Woods, 2015). Barker Ramirez-Marquez and Rocco (2013) used the definition of rebounding in their studies of networks and what stages the system passes through when handling a disruption. They referred to this process in the Performance Over time model (Barker, Ramirez-Marquez and Rocco, 2013).

Performance Over Time model

Barker, Ramirez-Marquez and Rocco (2013) defined resilience with four dimensions: reliability, vulnerability, survivability and recoverability. Figure 2-13 illustrates their model, which also features Henry's and Ramirez-Marques' (2012) work. In their context, reliability governs the system in its original stable state and is the absence of disruption. Vulnerability is the effects on the system performance following an event which happens at the time t_e. For compensating vulnerability, survivability describes the minimization of the original effects of the disruption. The system reaches its disrupted state at the time t_d. Recoverability is *"the speed at which an entity or system recovers from a severe shock to achieve a desired state"* (Rose, 2007, p.384). The system recovery from the event starts at the time t_s until a new, stable, recovered state of the system is reached at t_f. With the Performance Over Time model, Madni's and Jackson's (2009) metrics of time to restore operation or performance can be visualised.

It is essential to mention that the performance level of the stable recovered system can be the same as during the original stable state, lower, or even a recovery that exceeds the previous performance level is possible. This variance in restored operation is what Madni and Jackson (2009, p.188) referred to with the metric, "*degree to which pre-disruption state is restored*".

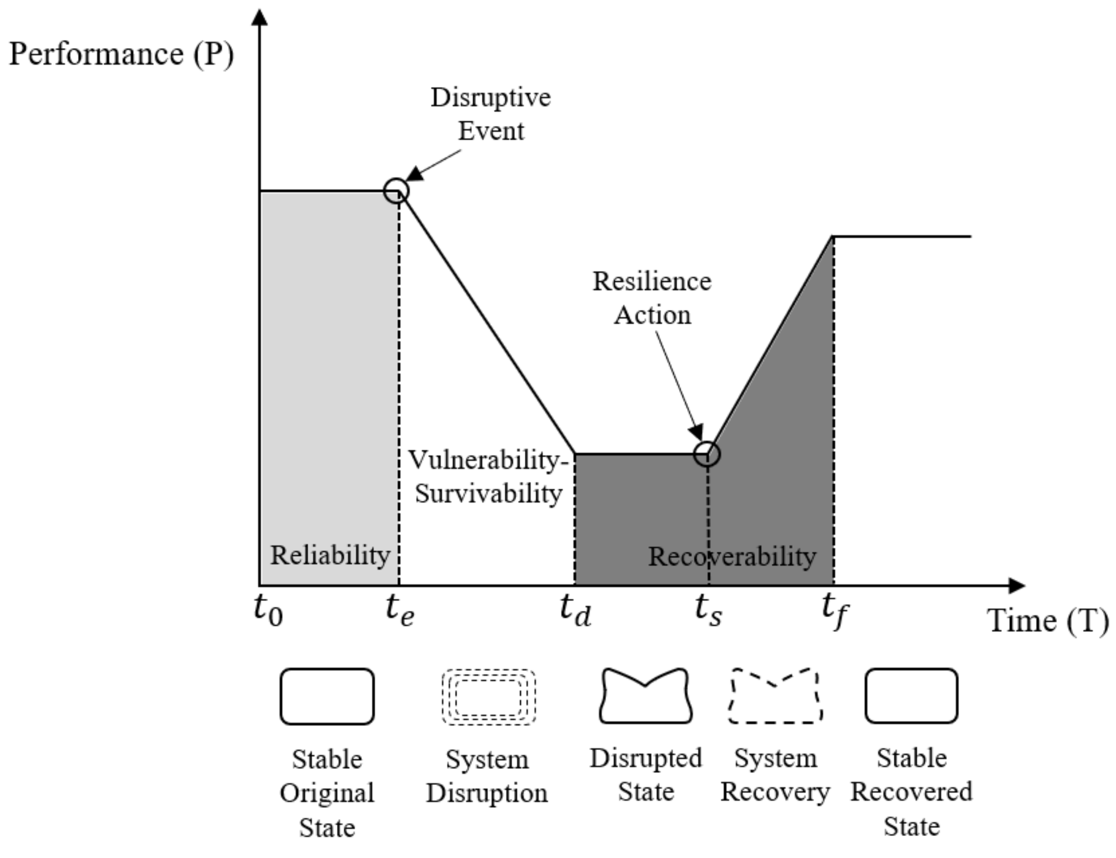


Figure 2-13 Performance Over Time model (adapted from Barker, Ramirez-Marquez and Rocco (2013))

The Performance Over Time model is a suitable example to illustrate the resilience of a system with the four characteristics (reliability, vulnerability, survivability, and recoverability). Tran, Domerc and Mavris (2019) also used this model to investigate the resilience of complex networked systems. The model further shows how extending the reliability of a system, strengthening the system's survivability, minimising the effects of disruptions, reducing the time to recover, and maximising the level of recovered performance are all ways to improve the resilience of a system.

It is essential to mention that different versions of the Performance Over Time model in the RE literature exist. Different names for the phases and states are used. However, the model's underlying theory and the performance line's shape are always similar. For example, Yodo and Wang (2016) used reliable, vulnerable, restoration, and new states to describe a system's various states in the Performance Over time model (see photo 1 in Figure 2-14). They also showed that a system could reach different performance levels after recovery. In another version, Fischer et al. (2018) used the preparation, prevention, protection, response, and recovery phase in their Performance Over Time model version (see photo 2 in Figure 2-14).

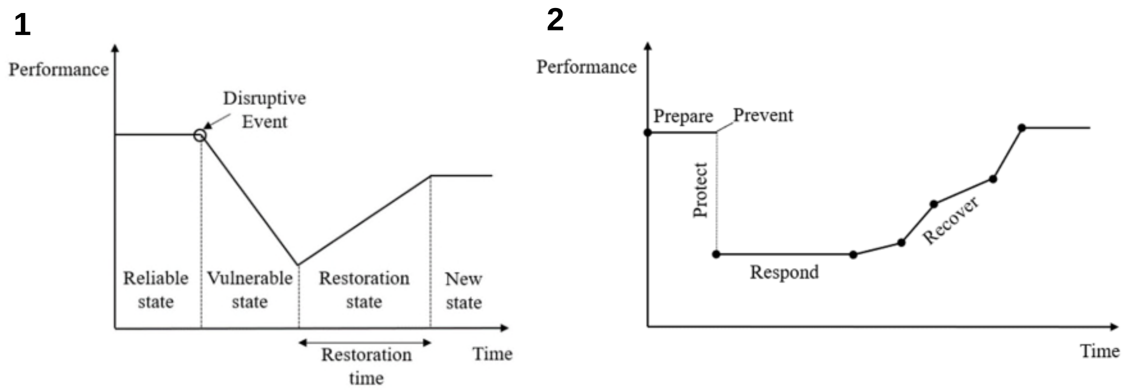


Figure 2-14 Examples for variations of the Performance-Over-Time model (adapted from Yodo and Wang (2016) & Fischer et al. (2018))

The Performance Over Time model is frequently used when referring to resilience in the context of rebound (Cai et al., 2015; Joannou et al., 2019; Nan and Sansavini, 2017). The authors aim to demonstrate how the performance decreases after a disruption and to what level the operation can be recovered with resilient actions. Taleb Berrouane and Khan (2019) used the model and applied a stochastic method to calculate an oil pipeline system's resilience based on absorption, adaptation and recovery capabilities. Li et al. (2019) proved that proactive risk assessment helped to improve the system and should include absorptive, adaptive and restorative measures of the stages in the Performance Over Time model and applied the model to a gas transmission process.

Lundberg and Johansson (2015) saw resilience as a robust resistance to the situation but, at the same time, acknowledged that it can also be an agile adjustment. Their model includes Safety I principles such as prevention and avoidance of danger and principles of Safety II, which describe how the system can adjust to these dangers. In their model, resilience is achieved by features of Safety II. With different functions and strategies the system can apply, the model tries to find a balance between Safety I, which describes stability-enhancing properties, and Safety II, which describes resilience-enhancing properties. Lundberg and Johansson (2015) stressed the importance of running system indicators that are needed to monitor and assess whether the appropriate response strategies and functions are used.

Branlat and Woods (2010) discovered that decompensation, working at cross-purposes and getting stuck in outdated behaviours can hinder the adaptive capacity and lead to adaptive failure in response to a disruption. This argument has been supported by Shipper (2017) when studying leadership in a multiteam setting during a disruption in the railway industry. Naderpajouh et al. (2018) concluded that a resilient response dramatically depends on the appropriate governance structure. The system should self-correct and adjust to the situation to enable recovery to regular operation (Ross et al., 2014). As well as the need for coordination in events like this, Ross et al. (2014) highlighted the importance that workers realize when they reach the limits of their expertise and require specialists' input in their study of diabetic care.

Systems need to understand how the current conditions impact the operation, how the conditions allow a proper operation with the available resources and how the resources can be applied to return to normal operation (Caldwell, 2014). On the other hand, Cai et al. (2018) took a slightly different approach and listed high redundancy, low failure rate, and high repair rate as enablers for resilient system response. These factors result in a *“high steady-state availability and short steady-state time before and after any shocks”* (Cai et al., 2018, p.217).

The testing of the emergency preparedness strategies might result in *“increasing the response to highly complex, unknown events and improving organizational resilience”* (Pescaroli et al., 2018, p.131). Furniss et al. (2011) studied the performance of nuclear power plant operators and argued that resilience is crucial in understanding adaptation challenges in complex socio-technical systems. Therefore, it enables better human adaptive behaviour. Lundberg’s and Rankin’s (2014) study of small response teams also stressed the importance of role improvisation during situations different from the plans made in advance. They recommended that improvisation of roles is added to the regular training. Aminoff (2007), on the other hand, warned that shifts in responsibilities and control make a system vulnerable as it demands time and resources to do it. Therefore, coordination and communication during an unexpected event are essential; hence Bechky and Okhuysen (2011) investigated how resilience can be achieved within a team and concluded that this could be done by drawing on socio-cognitive resources. In the face of surprise, shared task knowledge and a common understanding of the workflow expectations can enhance the response to disruptive events (Bechky and Okhuysen, 2011). Shared task knowledge is linked to the network's redundancy and that multiple members know how to complete specific actions. Common workflow expectation refers to the understanding of the sequence of events. Having cross-member expertise has been demonstrated to help cope with a situation and give appropriate instructions to involved parties since all parties know each other’s capabilities.

Furniss et al. (2011, p.2) saw resilience as “*the ability to deal successfully with unexpected events*”. They developed a framework for observing resilient behaviour at a small team level. They used four categories for their analysis. Resilient Repertoire contains skill, strategies, and competencies, while Mode of

Operation refers to how the system organises itself. Resources and Enabling Conditions describe the constraints which affect the strategy, and the last category consists of the Vulnerabilities and Opportunities of the system. It is possible to specify essential elements that influence resilient behaviour and successful situation handling with the framework. This tool helps that "*circumstances that facilitate the creation of new strategies in the repertoire can be created, and successful resilience strategies can be identified, enhanced, and shared within and across the situation*" (Furniss et al., 2011, p.10).

Scenario-based training can support staff to develop resilience skills and prepare for disruptions. The interplay between unexpected conditions and complexity in emergencies requires resilient emergency management based on role improvisation (Lundberg and Rankin, 2014). This flexible crisis response is needed when situations are encountered which do not meet plans made in advance, as discovered by their study of a small flexible crisis response team. While Lundberg and Rankin (2014) saw the role of improvisation as the enabler for resilience, they also warn that improvisation can have side effects and produce vulnerabilities that need to be managed and outline goals for the training of these teams.

Van der Beek and Schraagen (2015) developed the so-called ADAPTER questionnaire based on the four cornerstones. They assessed the resilience of a team and concluded that team responding, shared transformational leadership, proactive awareness, cooperation with other teams and interrelation amongst team members during unexpected situations are crucial factors. It was also demonstrated to help show the relationship between each party and how the data are transferred between the parties (Tveiten et al., 2012). The interdependency between sub-systems requires the management of interfaces to allow the sub-system to align. This management involves practical communication tools to coordinate the response. Tveiten et al. (2012) stressed the importance of proactive risk management and redundancies in the system. They showed how mapping out the different stakeholders could support the process and build resilience in emergency management. Furthermore, the response heavily depends on decision support systems that help systems understand the development of the situation and reach an agreement in the response process (Collis, Schmid and Tobias, 2014). Amodeo and Francis (2019) highlighted the importance of self-organisation through changing the governance structure by investigating illustrative cases of a port and inland waterway in the US. They discovered that both networks changed their inter-organisational relationships and information flow "*as the system moves from a normal response to a scenario to a non-uniform scenario*" (Amodeo and Francis, 2019, page not identified).

The purpose of the System Rebound theme is listed in Table 2-9. The table also summarizes the high-level principles that support the system's resilience mentioned in this section. For each principle, an illustrative source is given.

Table 2-9 Summary of the System Rebound theme

System Rebound
Purpose: Containing damage and returning to Normal Operation
High-level principles: • Building on principles of the System Robustness theme • Use of additional resources (e.g. Woods and Wreathall, 2008) • Restoring functions and repair rate/Rapidity (e.g. Filippone et al., 2016) • Governance structure for coordination and communication (e.g. Naderpajouh et al., 2018) • Agile adjustments (e.g. Lundberg and Rankin, 2014)

2.2.4.3.3 System Extensibility

The *System Extensibility* theme concentrates on the extension of the adaptive capacity of a system in the event of a surprise. This ability could be needed when a disruption pushes the system towards failure (Cook and Rasmussen, 2005). Some events may be so severe that regular adaptability and flexibility of a system are not enough to cope with the situation. These situations could be what Westrum (2006) described as unexampled events. Whereas the irregular threat may represent a scale-up of the regular threat, the threat level of an unexampled event cannot be foreseen in enough detail to develop mitigation responses. An event of this category severely challenges the system boundaries and pushes the responders beyond their collective experience envelope (Westrum, 2006).

System Extensibility can be seen when increasing demand results in new reconfigurations and adaptation, and new non-uniform regions evolve to escape failure in the Stress-Strain model (see Figure 2-11). The system is trying to prevent an overload and accommodate the demand by severely compromising the performance to avoid failure. This phenomenon is described as disturbed functioning in the Resilience State Space model (Hollnagel and Sundström, 2006). Brittleness can be observed when a system breaks down rapidly as soon as the system boundaries are breached, and according to Woods (2006c), the reverse of brittleness is resilience. Responding to an event of this magnitude is graceful extensibility (Woods, 2018).

A *System Extensibility* type of disruption requires the system to adapt to the new environment, and returning to regular operation may not be the primary aim. A resilient system's fundamental feature is maintaining or regaining a dynamically stable state, but the responses must never lead to the system losing control (Hollnagel, 2006). The mitigation strategy could either take on additional resources to cope with the additional demand or shift the system's structure to an emergency configuration.

An example of an unexampled event is the terrorist attack on the World Trade Centre in 2001 (Westrum, 2006). In a study about the restoration of electric power after the terror attacks on 11th September 2011, Mendonca and Wallace (2015) discovered that boundary spanning capability, the ability to restore linkages between systems, played a significant role in achieving resilience.

System Extensibility builds on features mentioned in the *System Robustness* and *System Rebound* theme. These features include self-organisation and the deployment of additional resources. Basic system features, such as self-organisation, monitoring or development of a series of responses, determine the outcome and whether the system can react effectively (Westrum, 2006). It was also found that language skills, domain knowledge and organisational structure can influence performance during crises (Rankin, Dahlbäck and Lundberg, 2013). The research team analysed the performance of a government crisis management team that assisted citizens after a crisis abroad during a role-playing exercise when the people had to act in improvised roles (Rankin, Dahlbäck and Lundberg, 2013). The study found that the team performance decreased when some members had to take on roles for which they were missing sufficient language skills, professional training, sufficient organisational structure of the task, or a lack of domain knowledge. These skills can be improved by strengthening the domain knowledge, training to take on roles or tasks outside the area of specialization, defining formal routines for change and using routines and tools for information sharing (Rankin, Dahlbäck and Lundberg, 2013).

Furthermore, available resources can also contribute to a positive response as they release extra capacity to deal with the disruption. A system can be confronted with information overload during a significant crisis. Confusion can be reduced by a single point of information which structures the information for the various stakeholders (Reichardt, Ulfarsson and Pétursdóttir, 2018). Reichardt, Ulfarsson and Pétursdóttir (2018) concluded that multi-sector partnership and the development of crisis management infrastructure are essential, especially when dealing with multiple disruptions, and enhanced cooperation and communication are an essential key for seamless mitigation of the situation (Alexander, 2013a). Clear communication and coordination strategies in place reduce confusion and contribute to successful management of the situation, as everyone knows their roles and how information is shared and updated.

Table 2-10 includes the purpose of the *System Extensibility* theme and summarises all the high-level principles that support the generation of resilience in the *System Extensibility* theme with an illustrative source.

Table 2-10 Summary of the System Extensibility theme

System Extensibility
Purpose: Avoiding loss of control and regaining stable state
High-level principles: • Building on principles of the System Robustness and System Rebound theme • Ability to avoid overload by shifting to emergency configuration (e.g. Hollnagel and Sundström, 2006) • Ability to restore critical linkages between systems (e.g. Mendonça and Wallace, 2015)

2.2.4.4 System Changes

The desire to achieve resilience in the long term defines the *System Changes* theme. The theme focuses on the ability of the system to remain functional and avoid becoming brittle in the future. This goal can be accomplished by proactive management, which includes anticipating challenges and preparing the operation for them.

Long-term sustainability is achieved by studying previous events, capturing the lesson learnings, and implementing them in operation. The need for learning, both on an individual and system level, is highlighted by Gajek (2019), who emphasised that major industrial accidents happened in the past and still happen contemporarily. Furthermore, Enjalbert and Vanderhaegen (2017) pointed out the need for reinforced learning to achieve resilience. Having survived a disruption, the system needs to analyse and learn from what could be improved and what went well to be resilient. Even in what can be classified as an unsuccessful response, good practices may be identified and preserved for future events (Kitamura, 2016). Including lesson learning is vital in making progress and improving the system (Ouedraogo, Enjalbert and Vanderhaegen, 2013). Learning from past events can help systems identify and mitigate uncertainties in their operation, as shown by Yazdi et al. (2019). The research team investigated the fire in a large petrochemical plant and showed how a thorough investigation of the accident improved the plant's design. Therefore, it is crucial to see disruptions as an opportunity for systems to prosper and integrate the lessons learned from previous disruptions into the operation. Martins Junior et al. (2012) urged companies to change how they investigate accidents and stop blaming people. This approach allows systems to learn from past events and uncover underlying issues.

Therefore, resilience in a system can be built through observation, analysis and design, and development (Nemeth and Herrera, 2015). Sustainability in this context means a system identifies what basic architectural principles need to be preserved and maintains the *“flexibility to continue to adapt over long scales*” (Woods, 2015, p.8). Losing resilience in this context indicates an adaptability deficit (Folke, 2006). Adaptability also includes responding to ecosystem dynamics and change (Berkes, Colding and Folke, 2003).

For Carpenter et al. (2001, p.765), *"resilience is the magnitude of disturbance that can be tolerated before a socioecological system (SES) moves to a different region of state space controlled by a different set of processes."* This view on resilience strongly supports the sustainability element. Even though the system's capabilities define resilience, environmental changes can influence the operation and impact the system's resilience. The adaptive cycle concept plays a key role in learning and enhancing organisational resilience (Chaffin and Gunderson, 2016; Gunderson and Holling, 2002). This concept is also used to describe the reactive side of *System Changes*.

The general perception of disruptions is negative. However, *"exposure to adversity in moderation can mobilize previously untapped resources"* (Fletcher and Sarkar, 2013, p.20). Resilience in this context is seen as a concept of bouncing forward and being better prepared for a similar disruption in the future (Nagenborg, 2019). Cook's and Nemeth's (2006) example of the bus bombing and how the response to it changed due to many bombings is a good example of how the *System Changes* theme works in its reactive form. Being faced with a reoccurring threat, the hospitals learned from the events and developed a coordinated response to mass casualty events (Cook and Nemeth, 2006). Another example of how learning through accident investigation can generate some learnings was shown by Yazdi et al. (2019) and their study of the fire at the Bouli Sina petrochemical plant. Learning can include changes in procedures, introducing new barriers, increasing resources or adjusting the operation, and learning is hugely important for achieving resilience (Hollnagel, 2009a).

However, changes to the system to improve performance or manage risk may have unintended effects on a different part of the system (du Plessis and Vandeskog, 2020). These side effects may even negatively impact the system or generate new risks, which are not evident from the beginning (Scheytt et al., 2006). Hence, the *System Changes* theme requires extensive knowledge about the operation and how it interrelates with the environment and a detailed prediction of the future. FRAM could be one option to investigate how the changes would impact the different parts of the system.

System Changes aim to achieve long-term sustainability, and adjustments are needed to adapt to the ever-changing environment (Folke, 2006). It includes identifying future challenges or anticipating bottlenecks ahead and then permanently adjusting the operation, ensuring long-term sustainability (Burbidge, 2018). Burbidge (2018) gave the example of adjusting the operation by looking at climate change challenges in the air transportation system. Da Mata et al. (2006) identified different goal conflicts which put pressure on the system. In highlighting the stressors on the system, they demonstrated that the system has not adapted to the environmental changes.

Resilient systems must successfully spot hazardous conditions and transform to dampen changes and disruptive events before serious harm occurs (Patterson et al., 2007). This view is supported by Garcia-Serna et al. (2007), who defined resilience as the design for adaptation. Similar to *System Preparedness*, the system anticipates future challenges through *System Checks*. However, unlike events in the *System Preparedness*, these challenges require fundamental and long-term changes to the structure, which lead to *System Changes*.

The purpose and high-level principles of the *System Changes* theme are summarized in Table 2-11, with an illustrative contribution for each principle.

Table 2-11 Summary of the System Changes theme

System Changes
Purpose: Ensuring long-term sustainability of system
High-level principles: • Creation of lesson learning (e.g. Yazdi et al., 2019) • Anticipation of future challenges (e.g. Burbidge, 2018) • Safe integration of long-term changes (e.g. du Plessis and Vandeskog, 2020)

2.2.5 Closing remarks

The literature review analysed how the term resilience is used in the research field of RE. In order to clarify the concept, the study's outcomes were classified into four themes of resilience. The PRF is a way to combine different views on resilience and is aimed to help conceptualise which part of resilience is generated in which theme. By analysing the RE literature and synthesising the outputs, it was possible to determine high-level principles for each of the themes and subthemes. Examples in the RE literature indicated that the themes interrelate. For example, Dinh et al. (2012) argued that the setup of a system influences the availability of resources during the response to the disruption.

Based on the outputs of the literature, the empirical work is aimed at addressing the two objectives:

- Collect empirical evidence of the identified high-level principles
- Refine the framework based on a synthesis of the outputs from the empirical investigation

In order to meet the two objectives, the refined framework in Figure 2-15 was applied to various case studies of the UK air transportation industry.

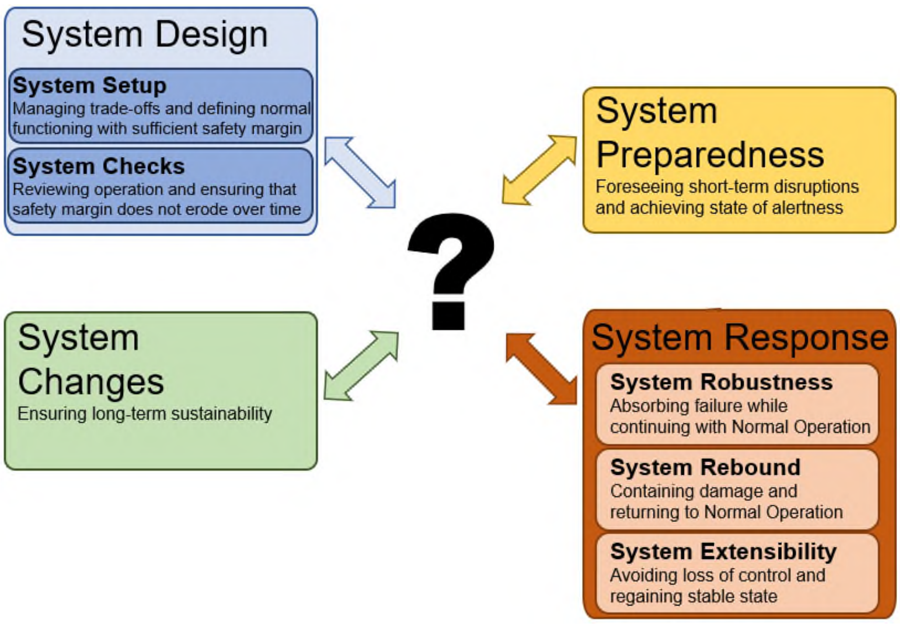


Figure 2-15 The Preliminary Resilience Framework

3 RESEARCH METHODOLOGY

3.1 Introduction

This chapter outlines the overarching approach followed to address the research question and add empirical data to the outputs of the literature review. The research question of this work was formulated as follows:

How is the UK air transportation industry resilient?

However, the literature review showed that there is not a distinct definition of what the concept of resilience is. *"Concept formation lies at the heart of all social science endeavors…Concepts are integral to every argument for they address the most basic question of social science research: what are they talking about?"* (Gerring, 2012, p.112). The literature review findings were used to conceptualise resilience by proposing four themes and defining principles for each resilience-generating (sub)-theme. The research methodology for the data collection was chosen to accommodate the divergent views of resilience and collected empirical evidence for the proposed framework. Therefore, the two main objectives of the empirical work are:

- Generating an empirical application of the PRF of the literature review by capturing empirical evidence to illustrate how the identified high-level principles were operationalised in the UK air transportation industry.
- Use the findings of the empirical work to determine connections between the themes.

Having studied the RE literature, the proposition is that a system's resilience can be generated through *System Design, System Preparedness*, *System Response* and *System Changes* themes. Five cases from the UK air transportation industry were used to address this proposition. Zaborek (2009) argued that the nature of the research problem is the most critical factor in selecting the research method. In case of this research, it was vital to select a research methodology that provide sufficient flexibility to deal with the complexity of the UK air transportation system and cope with the challenges added due to the COVID-19 pandemic. Furthermore, the research design must gather a reliable and complete set of evidence to give a qualified assessment of the proposition and explain resilience in the UK air transportation industry context.

3.2 Pragmatism

The research used pragmatism as a paradigm to respond to challenges encountered due to the worldwide pandemic (Creswell, 2013). The spread of COVID-19 impeded data access as key industry partners became unavailable. Reasons for this were multifaceted and included people being furloughed, increased workload did not allow industry partners to engage in the research, or lockdown and new safety measures prevented site visits. Therefore, the research methodology had to be adjusted in March 2020.

Pragmatism provided a helpful guide to finding a solution for revising the research outline. This type of paradigm is best suited for real-world practice-oriented research (Creswell, 2013). According to Creswell (2013, p.28), pragmatism encourages the freedom to "*choose the methods, techniques, and procedures of research that best meet needs and purposes*".

For achieving an authentic methodological rationale for a pragmatic approach, the research must have a viable research question and clear purpose (Robson, 2011). The research used empirical data from five cases to explain resilience in a UK air transportation context. In order to generate empirical evidence of how the identified high-level principles were present in the operation of the UK air transportation system, the data were collected and analysed from five different cases. According to Johnson and Onwuegbuzie (2004, p.17), "*pragmatism takes an explicitly value-oriented approach to research*". The case studies' value was to identify practical examples of where and how the identified principles were operationalised and use the empirical evidence to identify connections between the different themes.

3.3 Overview of Methodology

As mentioned in the previous section, pragmatism guided the data collection and analysis design. The researcher used exploratory qualitative research to establish detailed descriptions of five different UK air transportation industry cases. Exploratory research and how it was used for the thesis are explained in section 3.4.

Once a detailed description was established, thematic analysis was used to identify how the principles from the literature review were operationalised in each case. In order to meet the objectives of identifying principles and establishing new connections for the PRF, the thematic data analysis process, displayed in Figure 3-1, was developed and used in each case study. This thematic analysis process is an adoption of Fereday and Muir-Cochrane's (2006) work and is explained in greater detail in section 3.7.

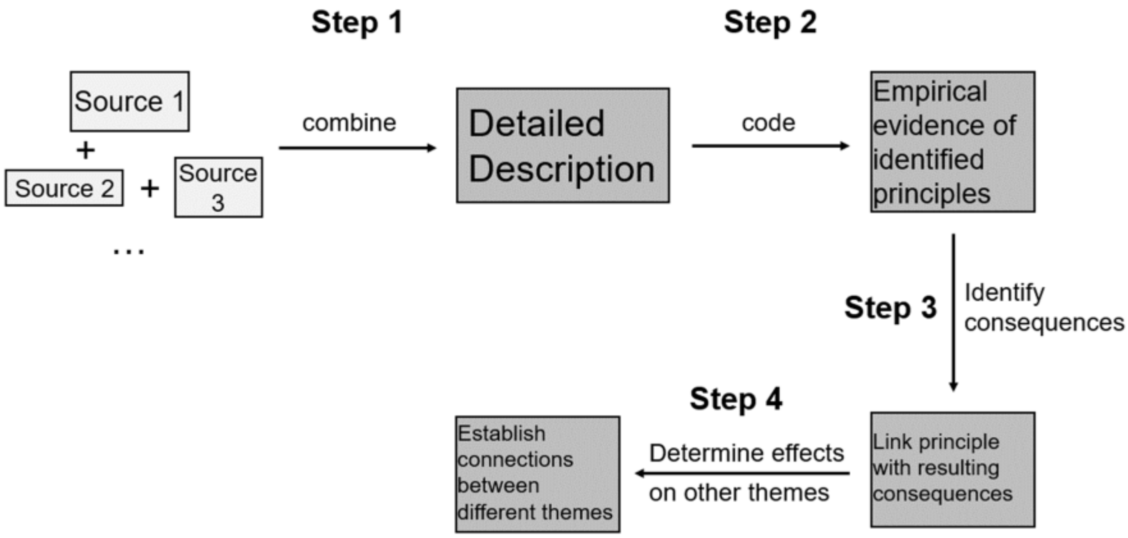


Figure 3-1 Methodology for data collection and analysis

The following section provides a brief overview of the steps that were taken for collecting and analysing the data in the empirical part of this research.

Step 1: Data from different sources were combined to describe the case comprehensively. Section 3.4 explains the approach and data collection tools used to obtain data for each case study.

Step 2: The detailed case description was thematically analysed using the high-level principles identified for each (sub-)theme in the literature review. Each identified principle was used as a coding category, and the case was searched for practical examples of the principles.

Step 3: Once the case description matched a principle, the data were analysed to determine what consequence the operationalised principle caused.

Step 4: After establishing the link between the operationalised principle and the resulting consequence, it was possible to determine if the consequence affected other themes from the literature. Based on the case studies and the identified link between operationalised principle and consequence, it was possible to establish connections between the different themes.

As mentioned previously, a more detailed description for Steps 2 – 4 is provided in section 3.7.

3.4 Exploratory qualitative research

There are two main types of data: quantitative and qualitative data. Quantitative data are countable data, such as aircraft movement or delay minutes. On the other hand, qualitative data cannot be measured in numerical values. The latter category is descriptive data, including interviews, observations, documents, and physical samples.

This research used the case study design by Robert K Yin (2018) as a guideline for the empirical research part. The design by Yin (2018) allows the use of both quantitative and qualitative evidence sampling. His book *Case Study Research Design and Methods* (Yin, 2018) has been continuously revised and updated since it was first published in 1984 (Yin, 1984) and is currently in its sixth edition. This type of case study consists of five core components: research question, hypothesis, unit of analysis, linking the data to the hypothesis, and criteria for interpreting the findings (Yin, 2018). The research investigated the question of how the UK air transportation industry achieves resilience. The hypothesis was that the identified high-level principles could generate resilience in a system. This research used an exploratory case study design to explain how the UK air transportation industry operationalised principles identified in the literature review and the results of the case studies highlighted the consequences of the applied principles to determine connections between the themes.

According to Yin (2018), exploratory case studies are a practical methodology for investigating and understanding complex issues within some real-life context. Case study research is the preferred method for "*how*" and "*when*" questions (Yin, 2018, p.11), when the researcher has limited control over events, and when the lines between phenomenon and context are blurry (Yin, 2018). Investigating how the UK air transportation industry generates resilience falls into these categories. Furthermore, Bradley, Curry, and Devers (2007, p.1754) mentioned that "*qualitative research is well suited for understanding phenomena within their context, uncovering links among concepts and behaviors, and generating and refining theory*". Qualitative research seemed a promising approach based on the research question and outputs of the literature review. The qualitative research approach would help to identify empirical examples for the principles and use the findings to refine the framework and conceptualise resilience in the UK air transport context. As a result, this research utilized exploratory qualitative research to address the research question.

In order to achieve high-quality research results, Yin (2018) listed three criteria of integrity that are important for exploratory case studies, as summarized in Table 3-1.

Table 3-1 Four tests of Case Study Integrity (based on Yin, 2018)

Quality aspect for integrity		Tactics
Construct Validity	Establishing measures that reduce the risk of subjective judgements	• Use of multiple sources of information • Establish chain of evidence • Have key informants review draft case study report
External Validity	Being able to create a domain to which the findings could be generalized	• Use theory in single-case studies • Use replication logic in multiple-case studies
Reliability	Allowing the study to be repeated and generating the same results	• Use case study protocol • Develop case study database

3.4.1 Construct Validity

Multiple sources of evidence have been utilized for this research and combined through triangulation. *"Triangulation is a technique to analyse results of the same study using different methods of data collection…Most often, triangulation helps validate research findings by checking that different methods or different observers of the same phenomenon produce the same results. It can also be used to interrogate inconsistencies and data that are not expected to align."* (Nightingale, 2020, p.477). An extensive literature review has resulted in the proposition that resilience can be generated through four themes. The case studies were used to collect empirical evidence of the identified principles using various data sources. The case studies were also used to elaborate the PRF more completely by adding connections between the themes. The data for the case studies was purposely collected from multiple sources of information, including interviews with industry experts, observations, and a review of appropriate documents.

Chains of evidence have been established for each case study, testing the proposition and adding new details to the resilience framework. The process that was used for analysing the case studies is explained in section 3.7. Each case study was written as individual sections, but the outputs were combined in an ICRF in the discussion chapter (see chapter 5).

Although several conferences and events have been cancelled or postponed due to the COVID-19 pandemic, key findings have been presented to aviation and non-aviation audiences, including industry professionals and academics, which supported the construct validity. These presentations and discussions allowed the researcher to gain feedback from groups of learned professionals on the concept and content of this doctoral thesis. This input supported the review of the thesis and refinement of ideas. A list of all presentations has been added to the appendix of the thesis (see Appendix B).

Furthermore, a review panel consisting of an independent reviewer, a Professor from Cranfield School of Management, and a chair, a Senior Lecturer in Cranfield School of Aerospace, Transport and Manufacturing, provided feedback to the researcher and its supervision team at various stages of the Doctoral thesis. The review panel assessed the context, aims, objectives, methodological approach, key findings, discussion, contribution to knowledge, impact, and delivery of the research after four, nine, 12 and 32 months of the start of the research.

3.4.2 External Validity

External validity concerns generalising the results and whether key findings apply to other domains, not just the air transportation industry. Generalisability would mean testing whether the ICRF works in other domains, using Yin’s (2018) replication logic in multiple-case studies.

The case studies have been used to elaborate on the literature review findings. The additional details collected through the case study were used to refine and adjust the PRF. It has taken a substantial amount of time and effort to build trust and credibility to reach out to industry experts and collect the data for the case study. Even though it was attempted to generalise the key findings, some of the case studies had characteristics specific to the air transportation industry. Therefore, it would have been unfeasible to validate the fundamental research outputs using Yin’s (2018) replication logic and test the research methodology in another system during the time frame of the Doctoral thesis. However, key findings have been shared for an International Association of Ports and Harbors (IAPH) research project. In addition, site visits to the Hamburg Port Authority and Port of Antwerp were undertaken to observe whether general principles and phenomena of the integrated resilience model could be applied to the maritime industry. Moreover, the ICRF was presented to the Technical Risk and Resilience Committee of the IAPH during the 2022 World Ports Conference. The applicability to the maritime industry was indicated as committee members used the framework to explain examples from the maritime industry. This occurrence may indicate that the research methodology and findings could be transferable to other industries to test its integrity.

3.4.3 Reliability

A case study protocol should help to ensure reliability. The processes and techniques used to collect and analyse the data were documented and explained in the *Data sources* section of each case study. The documentation allowed replication of the study, meaning other researchers would reach similar conclusions by analysing the data as Yin (2018) described. The researcher attempted to make the steps as transparent as possible and explain how the outputs of the case studies informed the refinement of the PRF. Building chains of evidence were also aimed at increasing the reliability of the research (Yin, 2018).

3.5 Selection of cases

Based on the findings of the literature review, themes and subthemes through which resilience can be generated were proposed. The purpose of the case studies was to examine the theoretical framework in the UK air transportation industry context. The decision was taken to study five cases from the UK air transport industry.

3.5.1 Elements of studying cases

Harrison et al. (2017) list several elements that are essential in studying cases:

a. **The case** – Identifying and defining an object for the case study as the unit of interest or analysis is vital. The object might include an individual, group, organisation, social situation, event, phenomena, process, or programme.
b. **A bounded system** – The case is bounded by space, activity, and time, which comprises a system of connections. This frame helps to manage the contextual variables of the case. However, the boundaries between the case and its context could be blurry.
c. **Studied in context** – The case is conducted in its natural environment or real-life setting. The contextual variables can include economic, cultural, social, political, organisational, and historical factors.
d. **In-depth study** – The case is selected to accommodate an intensive investigation and analysis of an issue, and the required fieldwork is

intrinsic to the research question. The level of analysis may vary in engagement and depth, depending on the research's orientation, method, and purpose.

e. **Selecting the case** – The case should reflect the purpose of the study and should be based on its conditions. The scope of the research may include single, within-case, and multiple case sampling, capturing ordinary, unique, varied and/or accessible aspects.
f. **Multiple sources of evidence** – The case uses multiple data sources to allow a comprehensive breadth and depth of analysis. Data collection methods include focus groups, artefact and document reviews, interviews, questionnaires, and surveys. The analysis method needs to be rigorous and systematic, and triangulation is a highly valued and frequently used method to combine various sources of evidence.

Five exploratory, single case studies were conducted to collect empirical examples of the identified high-level principles. Table 3-2 provides an overview of the unit of analysis, activities, and time frame used for each case study.

Table 3-2 Summary of case studies criteria

	Airspace Management	**IRG**	**Mass diversion protocol**	**Repatriation flight**	**IRG response to COVID-19**
Unit of analysis	Main UK ANSP provider	UK cross-industry working group	UK air transportation system	One UK airport	UK cross-industry working group
Activities that were analysed	Day-to-day operation	Day-to-day operation	Operation during mass diversion event	Operation during COVID-19 repatriation flight	Operation during initial stage of COVID-19 crisis
Time of analysis	Snapshot of operation on 14th May 2019	Formation and working of IRG from Dec 2017 until Jan 2020	Presentation of new protocol in Mar 2019 until review of first enactment in Jul 2019	Events prior to, during repatriation flight operation	Working of IRG from Jan 2020 until June 2020
Time when data were collected	14th May 2019	20th Mar 2019 – 26th Feb 2020	28th Mar – 17th July 2019	21st Sept – 30th Sept 2020	4th Feb 2020 – 12th Aug 2021

The table also outlines during which period the data for each case study were collected to cover Harrison et al. (2017) case study elements.

3.5.2 Rational for selecting the cases

- **Case study 1 – Airspace Management**

  Providing air traffic services is an essential element of the air transportation industry as it manages the flow of aircraft between airports. Therefore, it played a crucial part in the overall resilience of the air transportation system and was selected for the research. This case study about the management of UK airspace was used to investigate the day-to-day operation of the primary UK ANSP. Data were collected during a site visit on 14th May 2019. The processes and mechanisms to provide air traffic services were analysed to identify if the system was using principles identified in the literature review. The case study looked specifically at the system's design, and trade-off decisions in the *System Setup* could be observed. In addition, the case study also explored mechanisms that were used to maintain sufficient safety margins through *System Checks*. Therefore, the case provided a prime example of investigating high-level principles from the *System Design* theme. As shown in Table 3-3, the analysis also identified high-level principles from the three other themes.

- **Case study 2 – IRG**

  The second case study analysed the working of cross-industry collaboration. The UK air transportation industry concluded in 2017 that more collaboration was needed to improve the system's resilience (CAA, 2017b). The IRG has the word resilience in the group's name and appeared to be a highly suitable use case to analyse how the identified high-level principles were used in practice. Furthermore, the formation of the IRG is a sign of the *System Changes* theme as the UK air transportation industry proactively identified a bottleneck in the system and established the IRG as a result.

  The case study used the formation and working of the IRG to collect empirical pieces of evidence of how principles from the literature review were used in practice. The case study considered the time between

December 2017 and January 2020 for the analysis and data were collected between 20th March 2019 and 26th February 2020. The establishment and work of the IRG and how this cross-industry working group maintains and improves the level of resilience of the UK air transportation industry were explained and analysed. As the analysis showed (see Table 3-3), the case study showed elements of all four themes. The outputs allowed a refinement of the initial framework by adding connections between the themes.

- **Case study 3 – Mass diversion protocol**

  The case was selected as it provided a practical example of how the UK air transportation stakeholders worked together to strengthen the network's resilience by increasing robustness and incorporating additional capacity. According to one IRG document (IRG, 2019), the UK air transportation system had become brittle during mass diversion events, as described in subchapter 4.3. As a result, a mass diversion protocol was developed. For case study 3, the operation during a mass diversion event on 10th July 2019 was analysed. The time between the first presentation of the protocol in March 2019 and the IRG debriefing call on 17th July 2019 was reviewed.

  With this case study, it was also possible to describe the practical application of principles in the *System Setup* and the *System Response* theme, as shown in Table 3-3.

- **Case study 4 – Repatriation flight**

  This case was selected as it showed the response to an irregular threat and how the airport responded to it by also using resources from external stakeholders. The COVID-19 pandemic brought some unusual challenges to the aviation industry. Case study 4 investigates how a UK airport responded to a COVID-19 repatriation flight during the early stages of the COVID-19 pandemic. The case study investigated the time between the event's initial preparation (8th March 2020) and the operation's completion on 11th March. The data collection happened retrospectively, and data were collected from 21st September to 30th September 2020. With the case study results, it was possible to highlight principles of *System Design*, *System Preparedness*, and *System Response* (see Table 3-3). Furthermore, the outputs also helped refine the PRF by adding connections between the three themes.

- **Case study 5 – IRG response to COVID-19**

  The case was selected as COVID-19 was often described as an unprecedented situation (e.g. Sun, Wandelt and Zhang, 2020), which describes the response to an unexampled event. Case study 5 also used the IRG as the unit of analysis. It investigated what identified principles of the various themes could be observed in the working of the IRG during the initial phase of the COVID-19 pandemic. Data were collected between 4th February 2020 and 12th August 2021 to describe the working of the IRG between January 2020 and June 2020.

  The goal of the case study was to identify principles that the IRG used during the initial phase to increase the potential for the system's resilience. The outputs highlighted principles used in *the System Design*, *System Preparedness* and *System Response* (*System Extensibility*) theme (see Table 3-3).

Table 3-3 Overview of which (sub-)themes covered in each case study

		Airspace Management	IRG	Mass diversion protocol	Repatriation flight	IRG response to COVID-19
Themes	**Subthemes**					
System Design		✓	✓	✓	✓	✓
	System Setup	✓	✓	✓	✓	✓
	System Checks	✓	✓		✓	✓
System Preparedness		✓	✓		✓	✓
System Response		✓	✓	✓	✓	✓
	System Robustness			✓		
	System Rebound				✓	
	System Extensibility					✓
System Changes		✓	✓	✓		

3.5.3 Role of the researcher

In the first year of the research, the researcher invested a lot of time and effort in establishing close relationships with members of the industry and the CAA. This work included attending industry workshops, following up with individuals and arranging site visits to various industry stakeholders' headquarters. Becoming a member of the IRG added new and strengthened existing relationships. Those connections brought the researcher in a privileged position to gain unrivalled access to data. The researcher was invited to meetings with senior managers and executives, followed discussions between industry and government, and attended debriefing calls. Furthermore, the researcher could utilize briefing notes, after-action reports, and emergency protocols.

The researcher saw himself as a narrator of complex or fast-evolving situations involving multiple stakeholders. The researcher had the resources to document, report on, interpret and make sense of complex situations to associate five cases with the context of the PhD. Various data collection instruments were used to assemble information for building a detailed narrative of each of the cases, as explained in section 3.6.

3.6 Instruments of data collection

As mentioned in section 3.4, the integrity of the research was achieved by using multiple sources of evidence. Data were collected through various primary and secondary sources to ensure that sufficient data were captured to provide a detailed narrative. The list of primary sources of evidence consisted of observations and interviews, and for secondary data collection, reports and statistics were utilized. For each case study, various sources of evidence were used and listed in each case study under the section *Data sources* (see chapter 4).

3.6.1 Observations

Observations present a valuable source for case-study-based research. Kawulich (2005) referred to Erlandson et al.'s (1993) when describing observations as a method "*to describe existing situations using the five senses, providing a "written photograph" of the situation under study*" (Kawulich, 2005, page not identified). This data collection method was used in various studies in the RE literature (e.g. Praetorius, Hollnagel and Dahlman, 2015; Wachs et al., 2016). It allows observing activities and documents matches or differences between theory and practice.

For this research, observations during various occasions were made. The following two sections provide a high-level view of observations made during the research duration. Each case study describes what kind of observations contributed to the development of the detailed narrative.

3.6.1.1 Membership in the Industry Resilience Group

One month after the start of the research, the researcher was invited to attend a workshop in which the chair of the IRG also participated. The IRG is an industry-led working group that includes all the major UK air transportation stakeholders. The IRG works collectively on challenges regarding the UK air transportation system, and the IRG is explained in more detail in subchapter 4.2. The workshop provided an opportunity to discuss the meaning of resilience with the IRG chair, and the researcher was invited to attend and observe future IRG meetings and workshops. The IRG chair saw significant benefits in bringing an academic perspective to the working group and using the researcher's input to shape the group's future orientation. Since March 2019, the researcher has attended the monthly meetings of the IRG until it was suspended in November 2020. In addition, several workshops and (de-)briefing calls hosted by the IRG were attended during this time. The researcher also attended two meetings at which multiple executives from various UK aviation stakeholders attended.

The researcher took detailed notes during each meeting (usually between 3-6 DIN A5 pages), which provided valuable information and helped understand the research context. The notes included details about IRG projects and summaries of discussions between the IRG members observed during the meetings. The handwritten notes were studied after the meeting and stored electronically.

3.6.1.2 Observations during site visits

In addition to the IRG events, several site visits were arranged to collect data or support the researcher in understanding different parts of the air transportation industry. Site visits were also a popular data collection tool in the RE literature. For example, Pardo-Ferreira et al. (2020) went to a construction site to understand construction activities for concrete structures, or in a different study, Herrera, Hollnagel and Håbrekke (2010) observed helicopter landings during simulator sessions.

The site visits in this research helped create knowledge about the complexity of the aviation network and how the interfaces were managed. Furthermore, insights into the work environment were gained. During the site visits, detailed notes of the activities, processes and involved actors were taken. Table 3-4 provides an overview of site visits during the thesis's duration.

Table 3-4 List of site visits

Date	Site	Duration
25th April 2019	Heathrow Compass Centre – IT Team	3 h
14th May 2019	NATS Operations Centre	6 h
18th & 19th September 2019	Operations Centre TUI	3 h & 12 h
29th October 2019	Gatwick ATC Standby capabilities	2 ½ h
21st November 2019	Manchester Airport Operation Team	6 h
08th January 2020	Heathrow Airport Tower	2 h
23rd January 2020	Heathrow Operations Centre and Resilience Team	3 ½ h
06th February 2020	TUI Business Continuity Team	1 ½ h

Site visits were undertaken to the National Air Traffic Services (NATS) Swanwick Control Centre, where the researcher gained insight into the various operations at the control centre. Three site visits to Heathrow Airport were conducted where the researcher spent time in the airport operations centre, with the airport's resilience team, data management team and time at Heathrow Tower. During a trip to Gatwick Airport, the various standby capabilities and resources were shown to the researcher. A day at Manchester airport gave the researcher insights into the operation of the airport operation's team and interface with ground handlers. The researcher received insight into the operation of an airline by spending three days at the operations centre at TUI's headquarters in London Luton. The site observation included time with the operation, the engineering, the crew resourcing, the safety, the customer care department, and the crisis management team.

Some advantages of the observation method are:

1. **Natural environment** – The observation method collects data from a real-world environment and does not require an artificial research environment, unlike other research methods (i.e. laboratory testing). Observations describe phenomena as they occur in the natural environment, providing practical insight.
2. **Simple method** – Observations are a suitable data collection method. Daily routines and processes can be observed, making this method an accessible and straightforward research method.
3. **Minimal cooperation of participants** – Unlike interviews, the observation method does not require direct engagement with the participant. The research method of observation allows the researcher to capture processes and behaviours while not interfering with the participant's daily routine.

Although the observation method has several advantages, some disadvantages are associated with collecting data through observations, and the researcher needs to be mindful of those.

Some disadvantages of the observation method are:

1. **Not representative data** – According to the Hawthorne effect (McCarney et al., 2007), people react differently when being observed, which could influence the data that are being collected. Hence, it was essential to build trust, so it would feel natural for the participants to be observed. Furthermore, most data were collected when the researcher attended meetings or workshops as a participant rather than as an external observer.
2. **Not everything is captured** – The complexity of the observed situation could lead to the researcher's inability to capture everything. This inability is supported by the fact that all of the data were collected by a single person. The researcher tried to overcome this issue by following up with participants to confirm the collected information and add or clarify missing links.

3. **Resources** – Collecting data through observations is time-consuming, as accumulating data cannot be hurried. Travelling to various locations is also an activity that generates costs. All of this makes the observation method a prolonged and expensive affair.
4. **Personal bias** – Due to the layout of a Doctoral thesis, all observations were conducted by the same researcher and not a team of researchers. Although this may have supported the collected data's consistency, the researcher's subjective bias may affect the observations, as they could try and confirm their preconceptions. A confirmation bias would jeopardize the objectivity of the research. The researcher used monthly supervision meetings to discuss the collected data with the two supervisors. Furthermore, the mitigation strategies for the construct validity, listed in 3.4.1, were used to overcome the challenges of confirmation bias.

3.6.2 Interviews

It was essential to capture data through another source of evidence alongside the observation method. According to Ryan, Coughlan, and Cronin (2009, p.309), "*the individual interview is a valuable method of gaining insight into people's perceptions, understanding and experiences of a given phenomenon and can contribute to in-depth data collection*". Interviews are another form of qualitative data collection that was frequently used in the RE literature in combination with observations (e.g. Huber et al., 2009; Kaya, Ovali and Ozturk, 2019).

This research also used interviews as a data collection method, and various types of interviews were used to achieve the best possible data set for the research. The *Data sources* section of each case contains a list of the interviews used for collecting data. Some of these interviews were done in a formal and others in an informal setting. A date, time, and communication channel were arranged beforehand for the scheduled interviews. Unscheduled interviews, including unstructured discussions, were conducted spontaneously during meeting breaks or site visits. During or after unscheduled interviews, notes were taken. Scheduled interviews were recorded on an encrypted recording device and transcribed for analysis. The interviewee filled out an informed consent form (ICF) for all recorded interviews and approved for the data to be analysed. The participant could select to what extent the data would be anonymised and whether parts of the transcript could be published. A sample of the ICF is provided in Appendix C. The collected audio files were transcribed into text files. The transcripts were rechecked for correctness by replaying the entire audio file to ensure the interviews were transcribed correctly. In cases where the transcript did not match the words from the interview, the text was adjusted, and the entire sequence was played back. In interviews where recordings were not possible, notes were taken during the interview and summarized afterwards.

The following types of interviews used for this Doctoral thesis were:

1. **Semi-structured interview** – This type of research maintains a basic interview structure. High-level questions give the interviewer considerable leeway and flexibility to follow up on ideas (Kallio et al., 2016). The semi-structured questions can be found in Appendix D.
2. **Unstructured interview** – This type of interview intends to have an open discussion with a participant about an underlying subject with the purpose in mind of collecting data for the research. Unstructured interviews often start "*with a broad, open question concerning the area of study, with subsequent questions dependent on the participant's response*" (Doody and Noonan, 2013, p.29). This informal approach makes it easy to have a friendly and open discussion about the topic of interest, allowing the researcher to gain valuable insight into various areas of the air transportation operation. Informal conversational interviews mainly complemented data collected during observation. Some unstructured interviews started with a generic question about what resilience meant to the participants and what they think their organisation did to strengthen resilience.

In order to collect the data, various modes were used:

a. **Personal interviews** – The interviewer and interviewee met in person for this interview method. This method allowed the researcher to capture the most non-verbal cues.

b. **Web-based interviews** – Meeting in person was no longer the norm after the outbreak of the COVID-19 pandemic. Therefore, many interviews took place via a communication platform such as Microsoft Teams or Zoom. Both platforms offered a video feature, which was always used during the interviews.
c. **Email interviews** – Email exchanges with expert witnesses were the third method for collecting evidence through interviews. The benefit of this communication is that participants could respond to a question according to their time (Fritz and Vandermause, 2018). Furthermore, it provided the opportunity to attach supporting documents. This interview mode was mainly used to confirm data collected during observations.

Each case study lists the kind of interviews used to obtain the data. The description also outlines how the data were processed for the analysis.

The interview method has some advantages that make this type of data capturing suitable for this research:

1. **Flexibility** – Interviews give the researcher much flexibility in conducting the data collection. The interview can be framed differently, and the focus area may differ depending on the role and responsibility of the interviewee. Furthermore, additional explanations and opinions could be shared during the interview without causing any diversion in the discussion.
2. **Relationship** – Meeting for an interview, either physical or virtual, builds up a cooperative relationship and trust between the interviewee and interviewer. The interviewee can ask questions and engage more in the research, encouraging the participant to maintain an ongoing conversation.
3. **Non-verbal cues** – Collecting data using the interview method allows the researcher to capture non-verbal cues, such as body language. Body language could indicate a level of enthusiasm in the research or discomfort with a particular question, which could help the researcher interpret some of the collected data.

4. **Rectification** – The interviewer has immediately the chance to clarify questions or ask for clarification. Therefore, the chance of misunderstandings and misinterpretations can be reduced.
5. **Credibility** – The interviewee may support standpoints by giving various examples from the day-to-day operation, strengthening their argument. Moreover, interviews can be used for data collection and discussing and validating ideas and early findings of the research.

Even though numerous advantages support the use of interviews as a data acquiring technique, there are some disadvantages that a researcher needs to be aware of and protect against.

These disadvantages include:

1. **Resources** – Conducting interviews is time-consuming for both the interviewer and the interviewee. The collected data must be prepared to be analysed appropriately, presenting additional work to the researcher. The researcher benefitted from previous engagement with most interviewees. Therefore, most participants were familiar with the research. The researcher allocated sufficient time in his diary to prepare for and conduct the interview, transcribe the audio file and analyse the transcripts.
2. **Quality** – Several different factors may influence the quality of the accumulated data. Unlike questionnaires that could be filled out anonymously, each interviewee's response is known to the interviewer. Thereby, interviewees could feel shy and uncomfortable talking about specific fields. Moreover, there may be a chance that interviewees could have hidden agendas and give false or incomplete information.

   The researcher attempted to counteract these challenges by giving the interviewees the choice of having all of the collected data anonymised for the Doctoral thesis. Furthermore, the recordings were transcribed and reviewed for analysis of the interview. The use of multiple sources of evidence helped to validate any data that were collected during the interviews.

3. **Personal bias** – All interviews were held by the same researcher and not by a team of researchers. Like with the observations, this presented a similar challenge to the objectivity of the research and similar mitigation strategies were used to avoid confirmation bias. Using multiple data sources and discussing the results with other researchers were ways to counteract personal bias in the data. Discussions with the supervisors and mitigation strategies listed in 3.4.1 were used to overcome the limitations associated with confirmation bias.

3.6.3 Use of secondary data

The use of secondary data sources completed the data collection. Secondary data describe data collected previously by someone else through primary sources (Yin, 2018). The data may have been collected for a specific purpose, such as a report and made available to third parties. It could have also been accumulated for general use. Each case study contains a *Data sources* section in which the main secondary data sources are listed.

The secondary data sources used for this research include industry documents, both publicly available and internal documents, such as briefing notes and reports. In addition, data from government documents, statistics, newspapers, and websites were used. Whenever data from websites were used, the date the information was collected was mentioned in the references. Furthermore, the website was exported into a document and stored electronically to preserve the collected data.

3.7 Data analysis

The obtained data were combined into a detailed description of each case. A comprehensive description allowed the researcher to analyse each case thematically. According to Braun and Clarke (2006, p.79), "*thematic analysis is a method for identifying, analysing, and reporting patterns (theme) within data*".

As mentioned in section 3.3, the 26 identified high-level principles from the literature were used as coding patterns for the detailed description. This pattern-matching process was applied in the five case studies to identify empirical evidence of the operationalised principles. This method seemed suitable as thematic analysis is often used in the data analysis of primary qualitative research (Thomas and Harden, 2008).

Once an example was found, the case was analysed to determine the consequence of the operationalised principle. Building chains of events helped establish connections between the themes, as described in the following example.

3.7.1 Examples

The following section illustrates the methodology applied during the case study analysis. Tables like Table 3-5 and Table 3-6 were used to analyse the data in each case study in the findings chapter (see chapter 4).

3.7.1.1 Example A

In the first case study, the work of the leading UK ANSP, NATS, was investigated. The case study benefitted from data collected through observations from a six-hour site visit to one of NATS' control centres and multiple unstructured interviews. Furthermore, industry reports and website data were utilized to describe the ANSP operation in great detail. The maximum sector capacity was identified as one of the constraining factors. The sector capacity describes the number of aircraft handled in a sector by one Air Traffic Control Officer (ATCO). According to discussions with a planning team member, NATS constantly assessed whether the sector capacity needed to be adjusted. In addition, ATCOs had the opportunity to provide feedback on the maximum sector capacity and the perceived need for adjustments. NATS also used collected performance data to validate the feedback and adjusted the maximum sector capacity accordingly.

The thematic analysis classified this review process as a phenomenon of the *System Checks* theme in which the high-level principle of "*Recognizing changing risks in operation*" was operationalised. The adjustment of the maximum sector capacity had direct implications on the *System Setup* theme.

Table 3-5 Example of how data were analysed from case study 1

High-level principles	Example	Result	Connection with other themes
Recognizing changing risks to operation	Review process of maximum sector capacity	If deemed appropriate, sector capacity is adjusted	Input into System Setup

3.7.1.2 Example B

Another example was taken from the fourth case study, which analysed the operation of an airport during a COVID-19 repatriation flight. Various data sources, including interviews with two senior airport managers and studying the after-action report, were combined to build the narrative of occasions that took place during the preparation and arrival of the repatriation flight. During the preparation, the airport team decided to contact the Local Resilience Forum (LRF). The LRF is described in more detail in case study 4 (see subchapter 4.4) but is essentially a local partnership that provided additional resources in the form of workforce and equipment during the event. The analysis classified this as "*temporarily increasing the buffer capacity*" as these resources are typically unavailable during the day-to-day operation. These resources were proactively stepped up in anticipation of additional demand during the arrival of the repatriation flight. The result of stepping up the LRF was that additional resources were available. These additional resources had a direct implication on the *System Response* theme. As seen in section 4.4.5.4, additional resources were indeed required while handling the repatriation flight.

Table 3-6 Example of how data were analysed from case study 4

High-level principle	Example	Result	Connection with other themes
Temporarily increasing buffer capacity	Contacting LRF and stepping up additional resources	Availability additional resources	System Response

4 FINDINGS

The chapter contains the findings from five case studies conducted to generate empirical evidence of the high-level principles and identify connections between the themes.

Each case study contains information about data sources used to produce a detailed description of the case. The discussion section of each case study outlines the observed high-level principles and how the case study outputs were used to refine the PRF by adding connections between the themes.

4.1 Case study 1: Airspace management

4.1.1 Introduction

Hale's and Heijer's (2006a, p.36) definition of resilience as being *"the ability to steer the activities of the organisation so that it may sail close to the area where accidents will happen, but always stays out of that dangerous area"* uses Rasmussen's (1997) space of possibilities model as the fundamental baseline. The space of possibilities model is a conceptual model describing the performance envelope of a system using the boundaries of unacceptable workload, economic failure and unacceptable operation (Rasmussen, 1997). The challenge for organisations is never to breach one of Rasmussen's boundaries and maintain a safe operation. Resilience in this context describes the activities of organisations to anticipate and mitigate threats to the system's existence and primary goals. It also includes avoiding a loss of control over risk (Hale and Heijer, 2006a). Avoiding loss of control involves handling severe pressure and trade-offs between the safety and performance goals of the organisation. Organisations need to have a high level of awareness of where their operation is regarding the danger area and respond rapidly and effectively when signs of danger or approaching the boundaries are detected (Øien et al., 2010). Maintaining a sufficient safety margin in operation creates a so-called margin for errors (Cook and Rasmussen, 2005) and is vital for counteracting deviations and avoiding mishaps in the operation. Creating these margins is an essential consideration in the *System Setup*.

The following case study uses the UK airspace infrastructure as an example of how the design of the system and its operation can generate resilience. The following paragraphs further outline what processes are in place to provide safe air navigation services in the UK airspace. Moreover, the case study delivers empirical evidence of the connection between the *System Setup* theme with other resilience-generating themes, such as *System Preparedness* and *System Response*.

4.1.2 Data sources

Several different sources (see Table 4-1) were used for this case study to give a holistic view of how resilience was generated through various themes. The variety of data sources and effective triangulation also ensure a detailed description of the case.

Being a regular attendee of the IRG meetings also helped arrange a site visit to the Heathrow Airport Tower and the NATS control centre in Swanwick. The site visits greatly benefited the study as detailed information about the air traffic operation at the two sites could be obtained. A final source of information that proved critical for this study was the discussion with the IRG members. These discussions were held in person or via telephone and email exchanges. The following data sources delivered the majority of data for the case study on UK airspace management.

Table 4-1 Data sources used for case study 1

Primary data source(s)	Secondary data source(s)
Observations during six-hour site visit on 14th May 2019 • Tour of facility • Time with planning department • Time with ATCOs • Time with analysis team	Seven industry reports • CAA (2015) • CAA (2018a) • CAA (2018b) • CAA (2020) • CAA (2021) • DfT (2017) • NATS (2013) • NATS (2017) • NATS (2019b)
Follow-up discussions via email with member of planning department	Three websites • NATS (2019a) • NATS (2021a) • NATS (2021b)
Unstructured interviews with IRG members	

4.1.2.1 Visit to the NATS ATC centre in Swanwick

A site visit to the NATS control centre in Swanwick took place on 14th May 2019. The purpose of the visit was to gain insight into the processes and operation at one of NATS' control centres. The stay at the control centre included a tour of the facility and time with the planning department, ATCOs and the analysis team. During this time, an overview of the UK airspace infrastructure and the processes NATS uses to provide air navigation services in the UK was gained. The visit to the control centre helped the researcher understand the data sources the planning team uses to create a demand picture of the future. Furthermore, ATCOs were accompanied during their daily routine, which gave insight into their shift preparation and communication with aircraft during a 2-hour long shift. The stay was concluded by attending a meeting during which the performance of the previous day's operation was analysed.

4.1.2.2 Discussion with IRG member organisations

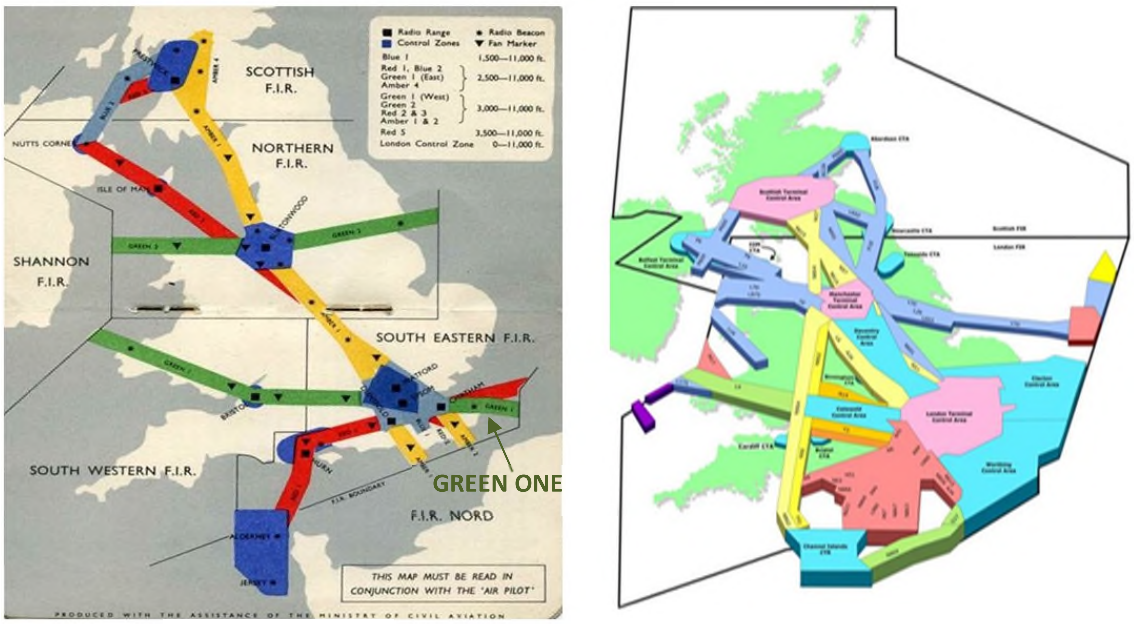
The IRG members offered their support whenever additional details were required or information had to be validated. Outputs from over 15 discussions with representatives of IRG member organisations, mainly NATS and Airport Coordination Limited (ACL), contributed to this case study. The role and objectives of ACL are discussed in a later section of the thesis (see section 4.5.4.1.2). The discussions were done in person or over a communication platform such as MS Teams. Email exchanges also proved to be a valuable source of information.

4.1.3 Airspace infrastructure

One of the limiting factors for the ATM in the European air transportation network is the sector capacity (D'Aspremont et al., 2006). The following case study looks at the structure of the UK airspace, how the aircraft movements in the UK are managed, what the sector capacity is and how the capacity of the UK airspace is determined. It further explains and analyses the processes NATS use to keep the operation within the workload limits of the ATCOs.

4.1.3.1 Evolution of UK airspace and UK airways

The design of the UK airspace has its origins in the 1950s and 1960s. The airspace system has evolved ever since, as shown in Figure 4-1 (Brown, 2019).



UK Route Structure in 1953

UK Route Structure in 2019

Figure 4-1 UK airways in 1953 and 2019 (Brown, 2019)

It was not until 1949 that the first structure to the UK airspace was introduced, the birth of modern ATC. Airlines approached the government to request to improve airspace management. They called for a system of airways already used in the USA. Airways are essentially invisible motorways in the skies that direct the traffic into a specific corridor, allowing more efficient use of the airspace. The following year, Europe's first airway, called *Green One*, was opened in the UK, and five more UK airways were added in 1951 (see Figure 4-1). As new airports such as Gatwick Airport opened in the 1950s, new airspace structures over southeast England had to be developed (NATS, 2021a). From 1950 until 2019, the traffic numbers have almost increased tenfold. Figure 4-2 is based on Department for Transport (DfT) and CAA (2020) data. The graph displays the rise in activity at civil aerodromes in the UK from 1950 to 2019. Activities include all take-offs and landings at UK civil aerodromes. To put the growth into context: London Heathrow has grown from 30-50 flights a day in the 1950s to over 1,300 in 2019 (NATS, 2021a).

The first substantial increase in flight movements occurred in the 1960s, with passenger numbers rising from one to 15 million. For standardizing ATC, NATS' predecessor, the National Air Traffic Control Services, was created in 1962. To handle the ever-growing traffic levels and improve safety and capacity, standardized departure and arrival routes were implemented in the 1960s.

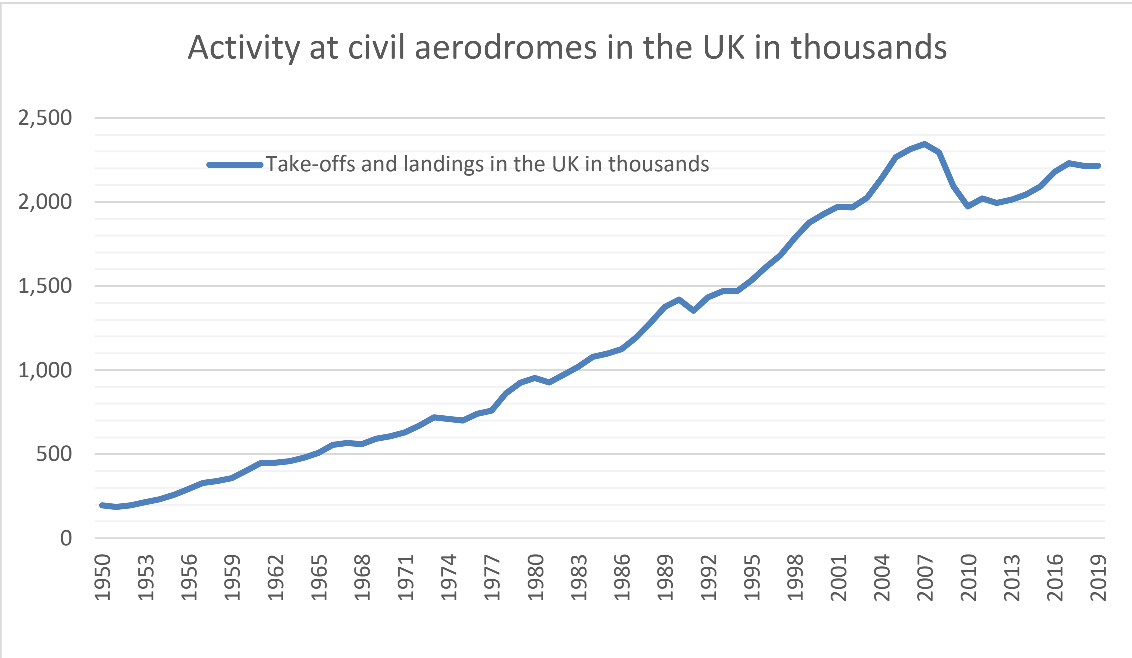


Figure 4-2 Activity at civil aerodromes in the UK

At the end of the decade, the shape of the UK airspace had evolved to a similar level, which is in use today. Many technological improvements were made in ATC technologies, such as the secondary radar in the 1970s. The secondary radar used a transponder on the aircraft and presented the ATCOs with more information about the aircraft, such as registration and flight number, enabling better traffic management.

In 1977, all UK airspace above 25,000ft was controlled by ATC. The traffic numbers kept rising throughout the 1980s, and the birth of the low-cost carriers in the 1990s led to a sharp increase in flights, resulting in further development of the airway structure. The financial crisis in 2007/08 caused a substantial fall in global air travel, which also can be seen in the UK aircraft movements (see Figure 4-2). After a sharp decrease, the traffic numbers increased again in the 2010s and have stabilised at around 2,200,000 activities at civil aerodromes per year in 2019. The original design was never meant to cope with today's traffic numbers, and new airways were constantly added to keep pace with the traffic volume (DfT, 2017). However, the airways structure basics from the 1950s and 1960s can still be seen in today's UK airspace structure.

4.1.3.2 General information about airspace management

There are two classes of airspace. One airspace class is controlled, and the other one is uncontrolled. All aircraft using the controlled airspace must follow ATC's instructions to maintain a safe separation between aircraft flying in controlled airspace. The airspace worldwide is managed by using so-called Flight Information Regions (FIR)s, the largest division of the global airspace. FIR describes a region of airspace in which air traffic services are provided, including flight information and alerting services (CAA, 2015).

The size of an FIR is not standardized, and the FIRs have different dimensions. The airspace of larger countries is sometimes subdivided into several FIRs. On the other hand, air traffic in smaller countries can be managed with only one FIR, or some FIR even include the airspace over several smaller countries. FIR can also include Oceanic Information Regions (OIR)s, describing the airspace over oceans (CAA, 2015). OIRs are typically divided into several FIRs, and operational control in these regions is facilitated by one of the bordering countries (NATS, 2021b). The International Civil Aviation Organization regulate which country is accountable for providing air traffic services in an FIR. A controlling authority of a country is then accountable for managing the movements of aircraft within an FIR. In the case of the UK, the controlling authority is the CAA. However, an ANSP provides air traffic services. The dominant ANSP in the UK is NATS. NATS handles all overflying traffic, traffic in the area control centres, and arrivals and departures at most major UK airports. Arriving and departing traffic from some UK airports is handled by other, smaller ANSPs.

The Transport Act 2000 formally separated NATS from the CAA (CAA, 2020). NATS was privatized in 2001 with the aim of a more sustainable investment source and greater transparency with the CAA. NATS is now a Public-Private Partnership between Airlines, Heathrow Airport, NATS employees and the UK government.

4.1.3.3 UK controlled airspace

As shown in Figure 4-3, the UK airspace consists of three FIRs containing various airways today.

Figure 4-3 UK FIRs (NATS, 2021)

The FIRs are the London FIR comprising England and Wales; the Scottish FIR, including Scotland, Northern England, and Northern Ireland; and the Shanwick Oceanic FIR covering 700,000 square miles of airspace over the North-East Atlantic.

The three FIRs are managed from two control centres, one in Swanwick for the London FIR and the other ATC centre in Prestwick, handling the air traffic in the Scottish FIR and Shanwick Oceanic FIR.

FIRs in the UK are further split vertically into upper and lower layers. NATS ATC centre in Swanwick combines the London Area Control Centre (LACC) and the London Terminal Control Centre (LTCC), as displayed in Figure 4-4.

The LTCC deals with all traffic below 24,500ft coming out or flying to airports in London, including major airports such as London Heathrow, Gatwick, Stansted, Luton, London City, Biggin Hill, Southend, and Farnborough.

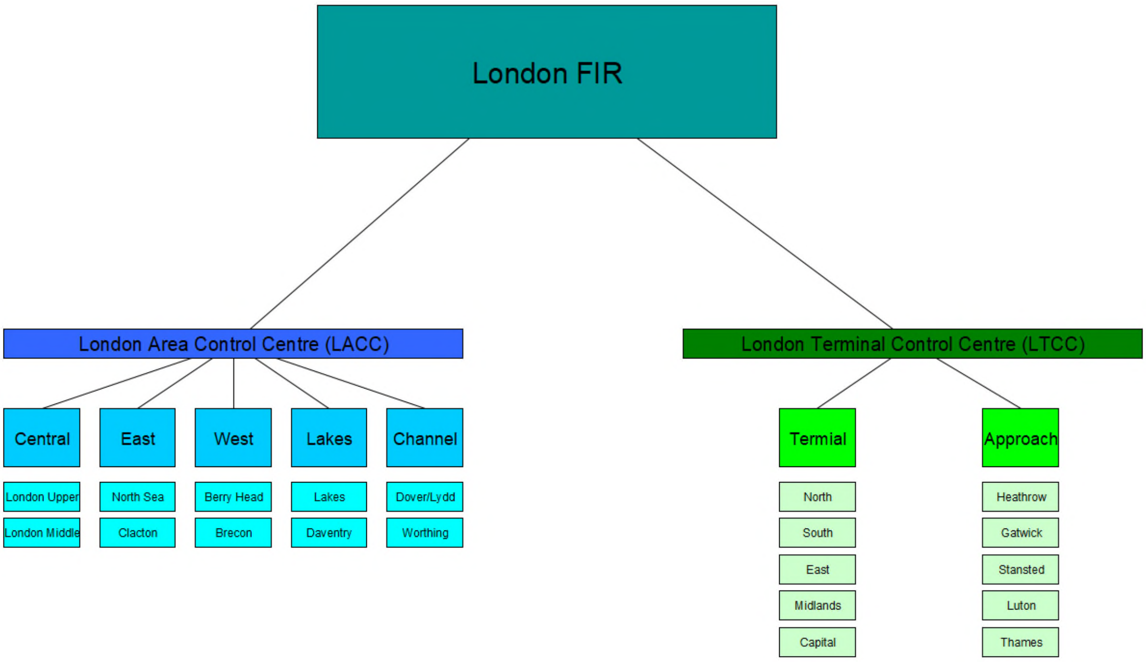


Figure 4-4 Structure of the London FIR

It stretches to the borders of the Netherlands and France and is one of the busiest control areas in Europe. LACC provides operational control to all en-route traffic over England and Wales. The Prestwick Centre consists of the Manchester Area

Control Centre, which is responsible for all traffic between 2,500ft and 28,500ft over Northern England, and Scottish Area Control, managing the airspace between 2,500ft and 66,000ft over Northern England, Northern Ireland, Scotland and the North Sea. The Oceanic Area Control Centre (OACC) complements the NATS ATC centre in Prestwick. The OACC handles all air traffic over the eastern half of the North Atlantic. The OACC includes the region of 45 degrees north and 61 degrees north. The work at the NATS Swanwick ATC centre is investigated for this case study.

As mentioned previously, the NATS ATC centre in Swanwick handles all traffic in the LACC and LTCC. The LACC is split into five local area groups (LAG)s (Central, East, West, Lakes, and Channel). Table 4-2 shows that each of the LAGs consists of two regions, which again contain sectors, the smallest airspace division. The total number of sectors in the LACC is 32.

Table 4-2 LAGs, regions and sectors in the LACC

London Area Control Centre					
LAG	**Region**	**Sector**	**LAG**	**Region**	**Sector**
Central	London Upper	1, 2 & 24	Lakes	Lakes	3, 4 & 7
	London Middle	25 & 26		Daventry	27, 28, 32 & 34
East	North Sea	10 & 11			
	Clacton	12, 13 &14	Channel	Dover/Lydd	15, 16 & 17
West	Berry Head	6, 9 & 36		Worthing	18, 19, 20, 21 & 22
	Brecon	5, 8, 23 & 35			

These sectors can be seen as 3D jigsaw puzzle parts with different dimensions interlocking to cover the UK airspace, as seen in Figure 4-5. The LTCC area consists of two main sector categories. These include the London Terminal Manoeuvring Area (LTMA), and approach sectors. The LTMA is controlled airspace over the five major London airports; London Heathrow, Gatwick, Stansted, Luton, and City. It was set up to deal with a large number of airports and the resulting complex interaction of departing and arriving aircraft and high volume of traffic levels. The approach sectors were established to manage the traffic into the five major London airports at a lower level. The traffic into Biggin

Hill and Southend airport is also managed in the approach sectors. In the final stage of the approach, the aircraft is passed on to the ATCO at the airport.

Figure 4-5 UK LACC airspace regions in the London FIR

Each LAG consists of multiple sectors, and a group supervisor is assigned to a LAG and is responsible for all sectors and ATCOs in the LAG. Each of the sectors in the LTCC and LACC has a unique number or name. One ATCO is assigned to a sector. The ATCO is responsible for the traffic within their sector. They provide guidance and advice to all the aircraft in the sector. They further manage the transition of aircraft between different sectors.

It is important to note that not all of the sectors are in operation all the time. The sectors of the airspace can be dynamically adjusted based on the demand. When airspace demand is high, more sectors may be operated, and more ATCOs are assigned to manage the air traffic. Creating sectors and allocating more ATCOs to an area of airspace is a mitigation strategy to maintain a level of safety and compensate for higher levels of traffic, especially in regions containing highly utilized airways, such as the Worthing region containing five sectors. In contrast, the Berry Head region only contains three sectors (see Figure 4-5).

On the contrary, in periods when the airspace is less occupied (e.g. during the night), sectors may be combined, and fewer ATCOs are required to provide air traffic services.

4.1.3.4 UK uncontrolled airspace

Furthermore, the UK airspace is divided into so-called Flight Information Service (FIS) regions for uncontrolled airspace (CAA, 2015). The London FIS regions are split into FIS North, FIS East and FIS West, and these FIS are different to the FIR, as shown in Figure 4-6. The chart from the International Flight Information Service Association (IFISA) (2021) shows that the FIR and FIS region boundaries do not always overlap. The FIS regions are operated by a Flight Information Service Officer (FISO), and the London FISOs are based at the NATS control centre in Swanwick.

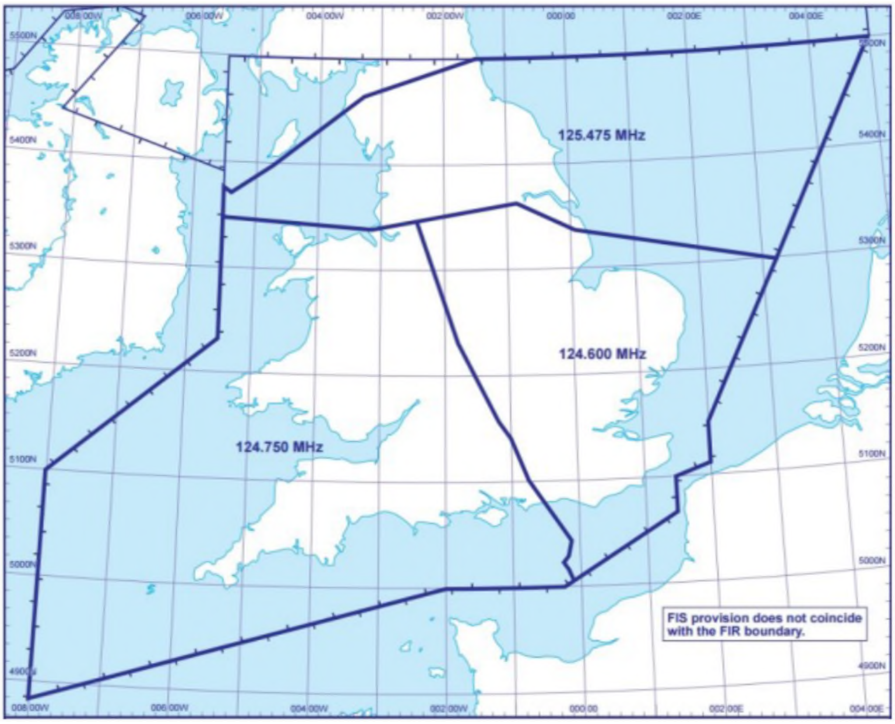


Figure 4-6 London FIS Regions (taken from IFISA (2021))

The work of the London FISO is to provide service to traffic below 19,500ft 24 hours a day. Unlike an ATCO, a FISO cannot control traffic unless instructed explicitly by an ATCO. Only essential and alerting services are provided to aircraft outside the controlled airspace, such as weather information and other aircraft in the area. FISOs may also relay information about air shows or parachuting activities to assist pilots and avoid dangerous occurrences. Pilots can access this service through the different radio frequencies, as shown in Figure 4-6. Commercial air traffic can also use this service for route or weather information. There is no radar-based surveillance in FIS regions, and FISOs rely on pilots to provide information about their position and intentions to form a demand picture.

4.1.4 Operation at NATS

As defined in CAA (2020), NATS' responsibility is the safe and compliant operation of the UK airspace.

Several processes are in place to ensure the boundaries of a safe operation are never breached. The case study looks at how the controlled airspace is managed.

4.1.4.1 Sector capacity

The sector capacity is determined by the aircraft per hour, and each sector has a maximum number of aircraft that can be safely handled. This capacity threshold works as an ATCO's workload limit indicator and is sometimes called the monitor alert parameter (Sridhar et al., 2002). Although the sector capacity describes the number of aircraft that one ATCO in a sector can handle, it is a monitoring value. The sector capacity depends on other parameters beyond a simple aircraft count (Kopardekar et al., 2008). It can be tactically adjusted based on the complexity of flights in the sector or expected weather. According to Kopardekar et al. (2007), factors that affect the complexity can be speed variation and heading between aircraft, number of altitude changes and potential conflicts of aircraft trajectory.

Should the demand exceed the monitoring value, the LAG supervisor may decide to open more sectors to handle the additional aircraft movements. Once all sectors are in use and the traffic is still beyond the ATCO's work limit, flow restrictions can be put on the sector (Jakšić and Janić, 2020). Aircraft can no longer enter this sector and need to be rerouted through other sectors, or in some cases, aircraft are held on the ground until the situation in the affected sector relaxes. Furthermore, monitor alerts may be installed to notify ATC centres when the future traffic volume in a sector is predicted to exceed the monitoring value (Kell and Marr, 2019).

4.1.4.2 Planning department

Understanding what the future demand would look like is crucial for NATS to ensure sufficient resources are available to cope with the expected traffic. For example, bank holidays or school half-term have historically resulted in more flights in UK airspace. Families are using this time for a break abroad, causing a rise in flight movements. Therefore, NATS keeps track of all the UK bank holiday weekends and school holidays to estimate and accommodate the peak in the number of flights, as seen in Figure 4-7 (NATS, 2019a). Mitigation strategies could include the scheduled use of more sectors to be able to handle a higher volume of traffic.

Furthermore, special occasions such as state visits or sports events create additional stress in the system. In 2019, four English football teams made it to the final of the Europa League in Baku and the Champions League in Madrid, respectively (BBC, 2019). Airlines responded to English fans' demand to travel to Azerbaijan and Spain respectively to support their teams by adding additional scheduled flights. All these flights were going to the same destination, using the same air corridors, adding an uneven load to the system. With the UK having one of the busiest airspaces in Europe, this selective demand could significantly impact the system and needs to be accounted for by creating additional resources in advance.

Another event that presents a common challenge to the system is the Formula 1 Grand Prix in Monaco. The sports event regularly attracts British people with private jets who want to travel to the French Riviera. Many of these private jets are taking off from Farnborough Airport, a popular airfield for private jets. With Farnborough being close to the LTMA, it is vital to protect and reduce "*the impact of any infringement on safety, whilst also minimising disruptions to commercial operators*" (NATS, 2013, p.3). Another challenge is the short notice given to NATS about the demand for the business jets. Flight plans for business jets are sometimes filed quite late, which does not give the planning department much lead time. Therefore, historical data from previous years estimate the likely impact of the next F1 Grand Prix in Monaco. Forecasting the traffic numbers and estimating the impact of these occasions is a significant part of the planning department at NATS.

Furthermore, NATS keeps track of the seasonal demand picture from previous years. The summer season is usually busier than the winter, and NATS also uses historical data to predict when the schedule will likely increase and ramp down (see Figure 4-7).

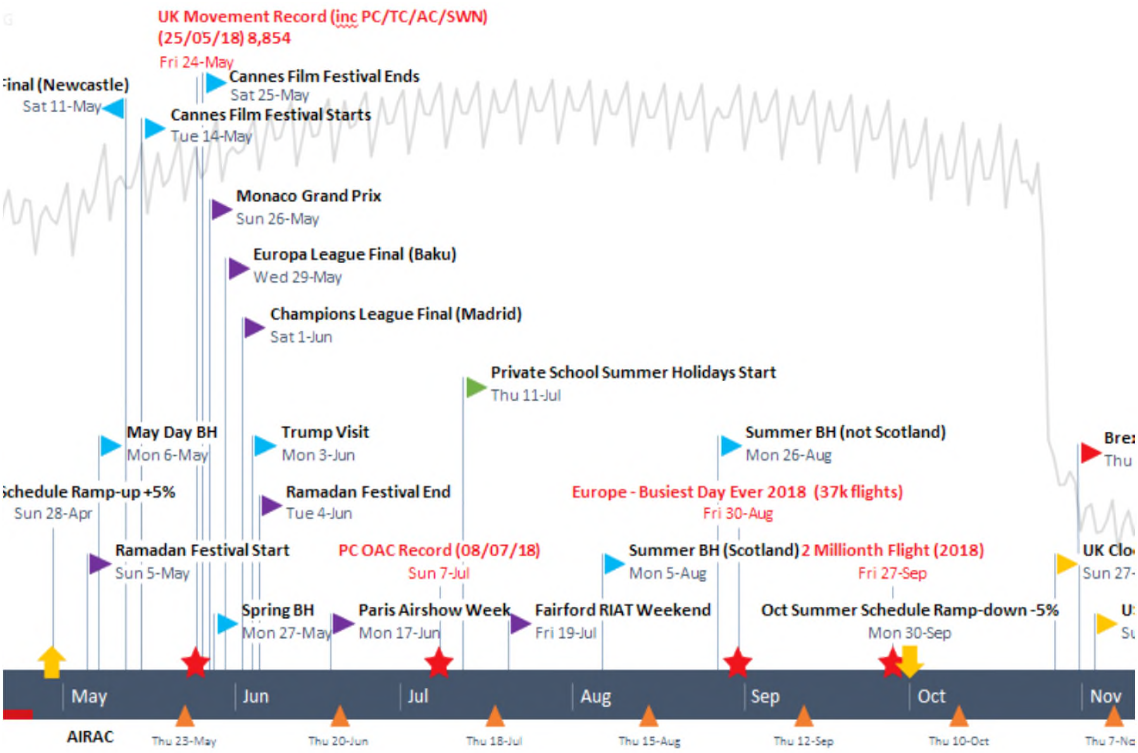


Figure 4-7 Timeline showing possible disruptive events in 2019 (taken from NATS (2019a))

The planning department presents NATS with an overview of where the bottlenecks are likely to be. This feedback provides insight if some of the traffic needs to be rerouted to relax the pressure on specific sectors. Hence, airspace capacity management is critical to ensure optimized use of the airspace, which reduces delay and increases efficiency (Tofukuji, 1993).

The planning department starts the detailed planning six days before the day of the operation. This time is referred to as D-6 and lasts until the day before the operation (D-1). During the planning phase, the planning team looks at the expected sector demand and estimates how many sectors need to be opened to handle the traffic. Once the number of sectors is determined, the staffing requirements match the demand. From D-6 to D-1, the demand picture becomes more accurate as the schedule shapes up and more and more airspace users file their flight plans.

NATS uses various sources to create a pre-tactical traffic forecast, including airlines schedule data and EUROCONTROL Demand Data Repository. These sources are combined with the traffic forecast data from the NATS Analytics department. During the day of operation, the so-called D-0, it is up to the LAG's supervisor to decide whether more sectors are required to handle the air traffic. Splitting sectors is usually only a matter of minutes, as additional ATCOs can be brought in, and traffic is handed over to them.

4.1.4.3 Review process

Statistics from the past few years suggest that NATS' approach to providing air traffic services is successful. While NATS handled about 25% of the European traffic in 2018, it only contributed 2.6% of the delay caused by ATC in 2018 (NATS, 2019a).

A factor for the successful outcome is that NATS uses a collaborative decision-making process and regularly speaks to the airlines to understand their needs. This process drives the goal of reducing delays to passengers. Every day NATS holds a *UK Network call* during which the previous day's operation is reviewed, and airports and airlines provide feedback to NATS and can raise any questions. These calls are also used to give an overview for the next day, where any hotspots in the network are highlighted, re-routing scenarios are discussed, or challenges or risks that could impact the airlines' schedule are raised. This overview enhances the situational awareness of all the stakeholders in the system.

In addition, NATS arrange several planning meetings and workshops throughout the year, during which the latest estimate of the seasonal schedule is shared and discussed. The events are supported by the IRG and also allow airlines and airports to discuss mitigation strategies to avoid potential delays during peak schedules. These conversations started the development of a diversion protocol to mitigate mass diversion scenarios. The diversion protocol is discussed in subchapter 4.3 of this PhD thesis in a separate case study.

These measures are part of NATS' Plan, Execute, Review and Learn (PERL) strategy. The PERL approach was adopted to engage stakeholders in the system and ensure a safe and efficient operation of the traffic in the UK airspace. According to the NATS planning department, the more detailed the planning, the better the performance. It was also realized that ongoing operation improvements require a continuous review of the actual execution, identifying what can be improved and works well. This review process also drives efficiency as areas of improvement can be identified and best practices shared. All of this leads to an optimized use of airspace.

The UK airspace is continuously updated to improve its design. Every time changes to the sectors are made, the airspace design team within NATS would reassess the capacity of a sector. The team uses simulations to determine the sector's capacity and whether their assumptions are correct. Those simulations also investigate how the changes would influence the traffic flow of the specific sector and how the adjustments affect the bordering sectors. Once the updated airspace is in use and the ATCOs experience with the sector grows, the sector capacity monitoring alert might be further altered.

Furthermore, NATS holds monthly Service Provision Working Group (SPWG) meetings during which the supervisors discuss any challenges and issues that the ATCOs raised. These issues may be connected with unusual high workloads due to the traffic complexity in specific sectors. Should sufficient evidence support these claims, the sector capacity monitoring value may be changed.

4.1.4.4 Back-up capacity

Part of NATS' contingency planning is to have ATCOs on standby at the control centre. These ATCOs attend meetings or training courses at the centre and could be called to work if required. Having ATCO on standby is part of the pre-tactical planning, and the ATCOs know they could be recalled if needed.

Another element of contingency planning is a scenario in which an entire control centre is lost due to a disruption. Looking at the fire in the Chicago ATC centre (Tokadli, Marzuoli and Boidot, 2016), this is a plausible scenario. As mentioned in 4.1.3.3, NATS operates two control centres. Losing one control centre for a sustained period can have massive implications on the entire infrastructure. To counteract the impact, NATS has the following contingency plan in place. In the unlikely event that one of the control centres is out of operation for an indefinite period, ATCOs from the affected centre would be moved to the remaining one. Therefore, each control centre has spare capacity for these events. There are additional workstations at either of the centres where ATCOs could provide essential air traffic services and operate their sectors.

4.1.4.5 Governance structure for major ATM incident

The so-called National Crisis Management Executive (NACME) protocol was established to provide a governance structure to coordinate the joint recovery effort from a significant ATM incident (CAA, 2018a). The NACME protocol aims to provide directions to organisations involved in the recovery and act as a conduit for information exchange between the involved organisations and government departments. The NACME protocol should provide guidance for establishing emergency procedures and advise the government on a coordinated recovery from major ATM incidents impacting UK airspace. The NACME membership comprises representatives from the CAA, Ministry of Defence, NATS, Military Aviation Authority, DfT, and the Irish Aviation Authority, where appropriate. The accountability of NACME sits within the CAA. The CAA can also activate the protocol whenever a major ATM incident is anticipated or declared. It is also stated that NACME members can recommend activating the protocol.

4.1.4.6 Airspace Change Organising Group

NATS (2018) highlighted that the current airspace design originated in the 1950s and 1960s. Airways were based around existing technologies, and corridors were defined between ground-based radio transmitter navigational aids (Brown, 2019). The government has recognised the need to modernise the UK airspace, moving away from the existing airways based on the 1950s design (DfT, 2017), as modern technology allows different concepts that are no longer constrained by ground-based infrastructure.

The government aims to enhance the UK's airspace infrastructure and make flying quieter, quicker and cleaner (CAA, 2018b). As part of the government's Airspace Modernisation Strategy (AMS), the Airspace Change Organising Group (ACOG) was launched in 2019 to facilitate the entire redesign of the UK airspace. ACOG operates as a fully independent organisation within NATS and is overseen by the DfT and CAA. The AMS is supposed to lead to flight efficiency improvements, maximising airspace capacity, and enhancing the environment's performance with increased airspace access for all users (CAA, 2018b). ACOG has recognised that some changes may also lead to negative impacts or disadvantages for some stakeholders. Therefore, one core objective of ACOG is to identify the advantages, disbenefits and trade-offs of airspace changes and maintain a close information exchange with all the involved stakeholders. ACOG's purpose is to create and maintain a master plan and be the focal point for any work related to airspace changes (CAA, 2021). The aim is to support the government in delivering the AMS. ACOG manages the development and deployment of various interconnected airspace changes, drawing together co-dependent workstreams from the different stakeholders.

4.1.5 Discussion

One of NATS’ priorities is to “*provide safe and resilient air traffic services…*” (NATS, 2017, p.12). During this case study, several high-level principles from section 2.2.4 were observed, and the methodology described in subchapter 3.7 was used to analyse the data.

This section describes the findings of the case studies that were used to empirically validate the PRF of the literature review (see Figure 2-15). This case study contained empirical examples from the four resilience-generating themes. Furthermore, the practical examples were used to refine the framework and add connections between the themes. The examples and matching resilience principles are explained for each theme.

The literature review argues that resilience can be generated through the system's design. According to the basic framework, the *System Design* theme consists of the *System Setup* and *System Checks* subthemes.

4.1.5.1 System Setup

The high-level principles from the *System Setup* theme were matched with the empirical examples in Table 4-3. Furthermore, the table highlights the resulting consequence of the operationalised principles and outlines how they affected other themes.

Table 4-3 System Setup principles observed in case study 1

High-level principle	Example	Result	Connection with other theme(s)
Buffer capacity is incorporated	Maximum sector capacity is only monitoring value and can be exceeded without hampering the safety	Operation can handle deviations in performance without failure, and buffer capacity is increased	Decreases likelihood of internal disruptions
Buffer capacity is incorporated	Ability to split sectors to increase network capacity	Scalable operation increases buffer capacity	Input into System Response
Sufficient resources are available to monitor operation	Resources are available to monitor and ensure safe operation actively	Early warnings of exhaustive resources are identified	Input into System Checks
System is aware of interfaces with other systems	Regular network calls	Increases situational awareness across stakeholders	Input into System Response
Built-in redundancies	Standby facilities at another centre	Increases redundancies	Input into System Response
Flexible mode of operation	Predefined plans and command/control Structure for disruptive events	Provides hierarchy, processes and communication lines	Input into System Response

<u>Principle: Buffer capacity is incorporated</u>

Rasmussen's (1997) model of system boundaries can be used as a baseline model to define the normal operation at NATS. Calculating the maximum sector capacity monitoring value is a trade-off decision (Hollnagel, 2009b) between maximizing the traffic in one sector and the amount of aircraft an ATCO can safely manage. Classifying the sector capacity as a monitoring value suggests that more traffic could potentially be managed, introducing a safety margin to the operation (Rasmussen, 1997). This safety margin accounts for peaks in flight movements that momentarily exceed the sector capacity monitoring value or when multiple complex flights must be managed in the same airspace.

Furthermore, the defined process to spilt sectors to increase the amount of traffic that can be safely managed in the airspace system is a vital sign of flexibility (Wreathall, 2006). A flexible operation means that the operation is scalable, which ensures that the resources can be adjusted to meet the required demand, which Cook (2006) describes with the first resilience pattern (see Figure 2-12). The first pattern describes the phenomenon when the performance of a system always meets the demand.

Principle: Sufficient resources are available to monitor operation

During the *System Setup* theme, the organisation also ensures that adequate resources are in place to monitor the operation. Monitoring is one of Hollnagel's (2009a) four cornerstones. The ability to monitor is linked to Wreathall's (2006) properties of awareness and opacity. Those properties give NATS a detailed understanding of their operation and what factors to look for that could influence the operation and performance.

Principle: System is aware of interfaces with other systems

Another part of the setup of the system is regular network calls. These calls bring together relevant stakeholders and provide a platform for information exchange. Regular updates improve the situational awareness of the system, and according to van der Beek and Schraagen (2015), situational awareness increases the resilience within a system.

Principle: Built-in redundancies

The choice of NATS to have standby resources in place, such as workstations for other ATCOs, highlighted that decision taken during the *System Setup* influences the performance during disruptive events. The purpose of those backup facilities is investigated in section 4.1.5.4.

Principle: Flexible mode of operation

The NACME protocol is another example of how the system planned and defined a framework that can be used to provide clarity in disturbed functioning (Hollnagel and Sundström, 2006). The use of the protocol is highlighted in section 4.1.5.4 of this case study.

4.1.5.2 System Checks

Various high-level principles from the *System Checks* theme were observed in case study 1. Table 4-4 matches the principles with the observed practical examples and summarises the high-level principles' effect on other themes by showing the consequences.

Table 4-4 System Checks principles observed in case study 1

High-level principle	Example	Result	Connection with other theme(s)
Recognizing changing risks to operation	Review process of maximum sector capacity	If deemed appropriate, sector capacity is adjusted	Input into System Setup
Recognizing changing risks to operation	Review process to estimate future demand	Preparation for short-term peak/ Fundamental changes to cope with long-term challenges	Input into System Preparedness and System Changes

<u>Principle: Recognizing changing risks to operation</u>

As mentioned previously, NATS invests significant time and effort to monitor the operation closely. This process includes tracking the ATCOs' work and how external influences, such as severe weather or complexity of air traffic activities, may influence the performance of ATC. Awareness about the state of operation is vital, and data gathering creates insight for the management about the operation and the quality of human performance (Wreathall, 2006). The aim is to pick up leading indicators of danger that would undermine the system's safety (Ray-Sannerud, Leyshon and Vallevik, 2015). The worker's well-being could be a leading indicator for monitoring the system's safety (Ray-Sannerud, Leyshon and Vallevik, 2015). For example, this could be the demand in a sector is constantly exceeding the ATCO's workload causing higher stress and potentially a trade-off between performance goals and safety, as referred to in the ETTO principle by Hollnagel (2009b). NATS aims to identify these early indications and respond before a dangerous situation arises. It further creates an awareness of how close the operation is to the system's boundaries and how much the defences and barriers have degraded – a sign of opacity (Wreathall, 2006).

Various review meetings generate learning and knowing what to look for allows NATS to update its normal operation and perception of risks frequently. This process can be observed when adjustments in the maximum sector capacity are made. All of this shows that maintaining safety in operation is a continuous process which refers to Hollnagel and Woods (2006, p.347) statement *"that safety is something a system or an organization does, rather than something a system or an organisation has"*. This example shows that an organisation needs a process that constantly reviews its operation and determines whether the conditions are similar to when the system was set up. As a result, the *System Checks* theme counteracts the drift into failure and ensures that the operation stays within the space of possibilities.

The feedback mechanism with people at the sharp end also allows the supervisory staff to anticipate a change in risk and make adjustments before failure occurs (Qureshi, Ashraf and Amer, 2007). This process combines two of Wreathall's (2006) properties, essential for a resilient organisation. These are just culture and learning cultures. Just culture is essential for reporting issues, and ATCOs are encouraged to raise issues or concerns about the operation. This culture allows NATS to learn about its weaknesses in the operation and current defence mechanisms (Benn, Healey and Hollnagel, 2008). Learning culture describes the processes and willingness of an organisation to use the outputs of reports and create learning (Chaffin and Gunderson, 2016). Having a monthly review meeting also indicates to the people at the sharp end that their concerns are taken seriously, and if sufficient evidence supports the reports, changes occur. The SPWG are also examples of how the operation's reliability is improved, as it avoids breakdowns and minimizes the likelihood of internal breakdown by ensuring sufficient safety margin. The review process can be seen as an estimation of the safety boundaries and an attempt to *"sail close to the area where accidents will happen"* (Hale and Heijer, 2006a, p.36) but to avoid crossing them. According to Barker, Ramirez, and Rocco (2013), increasing reliability also strengthens the resilience of a system.

The SPWG meetings are a good example of how regular checks occur in operation at NATS. Every month supervisory staff review concerns or challenges raised by ATCOs. Flight data were used to determine whether there is sufficient ground for changes in the procedures, such as altering the sector capacity monitoring alert. These adjustments could either increase or decrease the ATCO workload limits threshold. The different principles of the review prevent the pressure for more efficiency or flight movements from pushing the operation towards the boundaries of acceptable safety performance (Dekker, 2006).

The SPWG also shows the commitment to human performance concerns and the recognition of the significance of human performance, one of the critical enablers to achieving a resilient operation (Furniss et al., 2011). The priorities of NATS' CEO (NATS, 2017, 2019b) to provide safe and resilient operations reflects the top-management commitment highlighted by Wreathall (2006). The top-management commitment is essential to achieve resilience in a system, enabling extensive and continuous support and actions to address the human performance in the organisation. Having the commitment from top management gives a system the opportunity to devote enough resources to monitor the operation and the review process. The monthly review meetings show how this goal can be operationalised.

The planning department also uses historical data and a variety of data sources to predict future demand. The strategic seasonal outlook shows the likely future demand, and adding key events, such as holidays and sports events, provides insight into where peaks in flight movements may occur. State visits or events with a high-security level may limit the availability of certain airspace, and other traffic needs to be rerouted. This creation of foresight identifies potential bottlenecks in the system and appropriate action, such as proactively issuing flow restrictions in the *System Preparedness* theme described in section 4.1.5.3.

Moreover, assessing the internal operation and environment during the *System Checks* enables NATS to foresee long-term challenges. One example is the realisation that the airspace needs to be modernised, which gives the system sufficient time to prepare for those changes in the *System Changes* theme. This process is described in section 4.1.5.5.

4.1.5.3 System Preparedness

Case study 1 provided practical examples of operationalised high-level principles from the *System Preparedness* theme. Table 4-5 summarizes all the identified operational examples, shows the resulting consequences, and highlights the connection with other themes.

Table 4-5 System Preparedness principles observed in case study 1

High-level principle	Example	Result	Connection with other theme(s)
Ability to anticipate bottlenecks	Proactively opening sectors	Increasing buffer capacity	Input into System Response/Output from System Checks
Preparing operation for expected disturbance	Proactively issuing flow restrictions	Restricting demand and maintaining safety margin	Input into System Response/Output from System Checks

<u>Principle: Ability to anticipate bottlenecks</u>

Creating foresight in the operation allows NATS to mitigate potential disruptions and lessen the impacts on the rest of the system (Hollnagel, 2009a). During the tactical planning that occurs during the time from D-6 to D-1, a detailed demand picture is created that helps match staffing requirements to the demand. Detailed oversight of the expected flight movements also allows efficient use of the available resources. The planning department's goal is to develop an accurate demand picture of the future traffic which is a sign of preparedness (Wreathall, 2006). Estimating peak traffic numbers caused by holidays or sports events strongly indicates that NATS "*actively anticipates problems and prepares for them*" (Wreathall, 2006, p.280). Anticipation and knowing what to expect help NATS match the staffing and ensure enough resources are in place to handle the workload.

<u>Principle: Preparing operation for expected disturbance</u>

The planning helps with the appropriate staffing, and the challenge is keeping the operation within the system boundaries during the day. Multiple goals must be achieved simultaneously, and dynamic trade-off decisions are required. One goal is to keep the delay minutes to a minimum, while another is to avoid a breach of the acceptable workload of the ATCO. According to Dekker and Pruchnicki (2014), this generates a drift towards the safety boundaries. However, another goal of NATS is to provide safe air traffic services. Therefore, NATS may proactively issue flow restrictions to prepare for expected disturbances and keep the operation within the system's boundaries.

4.1.5.4 System Response

Despite all the anticipation and preparation, unexpected events may still occur that require the system to respond accordingly. Various *System Response* high-level principles were identified, and Table 4-6 connects the high-level principles with practical examples. Furthermore, it shows the resulting consequences and highlights that outputs from other themes directly influenced the principles.

Table 4-6 System Response principles observed in case study 1

High-level principle	Example	Result	Connection with other theme(s)
Use of internal buffer capacity	Availability of standby controllers	Additional buffer capacity for system is added	Output from System Setup
Use of internal buffer capacity	Rerouting traffic through other sectors	Pressure in specific sector is released	Output from System Setup
Use of redundancies	Availability of backup facilities	Alternative mode of operation	Output from System Setup
Governance structure for coordination and communication	Availability of NACME for major incidents	Clear hierarchy, processes, and communication lines	Output from System Setup

<u>Principle: Use of internal buffer capacity</u>

The additional pressure during disruptive events challenges the boundaries of safe operations, and adjustments are required to ensure that the operation *"stays out of that dangerous area"* (Hale and Heijer, 2006a, p.36). According to the interviewees, operational actions such as the opening of sectors or rerouting are the most common mitigation strategies. NATS uses those measurements to mitigate additional demand.

Figure 4-8 shows those two mitigation strategies concerning Rasmussen's (1997) space of possibilities. Opening sectors and bringing in additional human resources is one strategy to respond to exceeding demand. Adding additional resources extends the boundaries of unacceptable and marginal operation and broadens the available space of possibilities.

Another option is to reroute traffic through other sectors, which moves the operation in the sector away from the boundary of unacceptable operation (see Figure 4-8). Rerouting flights through other sectors results in longer flight paths and flight time. Hence, performance goals are compromised to maintain a sufficient level of safety in the system. This compromise signifies a resilient operation as safety is a core value (Woods and Hollnagel, 2006).

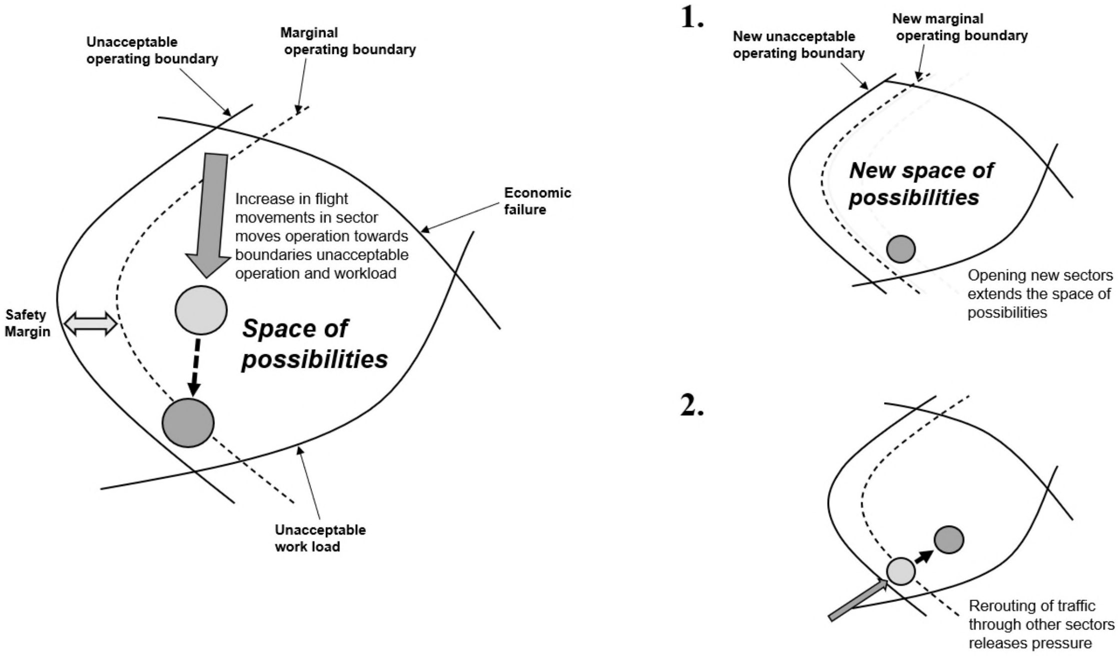


Figure 4-8 Mitigation strategies to handle an increase in flight movements

Principle: Use of redundancies

Additional workstations at either control centre to provide essential air traffic services in case of a severe disruption are a sign of redundancy (Bruneau et al., 2003). This redundancy is of utmost importance to avoid brittleness in unusual events, such as a fire in one of the control centres (Tokadli, Marzuoli and Boidot, 2016).

Principle: Governance structure for coordination and communication

In their study about the governance of infrastructure systems, Naderpajouh et al. (2018, p.311) highlighted "*the critical role play by regulatory and governance institutions in resilience*". NACME provides a framework that can be used to bring members from the private sector, regulator, government, and military together to develop mitigation strategies in the event of a significant ATM disruption.

4.1.5.5 System Changes

As described in section 2.2.4.4, the *System Changes* theme should help the system to achieve long-term sustainability. This case study identified various principles NATS uses to achieve this goal. Table 4-7 lists all the observed high-level principles and provides practical examples for each of the principles. It also shows the resulting consequences and whether the principles directly impacted other themes or were directly influenced by outputs from other themes.

Table 4-7 System Changes principles observed in case study 1

High-level principle	Example	Result	Connection with other theme(s)
Creation of lesson learning	Review meetings following events	Best practices and potential for improvement are identified	Output from System Response
Safe integration of long-term changes	Facilitation of network calls	Opportunity to ensure that all plans are aligned	Input into System Setup
Anticipation of future challenges	Realization that current system may not be able to cope with future demand	Establishment of Airspace Change Organisation Group	Outputs from System Checks
Safe integration of long-term changes	Airspace Change Organisation Group facilitates discussion about changes to the airspace structure	Assessment of potential trade-offs that support safe integration of changes to the airspace structure	Input into System Setup

Principle: Creation of lesson learning

According to Nagenborg (2019), disruptions provide systems with the opportunity to learn and be better prepared for a similar event in the future. NATS uses post-disruptions review meetings with the network to investigate the performance during these disruptive events. These review meetings allow the system to identify lesson-learnings (Gunderson and Holling, 2002). Furthermore, NATS can also highlight what went well during these events (Hollnagel, 2014a).

The creation of lesson learning is an example of how a system can use outputs from the *System Response* theme to enhance the potential of a more resilient operation through the *System Changes* theme.

Principle: Safe integration of long-term changes

NATS uses the findings from these review meetings to share best practices or update its plans to ensure they align with the plans of its stakeholders (Woods, 2015). This process raises situational awareness across all the stakeholders in the system (Le Coze, 2019). It helps to better prepare for disruptions and train the staff members accordingly (Saurin et al., 2014).

Furthermore, NATS' PERL process is another example of how active learning occurs within the organisation. The PERL process is an adaptation of Deming's (1986) Plan-Do-Study-Act methodology. It allows NATS to do scenario planning for disruptions, outline what tactical measures work best in these events and share playbooks with its customers.

This process shows the connection between the *System Changes* and *System Setup* theme.

Principle: Anticipation of future challenges

Another example of how the *System Changes* theme is applied in practice is ACOG. The realization that long-term changes to the airspace are required to provide safe and resilient services in the future resulted in the establishment of ACOG. NATS avoids becoming brittle by using the principles described in the *System Changes* theme (see section 2.2.4.4). Using the principles of anticipating future challenges ensures the system's long-term sustainability (Woods, 2015).

Although the 1950s and 1960s design accommodated the rise in traffic numbers, the DfT and NATS have recognised that fundamental changes to the airspace design were required to cope with future challenges.

ACOG is an example of how the outputs from the *System Checks* theme can proactively lead into the *System Changes* theme. The realization that a new airspace structure is needed to cope with the predicted demand and new airspace users such as air taxis led to the formation of this working group.

Principle: Safe integration of long-term changes

The current system would not be able to deal with the numbers and complexity of future aircraft movement; therefore, change is imperative. However, the transition is a gradual process and outputs from ACOG will steadily update the *System Setup*, leading to a change in how the *Normal Operation* is executed. This case study produced empirical data that shows how organisations can use Woods' (2015) fourth concept of resilience to avoid becoming brittle in the long term. ACOG is a prime example of how outputs from the *System Changes* themes update the *System Setup* theme, increasing the potential for a more resilient operation.

4.1.5.6 Integration of findings

Analysing the UK airspace infrastructure operation has identified how numerous resilience principles are operationalised when providing air traffic services. The insights have also generated empirical data to refine the PRF (see Figure 2-15) by showing how the various resilience themes interrelate and influence each other.

The outputs from sections 4.1.5.1 – 4.1.5.5 were used to refine the PRF by adding additional connections.

- Connection between *System Setup* and *System Response*
  Section 4.1.5.1, the high-level principles of *Buffer capacity incorporated*, *System is aware of interfaces with other systems, Built-in redundancies,* and *Flexible mode of operation* improved the operation during the *System Response* theme.

- Connection between *System Setup* and *Normal Operation*
  The *System Setup* also defined the *Normal Operation* and its safety margin, as shown in section 4.1.5.1.
- Connection between *System Setup* and *Disruptive Event*
  The case study also showed that by operationalising the principle of *Buffer capacity is incorporated,* the system could handle deviations without failure, which decreases the likelihood of internal disruptions (see section 4.1.5.1).
- Connection between *System Checks* and *System Preparedness*
  Section 4.1.5.2 demonstrated that the principle of *Recognizing changing risks to operation* could lead to preparation for short-term demand peaks in the *System Preparedness* theme.
- Connection between *System Checks* and *System Changes*
  In addition, the principles of *Recognizing changing risks to operation* can also inform future planning in the *System Changes* theme (see section 4.1.5.2). The recognition can lead to the principle of *Anticipation of future challenges*.
- Connection between *System Preparedness* and *System Response*
  As shown in section 4.1.5.3, the case study demonstrated that the operationalised principles of *Ability to anticipate bottlenecks* and *Preparing operation for expected disruptions* increased the buffer capacity and limited the demand. These preparations put the operation in better shape for expected disruptions handled in the *System Response* theme.
- Connection between *System Response* and *System Changes*
  Section 4.1.5.4 highlighted that the *System Changes* themes could utilize outputs created by the *System Response* theme to improve the potential for resilience in the *System Changes* theme. Reviews of previous incidents can lead to the principle of *Creation of lesson learning*.
- Connection between *System Changes* and *System Setup*
  The principle of Safe integration of long-term changes ensured the safe update of the *System Setup*, as mentioned in 4.1.5.5.

Figure 4-9 visualises how the findings from case study 1 were used to refine the PRF. For the development of the figure, empirical examples were used to explain the content of each theme. The practical applications of the principles also highlight the connections between the themes.

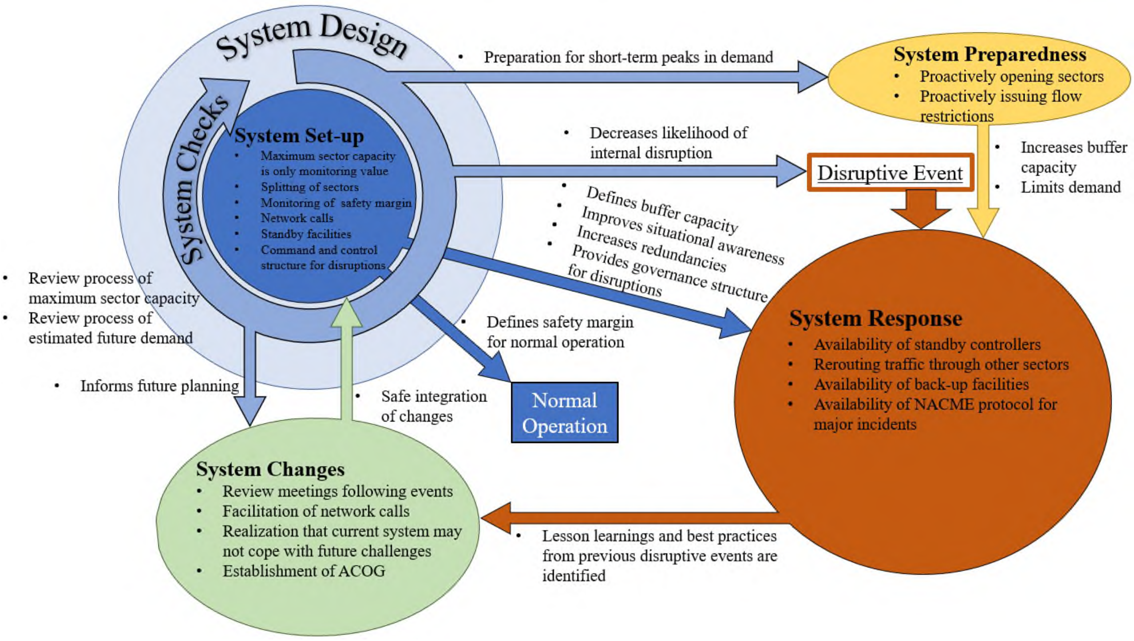


Figure 4-9 Integration of findings from case study 1

4.1.6 Closing remarks

The ability to investigate various aspects of the operation provided a holistic view of how the organisation's potential for resilience is created. Multiple elements of the integrated resilience framework could be developed using multiple sources to gain insight into the management of the UK airspace.

NATS is a crucial part of the resilience of the UK air transportation industry. Being responsible for all aircraft travelling in UK airspace, NATS control the traffic flying in and out of the UK. Problems in airspace management can lead to severe delays for airlines, also causing issues for airports when aeroplanes cannot take off due to congested skies. This case study has shown how NATS operationalised principles from all four themes to provide a safe and resilient operation.

It was also highlighted that collaboration between stakeholders is vital. The more data about future flight movements are shared, the more detailed the demand picture and the more accurate the staffing level. This data sharing leads to a better match between demand and performance (Cook, 2006), improving the system's resilience. NATS regularly reviews and refines its processes, shares best practices across the UK aviation network, and integrates lesson learnings.

Despite providing valuable empirical data and maturing the resilience framework, this case study includes some limitations. The findings are mainly based on qualitative data, using observations and interviews. The study may benefit from utilizing the Resilience Analysis Grid to collect quantitative data on how the four cornerstones are operationalised when providing air traffic services in the UK. However, this was unsuitable for this PhD thesis due to the difficulties in gaining access to people and data.

Another study enhancement may be comparing NATS processes with an ANSP in another European country. Data from EUROCONTROL suggests that NATS is one of the best-performing ANSPs in Europe (NATS, 2019a). This comparison was beyond the timeframe of this research.

4.2 Case study 2: Industry Resilience Group

4.2.1 Introduction

Although disruptions can be an accelerator for change and improvements (Yazdi et al., 2019), changes to the system can also happen proactively and in the absence of a disruptive event. Identifying a problem may be one driver to changing the system proactively (Chen et al., 2003).

The second case study investigated a UK aviation working group called the IRG. The case study investigated the group's work from its instalment in 2018 to the start of the COVID-19 pandemic in March 2020. This case study analysed what benefits the foundation and work of the IRG brought to the UK aviation industry and how it enhanced the potential for resilience in the UK air transportation system.

4.2.2 Data sources

Several different sources were used for conducting this case study (see Table 4-8). Since March 2019, the researcher has been a member of the IRG and regularly attended monthly meetings and several workshops. Being a member of the IRG allowed the researcher to observe meetings and gain an in-depth view of the cross-industry working group. Furthermore, the researcher studied several documents that referred to the IRG, which provided an overview of the history and objectives of this group. The data set was complemented by informal interviews conducted for the research.

Table 4-8 Data sources used for case study 2

Primary data source(s)	Secondary data source(s)
Observations during IRG meetings • 20th March 2019 • 17th April 2019 • 7th May 2019 • 18th June 2019 • 17th July 2019 • 11th September 2019 • 23rd October 2019 • 19th November 2019 • 18th December 2019 • 21st January 2020 • 26th February 2020 Observations during ODLG meetings • 23rd October 2019 • 26th February 2020	Three industry reports • CAA (2017a) • CAA (2017b) • IRG (2018a)
Observations during industry workshops • Mass diversion workshop on 28th March 2019 • Winter Operations Preparations 20th November 2019 • Summer 2020 Hotspot Meeting on 17th December 2019	
Unstructured interviews and discussions with IRG members	

4.2.2.1 Membership in Industry Resilience Group

On 6th March 2019, Cranfield University hosted a workshop that brought together participants from academia, technology firms and aviation stakeholders to discuss future challenges in aviation and how various consortia may approach them. During the workshop, the researcher met the chair of the IRG. Following a discussion about resilience, the researcher was offered the opportunity to join the IRG, observe meetings, and provide academic insight if and when possible. Two weeks later, on 20th March 2019, the researcher attended his first IRG meeting, and for this case study, eleven IRG meetings were attended and analysed. The IRG meetings lasted two hours and were hosted by the IRG members. The researcher wrote summaries for each meeting, containing information about attendance, discussion points, and agreed actions. The summaries contained 3-6 DIN A5 pages of personal notes for each meeting.

In addition to the IRG meetings, the researcher attended two Operations Director Liaison Group (ODLG) meetings, for which the researcher also wrote personal summaries, producing a similar output of personal notes. The IRG membership also allowed the researcher to attend industry workshops, and in total, seven workshops on several topics were attended.

The membership provided unique insight into the working of the cross-industry group. This insight helped to better understand the purpose of the industry collaboration and what the industry did to achieve the IRG objectives. The objectives are explained in a later section of the case study (see section 4.2.3).

4.2.2.2 Industry Resilience Group documents

Valuable data from secondary data sources were collected for this case study. These data sources include the CAA's report on resilience (CAA, 2017b), the report of the Voluntary Industry Resilience Group (VIRG) (CAA, 2017a), and the terms of references from the IRG (IRG, 2018a).

The documents contained information about the history of the IRG, objectives, and setup.

4.2.2.3 Interviews with Industry Resilience Group members

Being a member of the IRG also provided prime access to other IRG members. The time before and after meetings was used to understand some of the challenges experienced by individual stakeholders. The discussions helped to understand how the IRG members work together to address these challenges. In total, the output of eighteen unstructured interviews were used for this case studies.

Furthermore, the interviews conducted for the UK aviation response to the COVID-19 case study (see section 4.5) provided additional input into how stakeholders saw the IRG before the COVID-19 pandemic. Some of the outputs from the interviews were also used for this case study.

The researcher spoke with the chair of the IRG, Jon Proudlove, on several occasions. These unstructured interviews proved valuable as the researcher received deep insight into the working of the cross-industry working group and how the group was chaired. A total of six unstructured interviews with the chair of the IRG was used for this research.

The researcher also reached out to the previous chair of the (V)IRG, and conducted an unstructured, one-hour interview which clarified some of the statements from the VIRG report (CAA, 2017a). It also gave the researcher an understanding of the IRG before the researcher became a regular member.

4.2.3 History and objectives

In 2017 the CAA conducted a study to investigate how to balance the level of punctuality against the increase in the number of flight movements. The results were summarized in the CAP1515 report (CAA, 2017b), and it was determined that the UK's airspace and airport capacity was constrained, and no new airport capacity will be added in the next ten years. This lack of capacity extension meant that increasing the flight movements may lead to more delay minutes in the system and ultimately to a worse passenger experience. The report identified a fragile system, as minor disturbances could significantly affect the system's overall performance. The closure of one airport could potentially impact the operation at other airports as the system would have to cope with the additional diverted aircraft. This ripple effect could cause a significant challenge as there was insufficient buffer capacity at the other airports to take the diversions due to the high runway utilization at these airports, as shown in Figure 4-10.

With the runway infrastructure becoming more and more constrained, diversion events in the past, especially in the congested South East England airspace, had led to multiple fuel emergencies, which undermined the stability of the air traffic system. Emergency aircraft received priority over other traffic, and dealing with multiple fuel emergencies simultaneously could cause ripple effects as other arrivals had to be put on hold while the emergencies were expedited.

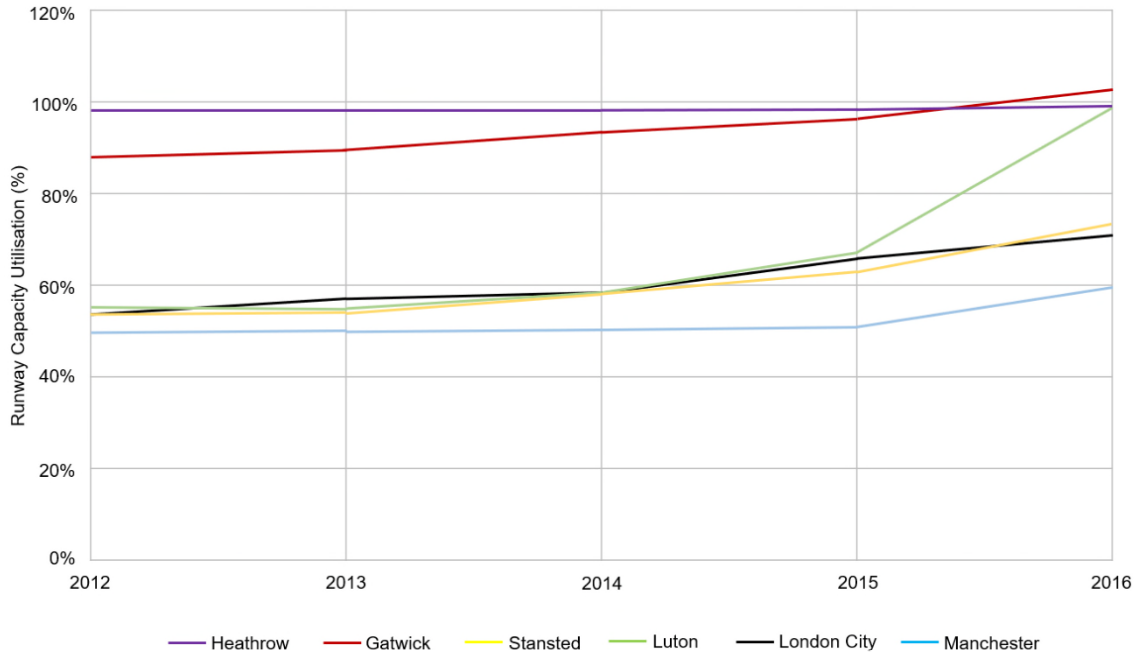


Figure 4-10 Runway Capacity Utilization at the six major UK airports (taken from CAA (2017b))

Therefore, actions on resilience were required to protect the system's performance and consumer interest (CAA, 2017b). The CAA concluded that no collective responsibilities were in place, addressing the resilience of the UK air transportation system. Achieving resilience across the system required a cross-industry collaboration approach. As a result of the CAP1515 report (CAA, 2017b) and discussions at the executive level, the VIRG was formed in December 2017. The CEO of the CAA also facilitated the work and discussions.

The CAP 1515 report (CAA, 2017b) specifically looked at the highly congested LTMA in South East England (for congestion in LTMA, see subchapter 4.1). Therefore, the VIRG focused on resilience issues in the LTMA and the founding members predominately operated in this area. Therefore *"airports and airlines based in the congested South East of the UK, along with NATS, ACL and the CAA formed the [VIRG] to pool their expertise and recommend actions (for industry itself or the Government's expected review of Aviation Strategy) to address current and future resilience issues"* (CAA, 2017b, p.13).

The founding members included ACL, NATS, Easyjet, British Airways, Heathrow Airport, Manchester Airport Holdings Limited, Gatwick Airport, Ryanair, Virgin Atlantic and the CAA. The VIRG was later rebranded as the IRG. In addition, the number of member organisations almost doubled; by 2020, 19 organisations were participating in the IRG. The IRG's objective is *"to improve in a systemised manner the way in which the UK's aviation network is planned and operated to enhance its day-to-day operating resilience, reduce delays and reduce the associated costs to both industry and passengers."* (CAA, 2017a, p.42). This statement highlights that the IRG was mainly concerned with improving the system's resilience in day-to-day operation rather than following abnormal events. The members of the IRG aimed to develop guidelines, procedures, and protocols to protect normal operations and stabilize the system after a disruption. The action points included data sharing, tackling mass diversion and ensuring business continuity, introducing performance measuring tools, and wider weather data integration for more accurate prediction and planning (based on the agenda of the IRG meetings).

4.2.4 Structure of IRG

Different stakeholders from the aviation industry were represented on the IRG and worked collectively on various challenges. The members included airlines, airports and other aviation stakeholders such as NATS, CAA and ACL, and the Met Office and the DfT were also represented at the group. The IRG was chaired by Jon Proudlove, NATS Industry Engagement Manager.

Figure 4-11 shows the hierarchy of the three-level cross-industry collaboration structure. The IRG was the lowest level of a three-level structure and represented the working group within this cross-industry collaboration. Attendees usually were at the head of operations level at their companies. The work of the IRG is monitored by the ODLG, which again reports to the Oversight Group (OG). The ODLG met twice or three times a year, and the stakeholders usually sent their operations directors to these meetings. The OG typically met once or twice a year but could be summoned more frequently if required. The invitation email was sent out to the stakeholder's CEO and COO.

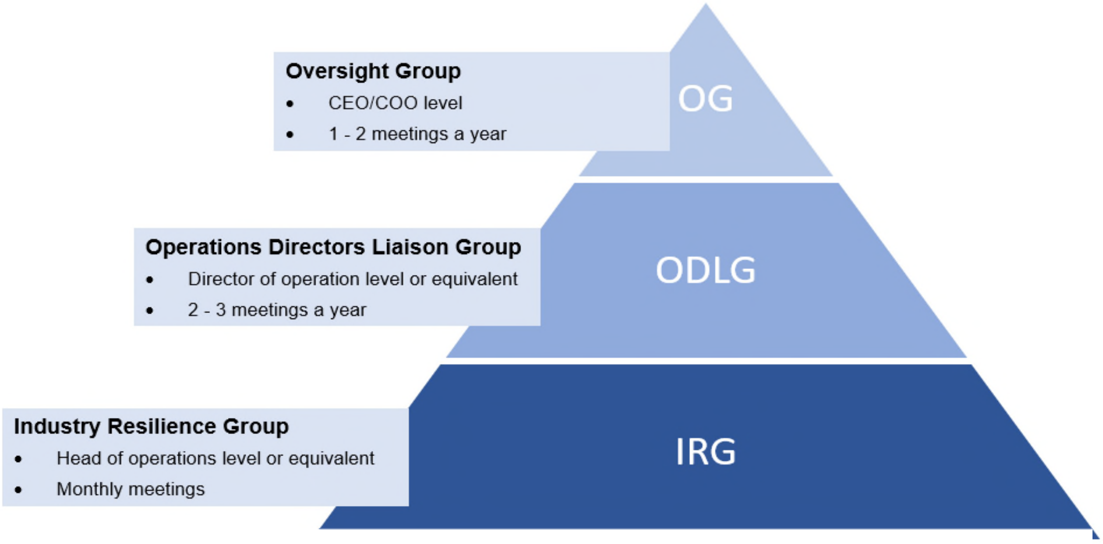


Figure 4-11 Hierarchy of cross-industry work

The idea behind the three-tier structure was that the OG set the general direction and tasked the IRG with developing concepts to mitigate identified issues. Once the work packages were established, the ODLG needed to approve the work of the IRG before the concepts could be implemented. The IRG was also tasked with identifying additional challenges and the ODLG then decided whether these areas were worth considering. A summary of the IRG work was presented at every OG meeting, and the OG advised the working group on the next steps.

The IRG was industry-led and chaired by one of the participating organisations that would supply one staff member as the chairman. The initial intention was to take yearly turns between the organisations to share the workload of the chairmanship. However, as shown in section 4.2.5.2, the chairmanship was not changed in practice after the first year.

4.2.5 Type of governance in IRG

Stakeholders form relationships by working in the same industry and interacting with other organisations. These relationships need to be managed, and inter-organisational governance defines the interventions and rules between stakeholders (Roehrich et al., 2020). Governance involves the use of a framework and structure of collaboration and authority. This framework is required to control and coordinate collaborative actions in the network. The coordination is achieved through interventions, and the literature on inter-organisational governance defines two main types of governance interventions: Contractual and relational governance interventions (Griffith and Myers, 2005; Rousseau et al., 1998). Contractual governance refers to more formal interventions such as written documents (Vandaele et al., 2007). These documents usually include legally binding agreements, standards, processes and a formal structure. On the other hand, relational governance is manifested in more informal interventions. These may include socially derived arrangements such as norms, values, information sharing and a social structure (Pilbeam, Alvarez and Wilson, 2012).

4.2.5.1 Modes of governance

Different modes can manage a network through formal and informal interventions. Appropriate management is crucial for effective network governance since tensions within the network must be managed (Provan and Kenis, 2008). Provan and Kenis (2008) examined the governance of organisational networks and categorized network governance into two dimensions. They differentiated whether network governance is brokered or not. Another distinction is made by looking at whether a network is a participant or externally governed. Based on this classification, Provan and Kenis (2008) defined three modes of network governance: Shared participant-governed networks (SPGN)s, lead organisation-governed networks (LOGN)s, and network administrative organisations (NAO)s. This categorization was also used for this research.

4.2.5.1.1 Shared Participant-Governed Networks

In this network governance mode, the network's stakeholders manage themselves, and no separate or unique entity is required. No recognizable, formal administrative body is a characteristic of these SPGN. Governance can be achieved formally by having regular meetings and designated contacts within the organisations. The network needs to deal with tension and conflicting interest by itself, and the participants are responsible for maintaining effective internal and external relationships (Provan and Kenis, 2008). The involvement and commitment of a significant number of organisations are essential for SPGN. All network members must participate equally to reach a high commitment to the network's goals. The power is almost symmetrical in the network with slight variances depending on organisations' size, performance, and resource capability. Shared network governance works best for networks with relatively few network organisations and with established trust between and across the participating members in the network. A high network-level goal consensus is also beneficial for reaching network-level outcomes.

4.2.5.1.2 Lead Organisation-Governed Networks

In a LOGN, one single participating entity acts as a lead organisation, coordinating network activities and critical decisions. The lead entity provides the framework and facilitates the activities of the network. The lead organisation often has the legitimacy and available resources for taking the lead role or may emerge from the participating members based on what seems most effective and efficient. Efforts to achieve network goals may align closely with the objectives of the lead organisation. Expenses for the network administration of the lead entity may be covered by membership fees, grants, or government funding. Unlike the shared network governance model, having a lead organisation allows many participating organisations while effectively achieving network-level outcomes. A lead organisation network governance structure also works when trust is narrowly shared among the network and network goal consensus is relatively low.

4.2.5.1.3 Network Administrative Organisation

An NAO is an example of an externally governed network. For this mode of governance, a separate entity is set up to govern the network and the activities. The NAO is not a participating member organisation, and apart from administrating the network collaboration, the NAO does not provide its service. The NAO could be a government body or a not-for-profit organisation. An NAO governance structure is most effective for a network with moderate to many entities. In order to get to effective network-level outcomes, a moderate to a high level of trust needs to be shared among the network members and a high network-level goal consensus.

4.2.5.2 IRG governance

The mode of governance of the IRG can be best described as a LOGN (Provan and Kenis, 2008). For the time between 2018 and 2020, NATS provided the chair for the IRG. NATS is the UK's primary ANSP and was considered a suitable lead organisation for the IRG. The assumption that NATS would be a good fit was mainly based on the fact that NATS was not involved in direct competition with one of the other IRG members. Furthermore, due to the nature of its operation, NATS already had a holistic view of the UK air transportation network operation. The target of the IRG was to keep the delay minutes within the system to a minimum which was in line with NATS' objective to provide good air navigation services to airlines operating in the UK. For the chairmanship, NATS provided its Industry Engagement Manager, Jon Proudlove. His primary responsibility was to lead the IRG and advance the IRG projects, such as better visibility of the traffic demand picture, which also shared some overlaps with NATS’ priorities (see subchapter 4.1). Due to the successful chairmanship by NATS and the lack of resources by other organisations in taking over the role of the IRG chair, no change in the chairmanship was conducted after the first year. According to discussions with IRG members, several IRG members appreciated Jon Proudlove’s work (e.g. “*He is an excellent chair. You know, he does a really good job when it comes to controlling that many people*” comment from one IRG member). NATS agreed to continue supplying the resources for chairing the IRG as the IRG objectives closely aligned with NATS’ minimising delay minutes.

The three-tier structure in the UK appears to build a framework for cross-industry work at various levels. IRG meetings were held monthly, and workshops for special briefings or traffic outlooks were facilitated through the IRG chair on an as and when required basis. Workshops included the work by the Met Office when weather forecasts for the next quarter were given together with a likelihood of severe weather events. ACL also provided data for a detailed traffic forecast for the upcoming winter and summer seasons, respectively. These workshops helped improve the stakeholders' situational awareness and be aware of the potential upcoming bottlenecks.

The regular meetings were facilitated by the chair of the IRG, who usually put an agenda for the upcoming meeting together and circulated the agenda via email a few days before the meeting. Another formal feature of the IRG was the list of contact details of the participating organisations. This list allowed the organisations to have follow-up discussions outside the regular group meetings.

However, despite regular meetings and contact lists of participating organisations, the IRG, ODLG and OG concept was not contractually governed, and the research was not aware of any formal agreement for being a working group member. The information exchange between the various groups was not clearly defined, and it was up to the IRG chair to collect information and update the ODLG and OG. As far as the membership is concerned, no formal conditions were attached, and no membership fees were present. The IRG was open to parties that would like to join the cross-industry collaboration. The membership was approved as long as none of the people on the ODLG had any objections to the new organisation joining. This process was witnessed in an ODLG meeting on 26th February 2020.

Moreover, no meeting minutes were taken, which made tracking the progress of the working group challenging. Without having a formal monitoring and reporting mechanism, the IRG relied on the work of its chair to define work packages and monitor that the work progresses. This lack of formal processes was challenging as the IRG did not formally hold authority and depended on the goodwill of the IRG participants to give input and contribute to the cross-industry collaboration. The IRG started as a voluntary concept and relied on people already working in a full-time occupation to spare time for cross-industry work. The expected value across all organisations was to make the system more transparent and create a level playing field while improving the system's resilience. Even though organisations realised that collaboration was the only way to achieve resilience on a network level, finding enough time for this cross-industry work was challenging.

However, the IRG created an informal platform where stakeholders from the UK aviation industry could come together and discuss topics about operational resilience with their counterparts in other organisations. Regular meetings and open discussions formed trust within the group, and relationships were established and strengthened. These relationships led to the informal sharing of information that benefitted the entire network.

A fundamental principle of the UK aviation industry was to have a free market, and the IRG aimed to protect this goal. Therefore, the IRG is not a central controlling body. Its purpose was to work collectively on operational issues to define and strengthen the safety boundaries of the system. The increasing demand put additional pressure on the system, and organisations realised that only by working together the system could accommodate the additional flights without putting further stress on the system and accumulating more delay minutes.

With the help of the CAA, the OAG database was analysed to determine the on-time performance of air transportation movement at UK airports between January 2018 and December 2019. Figure 4-12 is based on data from the CAA analysis of the OAG database. OAG is the leader in providing digital flight information, and the historical flight status database contains millions of flights and is constantly being updated with the latest information (OAG, 2022). The figure shows the deviations from the on-time performance in minutes. Each graph is divided into sub-categories to highlight what time band contributed to the overall delay minutes. As shown in Figure 4-12, the total delay minutes decreased from 13,813,829 minutes in 2018 to 10,811,689 minutes in 2019. The comparison shows that the deviation minutes decreased by ~ 21.7%. The most significant decrease was in July when the delay minutes decreased by ~ 31% from 2018 to 2019.

It is expected that many factors contributed to the improved performance. However, this analysis shows that one of the IRG's objectives to minimise delay minutes was achieved by decreasing the deviation from the on-time performance at UK airports.

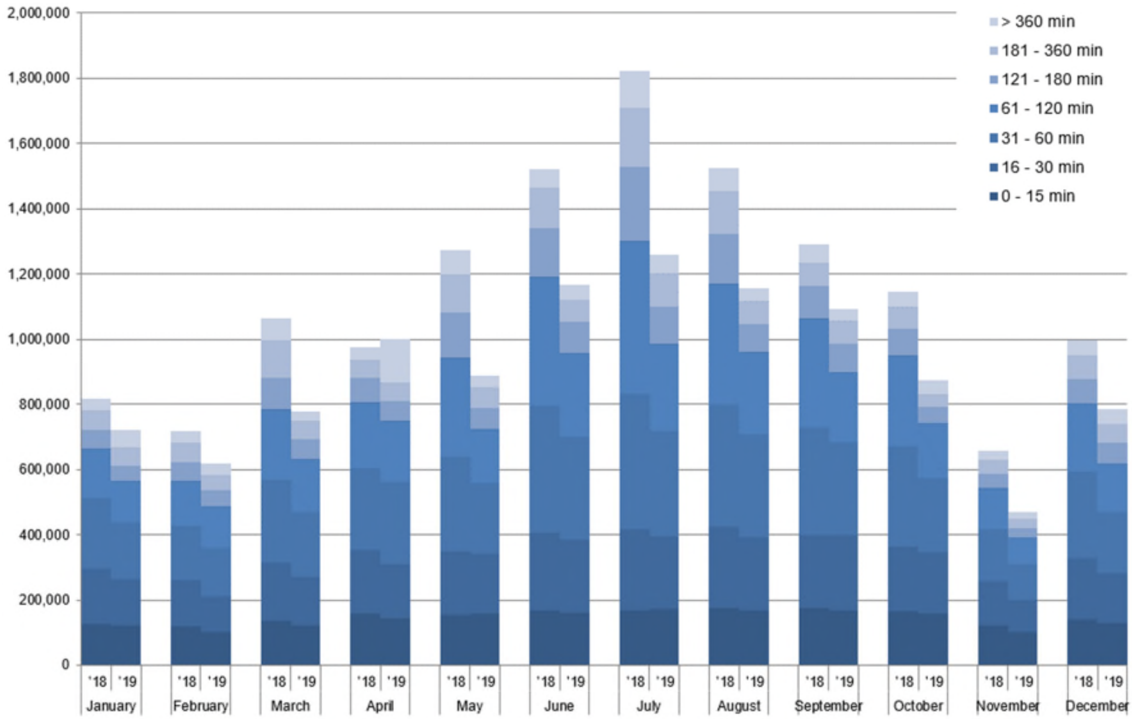


Figure 4-12 2018 vs 2019 comparison of on-time performance

4.2.6 Activities

According to the CAA (2017a, p.6), *"the UK system of open air transport competition operates without central control and coordination. This has served passengers and industry well to date"*. However, with the demand increasing and reaching the network capacity, the performance and resilience of the air transportation network were increasingly challenged. Without having a central control and coordination institution, the CAA Chief Executive Officer requested the formation of the VIRG. The VIRG provided a platform for the industry to work together *"to investigate ways of maintaining and improving network resilience"* (CAA, 2017a, p.9). The IRG used the VIRG report's recommendation (CAA, 2017a) as a baseline for their activities. These recommendations were grouped into five categories:

- Realistic Planning – Recommendations in this category addressed the need to work together to enable enhanced planning and mitigate early schedule conflicts.

- Flying the Plan – This category aimed at achieving shared situational awareness and collaborative decision-making processes to improve and inform operations.
- Serving the Plan – Having established a realistic plan, the report (CAA, 2017a) also highlighted the need to exploit and maximise contemporary technologies that would support the improvement of network resilience. The VIRG recommendation also flagged the establishment of a consistent level of capability and level of training to serve the plan and increase the level of resilience.
- Policing the Plan – The VIRG recommended clarifying specific rules when it was necessary to manage the capacity during disruptions or constrained operations.
- Network Coordination – The report (CAA, 2017a) mentioned that other countries experienced the necessity to install a central coordination institution as the demand exceeded the network capacity. The VIRG highlighted that the industry prefers a non-central approach with voluntary processes. However, the VIRG concluded that DfT and CAA were encouraged to consider a threshold in reducing network resilience which would justify centralised network coordination.

The IRG was set up *"to ensure the activities and changes identified by the [VIRG] in its report to industry are delivered"* (IRG, 2018a, p.1). Collaboration was highlighted as the key enabler for implementing the recommendations and improving network level coordination.

The terms of reference highlighted that the work of the IRG would first focus on the UK South East aviation network *"where day to day resilience issues are most acute"* (IRG, 2018a, p.2). However, as the work progressed, the IRG should consider changes to benefit the entire UK aviation network.

The discussions about highly utilised (airspace) infrastructure were driving the work, and resilience was initially considered to be the *"the ability of the UK South East air transport system to operate broadly to plan despite variances that arise during the operational day, to effectively handle disruptive forces when they arise,* *and to recover rapidly and robustly in the event of disruption"* (CAA, 2017a, p.8). More importantly *"it is noted that resilience is sometimes taken to mean the ability to recover efficiently from a significant disruptive incident, such as a runway closure. However, for the avoidance of doubt, this has not been the focus of the VIRG work"* (CAA, 2017a, p.9). In order to achieve the VIRG recommendations, the IRG defined several activities. A detailed description of all IRG projects would be beyond the scope of this research, and therefore only the most significant achievements are mentioned in this chapter.

The IRG mainly facilitated discussions, and as part of these discussions, a collaboration between ACL and NATS was established. ACL's database contained all the estimated movement at the major UK airports for the next season, providing roughly a six-month outlook. By accessing this data, NATS was able to predict future demand. Furthermore, the IRG hosted several meetings with ACL and presented their seasonal outlook for the UK and neighbouring countries, detailing sector load and comparison to previous years. This additional information was combined to highlight potential hotspots for the following season and provided information to the stakeholders on whether the schedule would be realistic.

The researcher attended a 3-hour workshop on 17th December 2019 at Heathrow Airport, attended by more than 20 people from various organisations. A follow-up teleconference on 05th March 2020 attracted a similar audience size. Many attendees indicated real value in these meetings as predicted flight movements and seat capacity for the next season were shared. In addition to the ACL outlook, the airports shared their views on challenges for the following season. One airport made the system aware on 17th December 2019 that they were planning to close one of their runways for refurbishment. The industry welcomed information sharing like this, as comments from the meeting confirmed. The IRG also arranged a meeting to examine challenges during the winter operation of 2019/20. On 20th November 2019, the IRG hosted a 3-hour long Winter Operations Preparation workshop, during which the Met Office gave a detailed weather update for the following months, based on their most recent predictions.

Furthermore, the IRG invited the CEO of Kilfrost to the meeting. Kilfrost is the sole supplier of de-icing fluid in the UK, and the CEO gave a presentation about their supply estimation and an update on their business continuity plans. Furthermore, airports shared best practices during the meeting and discussed learnings and issues from the previous winter.

One of the UK's frequently faced challenges was operating during bad weather. Dealing with certain storm events meant that airports could not accept as many arrivals as they would generally take during conditions with no wind. As mentioned in section 4.2.3, several UK airports *"currently operate at, or near to, their maximum capacity for significant parts of the day. Consequently, disruptive weather events can cause severe delays and last-minute cancellations, and the time required for the airport to recover can be significant"* (IRG, 2018b, p.3). Therefore, the IRG looked at the challenge of proactively reducing the system's capacity for predicted storm events. However, since the UK air transportation system operates without central control and coordination, capacity reduction processes were only voluntary. The IRG objective was to consider "*the options to improve and encourage capacity reduction compliance and fairness in the UK"* (IRG, 2018b, p.3). To achieve this, the IRG wrote a discussion paper in which the legislation was explained, and the IRG listed various options for improved compliance. However, as far as this research is confirmed, the work never progressed beyond the draft protocol, which was discussed at an IRG meeting on 28th February 2020.

One of the most significant achievements of the IRG was the development of a protocol for mass diversion events. This protocol and its resulting benefits are discussed in subchapter 4.3.

4.2.7 Discussion

This case study analysed the establishment and work of the IRG. It investigated the process from the realization that change was needed to establish the IRG. Moreover, it captured what high-level principles of the developed framework could be observed in the cross-industry work that the IRG facilitated. The case study used the findings to create empirical evidence to refine the PRF.

The observed high-level principles are categorised in themes of *System Design*, *System Changes*, and *System Preparedness* of the proposed framework (see Figure 2-15).

Looking at the IRG's definition of resilience, it can be argued that the view on resilience was limited. The IRG was mainly using elements of robustness to protect the day-to-day operation, as stated in the CAA (2017a) report.

As proposed in subchapter 2.2, the potential for resilience can be generated in the *System Design* theme. As stated in the same subchapter (subchapter 2.2), the *System Design* theme consists of two sub-components: *System Setup* and *System Checks*.

4.2.7.1 System Setup before the establishment of IRG

Analysing how the IRG was formed identified a high-level principle from the *System Setup* theme. Table 4-9 matches the principles with the practical example and outlines the resulting consequence. The connection with other themes is also shown in Table 4-9.

Table 4-9 Observed System Setup principle in case study 2

High-level principle	Example	Result	Connection with other theme(s)
Buffer capacity is incorporated	Operate broadly to plan despite variances that arise during the operational day	Review of network capacity	Decreases likelihood of internal disruptions

Principle: Buffer capacity is incorporated

Until the spread of the COVID-19 virus in Europe, the number of arrivals and departures at UK airports steadily increased from 2010 until 2019 (CAA, 2017b). As identified in the CAA report (CAA, 2017b), the demand approached the maximum network capacity in the UK's southeast corner. The lack of buffer capacity (Westrum, 2006) challenged the resilience of the aviation system.

People *"had reservations about whether it [airport capacity declaration process] prioritised greater utilisation at the expense of worse resilience"* (CAA, 2017b, p.9). This view on resilience can be traced back to setting up a system and dealing with trade-offs (Hoffman and Woods, 2011). In the CAA (2017b) report, resilience was defined by the number of delay minutes of the aviation system. A more resilient system would have fewer delay minutes, as seen in Figure 4-13.

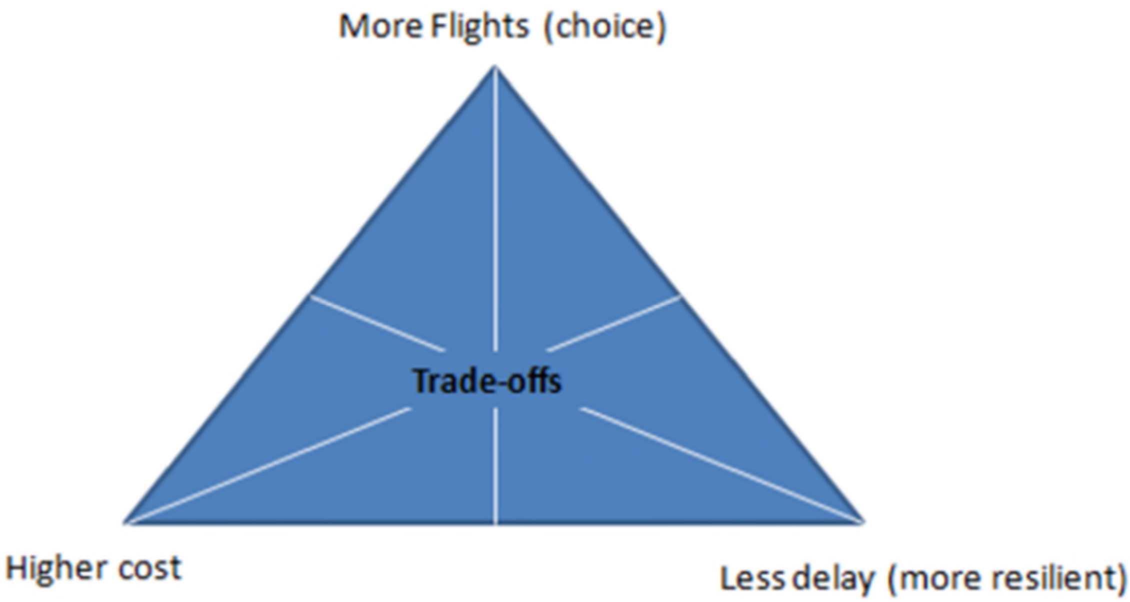


Figure 4-13 Trade-offs in the UK air transportation system

This practical example confirms that the setup of a system directly influences the system's resilience. However, assessing the system's resilience by only looking at the number of delay minutes is a rather performance-driven view. Although it captures that a system has to deal with trade-offs, it disregards the safety aspect, which could be observed in Rasmussen's (1997) model.

It could be argued that delay minutes could result from decisions on concerns over the system's safety. As mentioned in section 4.1.4, as soon as the system comes under any threat to safety, flight movements are reduced, increasing the delay minutes. Even though delay minutes may indicate the system’s resilience, it does not capture the complete picture of resilience as non-performance indicators, such as near misses, are also part of resilience (Cook and Woods, 2006).

4.2.7.2 System Checks before the establishment of IRG

In this case study, a working example of a high-level principle was observed, as shown in Table 4-10. The analysis of the resulting consequence helped establish a connection with other themes.

Table 4-10 Observed System Checks principle in case study 2

High-level principle	Example	Result	Connection with other theme(s)
Recognizing changing risks to operation	Recognizing that infrastructure and buffer capacity is limited	Realization that collaboration was needed	Input into System Changes

<u>Principle: Recognizing changing risks to operation</u>

Dekker (2006) argues that a system must constantly check whether the perception of risks still matches reality. During the review process, the CAA (2017b, p.5) report identified that the capacity of airports and airspace in the UK was constrained, and a constant increase in demand meant the UK's *“busiest airports are regularly among the worst performing in Europe in term of on-time performance”*. The UK aviation industry realized the infrastructure was limited, and a more collaborative approach was required to improve the system's performance. Collaboration could be used to share information and work together.

Having a review process in place that identified the current system could not handle the increase in demand is an example of how resilience can be generated through the *System Check* theme. The outputs of the findings of the *System Checks* were then used to change the system in the *System Changes* theme.

4.2.7.3 System Changes

High-level principles from the *System Changes* theme were identified in this case study. The empirical examples and resulting consequences are listed in Table 4-11. It further explains whether outputs directly influenced the principles from other themes or results from other themes directly affected the high-level principles of the *System Changes* themes.

Table 4-11 Observed System Changes principles in case study 2

High-level principle	Example	Result	Connection with other theme(s)
Anticipation of future challenges	Realization that collaboration was needed to cope with increasing demand	Formation of IRG and defining structure	Output from System Checks
Safe integration of long-term changes	Safe integration of long-term changes	Regular IRG meetings became part of routine	Input into System Setup

<u>Principle: Anticipation of future challenges</u>

No single disruptive event led to the formation of the VIRG. Instead, it was realised that proactive, long-term changes were required to prepare the system for the future. Having identified that change was needed, the VIRG was formed. Outputs from the CAA (2017b) report were used to write the report of the VIRG (CAA, 2017a). The recommendations of the VIRG were later formalized into the terms of references of the IRG (IRG, 2018a).

<u>Principle: Safe integration of long-term changes</u>

The formation of the IRG is an example of how resilience can be proactively generated through the *System Changes* theme. The IRG was set up on a permanent base to address resilience issues in the UK air transportation industry and became part of the operation and therefore updated the *System Setup*. Therefore, the IRG is an example of Woods (2015, p.8) fourth form of resilience and *“the ability to manage/regulate adaptive capacity of systems that are layered networks, and are also a part of larger layered networks, to produce sustained adaptability over longer scales”*.

4.2.7.4 System Setup after the establishment of IRG

Table 4-12 lists all the *System Setup* high-level principles observed after the IRG was established. It matches the principles with the empirical examples, shows the resulting consequences, and determines the connection with other themes.

Table 4-12 Observed System Setup principles in case study 2

High-level principle	Example	Result	Connection with other theme(s)
System is aware of interfaces with other systems	Providing platform for industry to come together	Improving situational awareness	Input into System Response
Flexible mode of operation	Defining protocols for mass diversion event and drone incidents	Protocols for handling disruptions are available	Input into System Response

<u>Principle: System is aware of interfaces with other systems</u>

Having integrated the IRG into the operation brought several benefits to the industry. The IRG provided a framework and platform for the industry to come together and collaborate on various topics. Based on comments during the meetings, this collaboration encouraged information exchange, which helped improve the industry's situational awareness. According to Le Coze (2019), better situational awareness improves a system’s resilience.

In addition to improving situational awareness, the IRG constantly reviewed its approach to resilience, tried to address emerging threats, and monitored the system closely. One example was the discussion about handling drones and drafting a flowchart of information sharing and hierarchy during a drone incident. This protocol was meant for sustained drone attacks, similar to that at Gatwick airport in 2018 (BBC, 2018).

Another priority of the IRG was to enable the sharing of best practices within the UK aviation industry. Using experiences and learning from other stakeholders enhances the system's resilience (Wreathall, 2006). The IRG’s purpose section actively encouraged the working group " t*o review best practices in other sectors and countries”* (CAA, 2017a, p.42). Furthermore, the OG supported the IRG work, a sign of top-management commitment (Costella, Saurin and de Macedo Guimarães, 2009). According to Costella, Saurin, and de Macedo Guimarães (2009), having this form of commitment by the board of each stakeholder is a sign of resilience.

<u>Principle: Flexible mode of operation</u>

The IRG developed a protocol for better managing mass diversion events. This protocol and its implications on the various themes are analysed in more detail in case study 3 (see section 4.3).

Furthermore, the IRG worked on clarifying the process during a drone event at an airport, which is another example of how the actions taken in the *System Setup* influence the *System Response* theme. A detailed analysis of the drone protocol was beyond the scope of this research.

Nevertheless, those two examples show that predefined protocols could provide clarity and a governance structure during disruptive events, resulting in a higher potential for a resilient operation (Naderpajouh et al., 2018).

4.2.7.5 System Checks after the establishment of IRG

One high-level principle from the *System Checks* theme after the formation of the IRG was observed. Table 4-13 lists the high-level principle, empirical example, resulting consequence, and connection with other themes.

Table 4-13 Observed System Checks principle in case study 2

High-level principle	Example	Result	Connection with other theme(s)
Recognizing changing risks to operation	IRG members doing internal risk assessment	Met Office and NATS sharing outputs through IRG	Input into System Preparedness

Principle: Recognizing changing risks to operation

Although the IRG did not have the resources to do any risk assessment, the working group was used to share the outputs from internal work done by various stakeholders.

The Met Office frequently provided weather forecasts for expected severe weather and updates on volcanic activities. Furthermore, the winter weather preparation forecast provided an outlook of the weather over the next three months to the IRG members.

4.2.7.6 System Preparedness after the establishment of IRG

Table 4-14 outlines the operationalised principles from the *System Preparedness* theme and matches them with the empirical examples. The table also explains the operationalised principles' results and determines the connections with the other themes.

Table 4-14 Observed System Preparedness principles in case study 2

High-level principle	Example	Result	Connection with other theme(s)
Ability to anticipate bottlenecks	Met Office sharing data on weather and volcanic activities	IRG members are aware of potential upcoming disruptions	Outputs from System Checks
Ability to anticipate bottlenecks	NATS and ACL sharing data on potential bottlenecks	IRG members are aware of potential upcoming disruptions	Output from System Checks

Principle: Ability to anticipate bottlenecks

Looking at Hollnagel's (2009a) four cornerstones of resilience, the IRG also used anticipation to improve the resilience within the system. According to comments made during the workshop on 20th November 2019, IRG members valued the information provided by the Met Office, which IRG members mentioned during conversations before and after the workshop. The Met Office also used the IRG channels to distribute detailed weather updates or inform the IRG members about expected storm events. This communication channel allowed the IRG members to ask the Met Office for clarification or further information should the situation require it. The Met Office informed the IRG community about volcanic activities on several occasions. The purpose of the constant update about abnormal volcanic activities was to provide early warning signs. Fortunately, the situation had never escalated into a situation like in 2010 when the aviation industry was heavily affected by the eruption of the volcano Eyjafjallajökull (Miller, 2011; Reichardt, Ulfarsson and Pétursdóttir, 2019).

During the Season Hotspot meetings, sector loads and potential bottlenecks of the system were discussed. Although there was no coordination or control over how the system may mitigate these bottlenecks, it provided the stakeholders with a more detailed view of the future demand within the system. The improved situational awareness allowed stakeholders to proactively adjust their operation accordingly, either by rerouting their aircraft or taking on additional staff to match the expected demand (e.g. they could anticipate disruptions).

Although the IRG was used to share information and identify upcoming bottlenecks, there was no collaboratively planning in the *System Preparedness* theme to develop joint-up plans to cope with the expected demand.

4.2.7.7 Integration of findings

One significant finding of this case study was that it did not need a disruptive event to change and improve the system. By analysing the UK air transportation system, the CAA and the industry realized that change was needed, and more collaboration was required to solve some of the resilience challenges. This case study predominantly looked at the formation of the IRG and what benefits it brought to the aviation system.

Subchapter 4.3 looks at one specific project of the IRG and how the IRG facilitated the enhancement of resilience in the *System Response* theme.

The outputs from sections 4.2.7.1 – 4.2.7.6 were used to refine the PRF by adding additional connections.

- Connection between *System Checks* and *System Changes*
  As shown in section 4.2.7.2, the case study demonstrated that the operationalised principles of *Recognizing changing risks* triggered actions taken in the *System Changes* theme. The realization that the (airspace) infrastructure was limited led to the recommendation that more collaboration between the various stakeholders was required.
- Connection between *System Changes* and *System Setup*
  Section 4.2.7.3 showed that the principles of *Anticipating future challenges* and *Safe Integration of long-term changes* led to an updated version of the *System Setup* theme. Through various iterations, the IRG was formed, and regular IRG meetings became part of the *System Setup*.
- Connection between *System Setup* and *System Response*
  In section 4.2.7.4, it was demonstrated that the principles of *System is aware of interfaces with other systems* and *Flexible mode of operation* improved the potential for resilience generated through the *System Response* theme. With the *System Setup* theme, protocols for disruptions were defined, and the situational awareness of the various stakeholders was improved.
- Connection between *System Checks* and *System Preparedness*
  The principles of *Recognizing changing risks* in the *System Checks* theme led to the principle of *Ability to anticipate bottlenecks* in the *System Preparedness* themes. The IRG communication channels were used to share outputs from risk assessments done by the Met Office and NATS. Those updates gave the UK aviation industry awareness of potential upcoming disruptions. However, no process in the IRG would allow a unified approach to reducing capacity for expected weather events (IRG, 2018b). This form of formalized capacity reduction process and resulting disconnect between *System Preparedness* and *System Response* may be one of the areas the UK air transportation industry could focus on in the future.

Figure 4-14 visualises how the findings from case study 1 were used to refine the PRF.

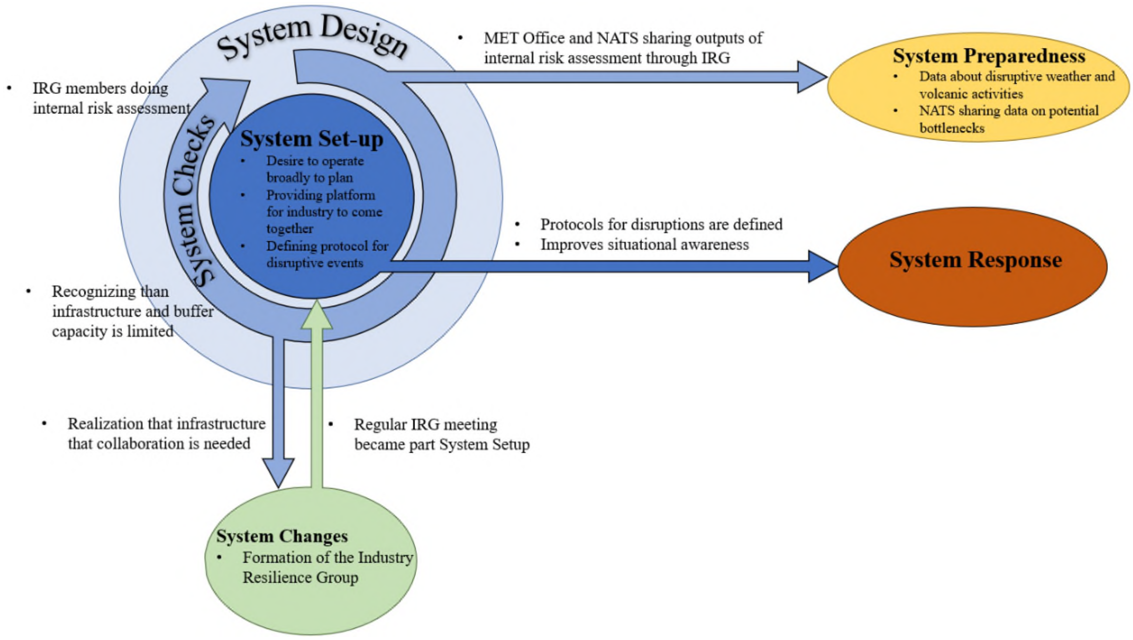


Figure 4-14 Integration of findings from case study 2

For the development of the figure, empirical examples were used to explain the content of each theme and highlight the connections between the themes.

4.2.8 Closing remarks

This case study used multiple sources to investigate the working of a collaboration of several UK aviation stakeholders. Analysing the UK air transportation system in the *System Checks* theme led to the drafting of the CAA report (CAA, 2017b) and the conclusion that collaborative work was missing, resulted in the VIRG and, later on, the IRG in the *System Changes* theme. By investigating the objectives and setup of the IRG, it was possible to highlight how the IRG enhanced the resilience of the UK air transportation system.

Being a member of the IRG for most of the duration of the case study allowed the researcher to obtain rare and unique data and investigate how various stakeholders worked together to strengthen the system's resilience collectively. Having looked at the IRG work between 2018 and 2020, outputs from the case study suggest that the IRG enhanced the resilience of the UK air transportation system by creating a platform for discussion and collaboration. Investigating the on-time performance between 2018 and 2019 showed that the IRG's objective to minimise delay minutes was met. Although the minutes of delay decreased from 2018 to 2019, it could not be determined what part the IRG played in improving the system's performance. The meetings' observations indicated that all members saw value in the cross-industry working group.

Despite enhancing the resilience framework and using it for a real-world example, this case study contains several limitations and could profit from further research.

The research used observations and outputs from discussions as a qualitative data source. These qualitative data sources were subject to interpretation, and the researcher used data from secondary sources to cross-check his findings. However, qualitative data collected using questionnaires could enhance the case study and better indicate the real value the IRG brought to the industry. Due to the time constraint of most people during the COVID-19 pandemic, it was not possible to do this during the scope of this research.

The case study was a first attempt to highlight how learning occurred in the UK air transportation system and how this led to the formation of a cross-industry working group supported by top-level management. Further research is needed to quantify the benefits of the IRG and potentially investigate other aspects of the working of the industry collaboration.

4.3 Case study 3: Protocol for mass diversion scenarios

4.3.1 Introduction

The *System Robustness* theme should help a system continue its normal operation while mitigating disruptions. Tools to prevent the failure from spreading across the system can, for example, include the use of barriers (Hollnagel, 1999), slack resources (Westrum, 2006) and buffer capacity (Woods, 2006b). This case study analysed how a newly introduced diversion protocol increased the resilience of the air transportation system by adding additional buffer capacity.

4.3.2 Data sources

The case study used a variety of sources to ensure a thorough analysis. Monthly meetings with the IRG helped to understand the context of the problem and how the developed diversion protocol was intended to mitigate the identified challenges. The study also benefited from a site visit to the NATS ATC centre in Swanwick, during which information from ATCOs and supervisors about the internal processes was collected. As mentioned in subchapter 4.1, the site visit on 14th May 2019 was mainly undertaken for case study 1 but also helped to understand the different roles within the centre and who would trigger the mass diversion protocol. In addition, a Plan 39 table-top exercise hosted by NATS was attended on 28th March 2019. The data collection was complemented by a debriefing call during which the first enactment of the Plan 39 protocol in real operations was discussed. Extensive data about the timeline and lesson learning were shared during this debrief.

Table 4-15 summarizes the main sources used for case study 3.

Table 4-15 Data sources used for case study 3

Primary data source(s)	Secondary data source(s)
Observations during workshop and debriefing call • Table-top exercise on 28th March 2019 • Debrief of first enactment on 10th July 2019	Two industry documents • IRG (2019) • NATS (2019c)

4.3.2.1 Table-top exercise

The table-top exercise was organised by NATS and attended by approximately 30 – 40 representatives from various aviation stakeholders, including several airlines and airports. The 3.5 hour-long in-person workshop took place on 28th March 2019 and was facilitated by NATS Deputy General Manager and the chair of the IRG. The intention was to use the workshop to brief the stakeholders and discuss the management processes during mass diversion events. It also facilitated discussions about potential obstacles and challenges of the new diversion protocol. Notes were taken during the workshop and combined later with the other sources.

The scenario used for the workshop looked at the possibility of protestors near the runway at Gatwick Airport that would lead to a temporary closure of the airfield. Protestors have disrupted the operation at airports in the past to generate media attention. For example, in 2015, climate activists blocked one runway at London Heathrow (Elgot and Siddique, 2015). A year later, Black Live Matter protestors interrupted the operation at London City airport (Weaver and Grierson, 2016). The table-top exercise talked the participants through all the steps after a runway closure. The brief included details about the notification process and how aircraft are diverted to other airfields. NATS could further clarify the terminology and procedures used in such an event.

The workshop provided prime access to briefing notes and details of the diversion protocol (e.g. IRG, 2019). Furthermore, coffee breaks enabled face-to-face discussions with the attendees and feedback from airports and airlines about the Plan 39 protocol was obtained. Notes taken during and after the discussions were also considered for the analysis.

4.3.2.2 Debrief of the first enactment

Plan 39 was enacted for the first time in actual operation on 10th July 2019. NATS organised a debriefing call on 17th July 2019. During the call, a timeline, a table of diverted aircraft, and experiences from the staff were shared with the IRG members. Attending the call and access to the internal NATS slide deck (NATS, 2019c) provided unique data for this case study, permitting detailed analysis of the case. Personal notes that were taken during the call were later combined with the slides that were shared by NATS (NATS, 2019c)

4.3.3 Utilization of airport infrastructure

As identified by the CAA (2017b), the aviation infrastructure in the UK is highly utilized, particularly in South East England, with many major UK airports within close proximity. Networks operating close to capacity are sensitive to disturbances, and such complex systems are fragile (Carlson and Doyle, 2002). Fragility in a system means minor disturbances can majorly affect the system's overall performance. The closure of one airport can significantly impact the operation at other airports as the system has to cope with the additional diverted aircraft. The additional diversions are a challenge since there is not much buffer capacity at the other airports in South East England that can be used to take the diversions. The lack of buffer capacity is due to the high runway utilization at these airports. As shown in Figure 4-10, the runway infrastructure at the major UK airports was becoming increasingly constrained. According to the IRG (2019), diversion events in the past, especially in the congested South East airspace, led to longer routes and additional flight time. Longer flight times resulted in multiple fuel emergencies during diversion events, which impacted the stability of the air traffic system. Emergencies receive priority handling over other traffic and direct routings to the nearest airport. Prioritizing aircraft that declared a fuel emergency could cause ripple effects as other arrivals have to be put on hold while the emergencies are expedited, which can result in more fuel emergencies. Fuel emergencies due to diversions significantly threaten the aviation system's safety. The loss of infrastructure can hamper the aviation system's safety, resulting in secondary emergencies (Pescaroli, 2018).

Furthermore, diverting aircraft increases the workload of the ATCO as the aircraft needs to be rerouted and an alternate aerodrome found. In a diversion event, ATCOs would usually call other airports and establish the availability for diversions (IRG, 2019). The controller may suggest alternative airports to the cockpit crew or ask for preferences. This procedure is time-consuming, and the industry recognized the need for a more structured approach.

Hence, one area of the IRG's interest was the challenge of rerouting aircraft in abnormal situations. With agreed protocols and guidelines, the IRG aimed to ensure safe operation even when infrastructure resources are severely compromised by quickly diverting aircraft to nearby airfields.

4.3.4 Plan 39 for a single loss of infrastructure

A disruption at one of the major UK airports, after which the airport can no longer take any arrivals, would trigger a mass diversion scenario. As soon as a mass diversion scenario is triggered, the ATCOs would try to clear the lower altitudes and put the aircraft into holding stacks while determining what alternate aerodrome can take the aircraft. The challenge is that ATCOs would have to divert multiple aircraft in a relatively short amount of time. During peak hours, aircraft may arrive within less than two minutes of separation. This spike in the ATCOs' workload can undermine the system's stability, as shown in case study 1 (see subchapter 4.1). Losing a single airport infrastructure was identified as a potential risk to the UK air transportation system (IRG, 2019).

4.3.4.1 General information

The goal of the IRG was to develop a protocol for a mass diversion scenario to stabilize the system by reducing the possibility of fuel emergencies shortly after the disruptive event and minimize the additional workload for ATCOs. The intention was to develop a concept that "*takes the heat off the situation*" (quote from the chair of IRG from 28th March 2019) and destress the system in the initial phase after a disruption. In addition, the protocol is intended to reduce uncertainty and help minimize the effects of the disruption on the operation at other airports. This protection means the network can contain the failure and cope with a single loss of infrastructure with no significant decrease in the overall system performance. The IRG engaged with the main airports in the UK. In consultation, airports committed to accepting a specific amount of additional aircraft that they would be able to take at any time during the day.

The developed protocol was named Plan 39. It was intended to work as an additional safety buffer in a mass diversion event. Plan 39 contained a list of 47 immediately available, pre-authorized slots for different aircraft types. There are six different types of aircraft, classified by code letters. The letters refer to the wingspan, and Table 4-16 provides an overview of the different types of aircraft.

Table 4-16 Aircraft types

Code letter	Wingspan	Code letter	Wingspan
A	< 15m	D	36m but < 52m
B	15m but < 24m	E	52m but < 65m
C	24m but < 36m	F	65m but < 80m

The slots for the developed mass diversion protocol were spread over 13 airports in the UK, as shown in Table 4-17 (IRG, 2019). The protocol should expedite the allocation of diverted aircraft in case an airport in the system goes offline. With the additional slot capacity available at alternative airports, controllers could also respond swiftly to airline requests.

Table 4-17 Pre-approved slots from Plan 39 protocol

Airport	Type of Aircraft	Airport	Type of Aircraft
Heathrow	4 Code C	Southampton	3 Code C
	2 Code E	East Midland	3 Code C
	1 Code F	Cardiff	2 Code C
Gatwick	4 Code C	Bristol	3 Code C
Stansted	4 Code C	Birmingham	3 Code C
Luton	4 Code C	Newcastle	4 Code C
Southend	3 Code C		

As explained during the table-top exercise, the activation of the Plan 39 protocol is executed by the NATS control centre in Swanwick. It usually follows the notification "*Delay not determined*" by the affected airport in the system. The command "*Plan 39 activated*" by the NATS control centre triggers the protocol, and all the pre-authorized slots at airports become available to the ATCOs.

The Plan 39 protocol was expected to cope with 15 to 20 aircraft within the first 45 minutes following a disruption (IRG, 2019). Should a cockpit crew of an aircraft request a diversion to an airport which has already used up all pre-authorized slots, the ATCO may notify the crew of Plan 39 capacity at other airports.

As soon as all pre-agreed slots were used at the airports, the standard notification process should be followed, and the diversion protocol loses its effect. The newly developed protocol should support ATCOs to reduce the immediate coordination challenges shortly after the disruption triggers a mass diversion scenario and "*buy the system some time*" (quote from participant of table-top exercise).

4.3.4.2 First enactment of Plan 39

On 10th July 2019, Gatwick Airport suffered a failure of their Electronic Flight Progress Strip (EFPS) system as two servers went down (BusinessInsider, 2019). The EFPS contains specific flight information, such as aircraft identification, transponder code and aircraft type. Without the EFPS, Gatwick Airport could no longer ensure a safe operation and stopped all arrivals and departures. Table 4-18 provides a timeline of the main events during the disruption caused by the IT failure (NATS, 2019c).

Table 4-18 Summary of main events

Time (Zulu / UTC+0)	**Event**
16:00	Last aircraft departs Gatwick and EFPS failure is detected
16:01	First arriving aircraft is sent around
16:02	Gatwick Airport notifies NATS about zero rate and stops all departures
16:04	Gatwick Airport notifies NATS that they can no longer accept any inbound aircraft. Cause and timescale undetermined
16:04	NATS initiate Plan 39 protocol
16:13	Gatwick Airports agrees to land some aircraft with residual data
16:29	Gatwick Airports starts to land some airborne aircraft again
16:56	Gatwick Airport stops arrival of aircraft again
17:32	Systems at Gatwick Airport are back online
18:01	First departure from Gatwick Airport after disruption
18:06	Arrivals resume at Gatwick Airport
18:22	Plan 39 protocol is formally closed

The last aircraft to depart Gatwick Airport was an Easyjet flight at 16:00 Zulu time. All the following time stamps are given in Zulu time, a synonym for UTC+0. As soon as the failure was detected, Gatwick Airport suspended all flying operations, and at 16:01, the first arriving aircraft was sent around. Gatwick Airport notified NATS about the loss of the EFPS system at 16:02 and informed them that they would stop all departures, and a zero rate was applied. A zero rate states that the airport no longer accepts incoming traffic at its origin airfield. However, an airport with a zero-flow rate may still be open for on-route aircraft. At 16:04, the supervisor at Gatwick Airport confirmed to NATS that they could no longer accept any inbound aircraft. The cause and timescale for the disruption were unknown, meaning "*delay not determined*". That meant that the NATS terminal control (TC) supervisor initiated the Plan 39 protocol, and all other London airports were immediately informed that the protocol had been activated.

Twelve aircraft were diverted in the first 45 minutes using the Plan 39 protocol. At 16:13, Gatwick Airport notified NATS that the airfield could land some aircraft again due to the availability of residual data, which provided some basic flight information. In the time between 16:29 and 16:56, a total of 15 aircraft landed at Gatwick Airport. However, this process was stopped again, and from 16:57 until 18:00, no aircraft landed at or departed from Gatwick Airport.

At 17:32, the systems at Gatwick Airport were back up again, and the airport requested an operation restart with a flow rate of 15 aircraft per hour for two hours once the data were ratified. At 18:00, a flow rate of 10 aircraft per hour for the next two hours was agreed upon. It was decided to first take all diverted aircraft and flights that were already on route to Gatwick. The first departing aircraft left Gatwick Airport at 18:01. Arrivals resumed shortly afterwards at 18:06. At 18:22, the Plan 39 protocol was officially closed. During the entire time, a total of 28 aircraft were diverted to other airports, as summarized in Table 4-19. 13 out of the total diversions used pre-approved slots from the Plan 39 protocol. According to NATS, the 13 diversions significantly reduced the workload of the ATCOs. Even though less than 50% of the diverted aircraft were handled with the Plan 39 process, it significantly affected the ATCOs workload, based on feedback from the debriefing call.

Table 4-19 Diversion Summary

Receiving airfield	Diverted aircraft using Plan 39 protocol	Diverted aircraft that needed to be approved	Total number of diverted aircraft
Heathrow	1	0	**1**
Stansted	3	3	**6**
Luton	4	4	**8**
Southend	2	0	**2**
Birmingham	2	2	**4**
East Midlands	0	4	**4**
Bristol	1	1	**2**
Manchester	0	1	**1**
Total number of diverted aircraft	**13**	**15**	**28**

4.3.4.3 Aftermath

Some airlines opted for a "*splash-and-dash*" strategy. This strategy describes the situation when the passengers were kept on the aircraft at the diversion airport. These airlines were hoping for a quick reopening of the affected airport and tried to return to the intended destination as soon as the airport was available again. Other airlines decided to disembark the aircraft, increasing passenger flow at the alternate aerodrome. Therefore, one of the stakeholders that would have liked to get more information about diverted aircraft was the Border Force at the alternative airport. Receiving more aircraft on short notice impacts their staff planning. Hence, early notification about diversions would be beneficial for ensuring appropriate staffing, handling the additional arriving passengers effectively, and avoiding queues at the border. This example highlights the need for better multi-agency coordination (Pescaroli, 2018).

Based on stakeholders' feedback during the follow-up call on 17th July 2021, the Plan 39 protocol generally proved to be a practical concept to minimize the effects of the disruption on the rest of the system and reduce the controllers' workload. This reduction in workload was echoed by the NATS TC supervisor, who said that "*…the plan was fit for purpose and very rapid to implement the initial pre-planned diversions. This took lots of pressure off the TMA and approach controllers. The stacks were kept at a manageable level*." Similar feedback came from the NATS supervisor for area control ("*Overall, this was much better and more organised than previous similar events*") and the flight management planning department ("*The process was much smoother than other experiences."*).

Even though the Plan 39 protocol worked well during its first deployment, stakeholders knew that certain factors benefited this first deployment. One beneficial factor for the successful outcome was the time of the day the incident occurred. Had the disruption happened during a peak in arrivals, the pre-approved slots would have filled up much more quickly, and Plan 39 would have reached its limitations much sooner. Another positive factor was that Gatwick Airport could land 15 aircraft with residual data, further relaxing the system as ATCOs did not have to find an alternative airfield for those flights. During the table-top exercise, airlines raised concerns over the lack of procedure for returning to normal operation. Airlines wished to have more clarity about who would get priority for the repatriation flights and if there were procedures to manage how all the aircraft could leave the diversion airfield.

The internal review at NATS investigated the processes, and some areas of improvement were found. Most of the internal communication within NATS was paper-based. The flights into Gatwick Airport were diverted to a total of eight other UK airports, and Figure 4-15 is a graphical representation indicating where in the UK the aeroplanes were diverted to. One of the learnings of the first enactment was that a live, updated electronic solution for creating an overview of diverted aircraft and repatriation flights would have been helpful for internal and external communication and coordination. Particularly in an event with more diversions, this could have been critical.

Another learning was that conference calls need to be smoother and require better use of technology. Several stakeholders mentioned this fact at the debriefing call. During the event, people were constantly dialling in and out of the NATS conference call, which always caused a break in the discussion when the automated voice announced: "*participant X has joined/left the call*".

Figure 4-15 Diversion Map

4.3.5 Discussion

The Plan 39 protocol is a prime example of one of the meanings of resilience, identified by Westrum (2006, p.59), who describes resilience as being "*the ability to prevent something bad from becoming worse*".

4.3.5.1 Introduction

The ATM system in the South East of England is a highly utilized system with a complex infrastructure. Due to the system's complexity and the number of stakeholders involved, the aviation industry in the UK acknowledges that incidents at airports will continue to happen and cause further mass diversion events. While other projects focussed on increasing the reliability of airports in the system and eliminating the causes of disruptions and airport closures, Plan 39 was a feature for the reactive theme once a mass diversion scenario occurred.

This case study analysed how principles of the identified resilience-generating themes were used in the development and deployment of the mass diversion protocol.

4.3.5.2 System Changes

A list of the observed principles with the matching empirical examples is provided in Table 4-20. Furthermore, Table 4-20 highlights the consequences of the operationalised principle. The connections with other themes highlight whether the principles were directly influenced by outputs from other themes or their results directly impacted other themes.

Table 4-20 System Changes principle observed in case study 3

High-level principle	Example	Result	Connection with other theme(s)
Creation of lesson learning	Realization mass diversion process needs to be enhanced	Development of mass diversion protocol	Outputs from System Response
Safe integration of long-term changes	Integration of mass diversion protocol	Availability of mass diversion protocol	Input into System Setup

<u>Principle: Creation of lesson learning</u>

The analysis started with the realization of the system that change was needed. Mass diversion events in the past led to multiple fuel emergencies that undermined the system's safety. Realizing that change is needed is the first step in achieving learning (Yazdi et al., 2019).

As mentioned in subchapter 4.2, the IRG brought various stakeholders together. A new protocol for more streamlined management of mass diversion events was developed through a collaborative effort in the *System Changes* theme.

<u>Principle: Safe integration of long-term changes</u>

The *System Changes* theme updated the operation setup, and the new protocols and procedures were integrated successfully. Furthermore, the Plan 39 briefing document (IRG, 2019) included all the crucial information, and the protocol was discussed during various IRG meetings. In addition, NATS hosted a tabletop exercise to ensure the newly integrated protocol was clearly communicated to all relevant stakeholders. Sharing the updated plans increased situational awareness across stakeholders (Wreathall, 2006).

4.3.5.3 System Setup

Dinh et al. (2012) argued that resilient performance could be designed into a system. In this case study, two high-level principles from the literature review were identified, as shown in Table 4-21. The high-level principles with the matching empirical example and resulting consequence are also listed in Table 4-21. It further shows the connection with other themes by highlighting whether output directly influenced the principles from other themes or its results had direct implications on other themes.

Table 4-21 System Setup principle observed in case study 3

Source	Example	Result	Connection with other theme(s)
Buffer capacity is incorporated	System is able to free up additional capacity	Robustness of system is strengthened	Input into System Response

<u>Principle: Buffer capacity incorporated</u>

Plan 39 was an empirical example of how the potential for resilience can be integrated into the operation's setup. Instead of maximizing the efficiency of the runway utilization, multiple airports in the network committed to retaining a certain amount of slots that can be used in a mass diversion scenario. This additional buffer capacity stopped the disruption at one of the airports from spreading across the system and leading to fuel emergencies. Hence, the *System Setup* theme choice put the entire network in a stronger position to cope with a short-term disruption.

4.3.5.4 System Response

The high-level principles were matched with the empirical examples. The analysis also determined the resulting consequences of the operationalised principle. In addition, Table 4-22 shows the connection with other themes by highlighting whether the principles were directly influenced by outputs from other themes or their results directly impacted other themes.

Table 4-22 System Response principles observed in case study 3

High-level principle	Example	Result	Connection with other theme(s)
Early detection of disruption	Plan 39 was activated four minutes after disruption occurred	Buffer capacity was freed up shortly after disruption	–
Use of internal buffer capacity	Use of combined airport slots	Additional capacity for dampening the effect on the system and minimizing additional workload for ATCO	Outputs from System Setup

Principle: Early detection of disruption

According to Dinh et al. (2012), early detection of disruptions can help a system contain the damage and mitigate the situation at an early stage. Four minutes after the failure occurred, Gatwick airport notified NATS that the cause and timescale of the disruption were undetermined. According to the debriefing call, within the same minute, Plan 39 was activated. This swift enactment supported the containment of the failure and stabilized the system.

Principle: Use of internal buffer capacity

The ability of a system to cope with change or disruption by reducing or mitigating the initial impact is called absorption (Nan and Sansavini, 2017). The Plan 39 protocol tries to stop the negative consequences from spreading to other parts of the system, aiming to protect the operation at other airports by using the principle of dampening the effects (Jackson and Ferris, 2012).

Looking at the stress-strain model, situations in which Plan 39 is used are within the uniform region of the graph. The system stretches uniformly using a developed procedure to compensate for the additional demand. By making the spare slots at other airports available, the protocol provides the system with additional capacity, protecting it from an overload. Figure 4-16 is a graphical representation of how Plan 39 enhances the resilience of the aviation system. The system's buffer capacity is increased due to the availability of additional slots at diversion airports. Buffer capacity was one of the resilience characteristics mentioned in the literature (e.g. Woods, 2006b). Therefore, Plan 39 extends the uniform section of the stress-strain model, and the additional buffer capacity, increases the demand the system can cope with before moving into the non-uniform region. The intention is to increase the ability to absorb any perturbation and keep the system's operation within functional limits (Miller and Xiao, 2007).

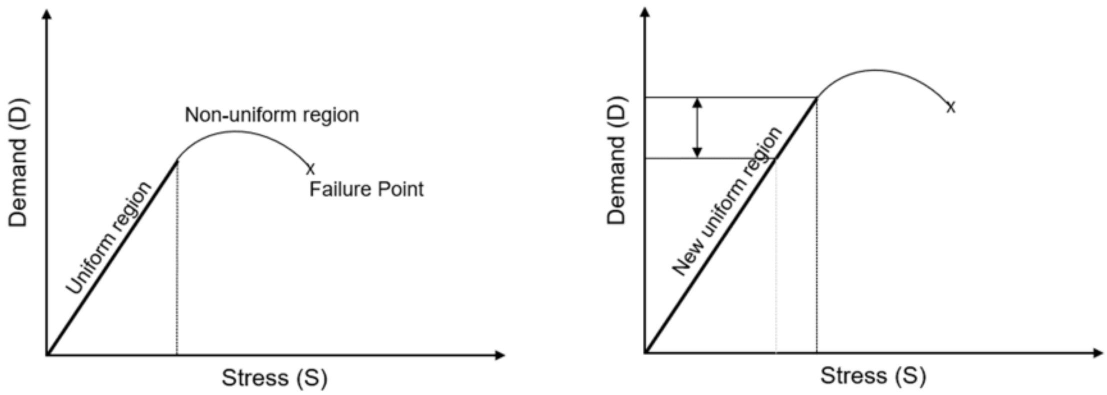


Figure 4-16 Additional buffer capacity introduced by Plan 39

Looking at the Performance over time model (e.g. Barker, Ramirez-Marquez and Rocco, 2013), the Plan 39 protocol strengthens the concept of survivability. The capability of the system to remedy perturbations makes the process more robust and minimizes losses (Said, Bouloiz and Gallab, 2019). Woods (2015) added that this is the ability of the system to absorb perturbation, and pre-planned protocols and procedures can be deployed in response to a disruptive event (Filippone et al., 2016). All of this shows that Plan 39 falls into the category of *System Robustness* theme of the PRF.

Although the operation at Gatwick Airport, where the disruption occurred, was significantly constrained, the effects on the overall UK aviation network were marginal. According to feedback from airports during the debrief call on 17th July 2019, no airports in the network experienced any impact on their operation. The Plan 39 protocol intended that airports which commit to the pre-authorized slots were supposed to continue their normal operation while landing the additional aircraft. This fact showed that the system stayed in the normal functioning state of the Resilience State Space model (Hollnagel and Sundström, 2006), and the system's functioning was never really reduced.

Besides protecting the network's overall performance and preventing ripple effects, such as multiple fuel emergencies, Plan 39 was supposed to keep the workload of the ATCOs within a manageable limit. According to NATS, the demand was always met with the required performance, which correlates with the first pattern of Cook’s (2006) Resilience Dynamics model (see Figure 2-12). NATS feedback showed that better administrative controls and procedures work as a factor that contributes to the resilience of a system (Dinh et al., 2012).

4.3.5.5 Integration of the findings

The findings were integrated into the framework established after the literature review (see Figure 2-15). By merging findings from the case study with outputs from the literature review, it was possible to add connections to the PRF.

The outputs from sections 4.3.5.2, 4.3.5.3, and 4.3.5.4 were used to refine the PRF by adding additional connections.

- Connection between *System Response* and *System Changes*
  As shown in section 4.3.5.4, principles of the *System Changes* themes can utilize outputs created by the *System Response* theme. Reviews of previous incidents led to the realization that mass diversion events need to be better handled, resulting in the principle of *Creation of lesson learning*.
- Connection between *System Changes* and *System Setup*
  Section 4.3.5.44.3.5.2 highlighted that the principle of *Safe integration of long-term changes* impacted the *System Setup* theme. Integrating the newly developed mass diversion protocol became part of the system's setup.

- Connection between *System Setup* and *System Response*

  The operationalised principle of *Incorporated buffer capacity* was discussed in section 4.3.5.3. This case study showed that pre-allocated slots in the *System Setup* theme incorporated buffer capacity into the system, which protected the system in the *System Response* theme.

Figure 4-17 visualises how the findings from case study 3 were used to refine the PRF. For the development of the figure, empirical examples were used to explain each theme's content and highlight the connections between the themes.

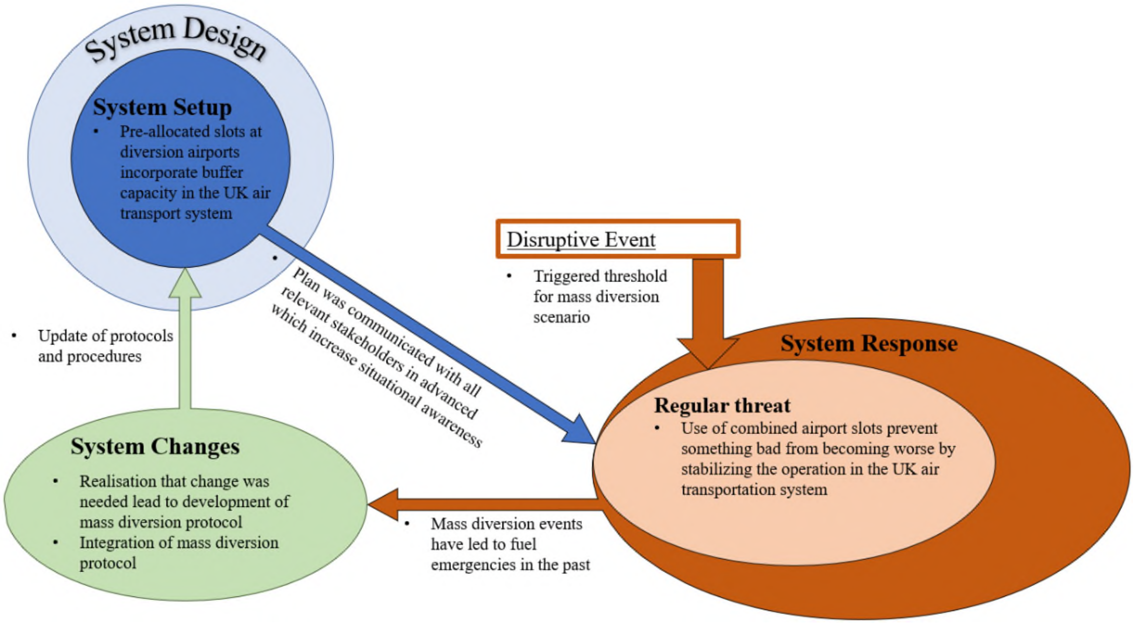


Figure 4-17 Integration of findings from case study 3

4.3.5.6 Limitations of Plan 39

Although Plan 39 proved to be a valuable tool to stabilize the operation during the analysed scenario, the protocol only focused on short-term disruptions, and its effectiveness stops when an airport is affected for several hours. The protocol introduces a short safety buffer and prevents ripple effects on the entire aviation system. The protocol worked well in the described case, but according to the briefing note, it is only supposed to deal with 15 to 20 aircraft in the first 45 minutes. Should the cause of the disruption cannot be found quickly, and the disruption is sustained, Plan 39 reaches its limits.

Furthermore, its use is considerably small should more than one airport is offline or London Heathrow loses both runways simultaneously. The loss of multiple infrastructures and the amount of diverted aircraft would overload the system, and the system could no longer remain in the state of *Normal Functioning* (Hollnagel and Sundström, 2006). The system would experience a significant drop in performance, and an escalation to the state of *Reduced Functioning* would be required (Hollnagel and Sundström, 2006).

To avoid becoming brittle and experiencing a sudden failure or collapse (Woods, 2015), once the Plan 39 protocol reaches its limits, it is essential to move the thinking beyond the theme of *System Robustness*. Therefore, the IRG started discussing a concept that deals with the simultaneous loss of multiple infrastructures, which includes losing both runways at London Heathrow.

4.3.6 Closing remarks

This study used multiple sources and engagement with UK air transportation network stakeholders and benefited from longitudinal data. The obtained access to stakeholders gave unrivalled access to how the UK industry worked collectively towards strengthening the resilience of the aviation system. The development and enactment of the new mass diversion protocol illustrated how the system improved its robustness.

Prior to the introduction of the Plan 39 protocol, mass diversion scenarios presented a significant threat to the safety of the UK air transportation system. The high runway utilization at airports had minimized the spare resources at alternate airports to accept diversions. Furthermore, the lengthy communication process between ATCOs and airports to establish the diversion capacity further impeded the diversion of aircraft. The previous process led to multiple fuel emergencies in the past.

This study captured the process from the implementation and table-top exercise of Plan 39 to the first enactment of the new diversion protocol. With the collected data, the research could show the effectiveness of the Plan 39 protocol and explain how the resilience of the UK aviation industry is improved by using elements of *System Robustness*.

Nonetheless, the study would profit from further research. The findings of this case study are mainly based on statements from IRG members, in particular NATS. The general feedback was that Plan 39 simplified the diversion process and stabilized the system. These statements could be confirmed by comparing the event from 10^{th} July 2019 with previous, similar events using data such as the workload of ATCOs based on questionnaires. However, this was not possible within the timeline and scope of the research.

Furthermore, two factors benefited the successful deployment of Plan 39 during this event. A simulation of the event could shed some light on the time of the day, and the fact that Gatwick Airport could land 15 aircraft with residual data prevented fuel emergencies. Further investigation could validate the true effectiveness of Plan 39 during this event. Again, this was not possible due to time constraints and data access.

4.4 Case study 4: Repatriation flight

4.4.1 Introduction

According to Hémond and Robert (2012), appropriate planning and preparation for expected disruptions may lead to better management of the situation and outcome. This case study analyses the preparation and execution of a COVID-19 repatriation flight arriving at one major UK airport. The case study is a good example for identifying practical applications of the principles in the *System Preparedness* theme. Furthermore, the importance of flexible adjustments by improvisation and adaptation during the *System Response* theme was highlighted.

4.4.2 Data sources

In order to ensure triangulation of the data, various sources were used for this case study. The data sources contained interviews, news article analysis, and information from an internal event report of the airport concerned, as shown in Table 4-23.

Table 4-23 Data sources used for case study 4

Primary data source(s)	Secondary data source(s)
Interviews after the event • 30min with Participant 5009 • 30min + 60min with Participant 5314	Airport's event report • See Anonymous Airport (2020)
	Public Health Responses Report • See Moriarty et al. (2020)
	Ten Websites • FCO (FCO, 2020a) • FCO(FCO, 2020b) • Scully et al. (2020) • Jersey Evening Post(2020) • Cavanagh (2020) • Sky News (2020) • ITV News(2020) • Morrison(2020) • Dyer (2020) • Narain (2020)

A 30-minute interview was held with the airport's Airfield Operations Director (Participant 5009) on 21st September 2020. A Director of Airfield Operations manages and oversees all activities to ensure and enforce compliance with airfield operations, safety, and security regulations. Hence, the person held valuable information about the event. Two interviews (24th September and 30th September 2020) were conducted with the airport's Head of Fire and Emergency Planning (Participant 5314). The first interview lasted 30 minutes, and the second discussion 60 minutes. All interviews were recorded and transcribed for analysis. The interviews provided crucial information about the event, as the interviewees were responsible for planning and handling the repatriation flight.

Furthermore, the airport's internal event report (Anonymous Airport, 2020) was analysed. The report summarized the event and included internal lesson learnings and factors that supported the operation. It also summarized the outputs from the internal debrief, teleconferences with all the key interested parties and the event log. The data collection was complemented by secondary data sources such as websites and reports.

4.4.3 Description of the event

The repatriation flight took place on 11th March 2020 and attracted much media attention as it was the first COVID-19 repatriation flight that arrived at a commercial airport in the UK (e.g. ITV News, 2020; Jersey Evening Post, 2020; Sky News, 2020). The actions from 8th March until 11th March 2020 were analysed for the case study.

4.4.3.1 Background information

The purpose of the repatriation flight was to fly UK citizens back to the UK who were onboard a cruise ship on which several people had tested positive for COVID-19 (Moriarty et al., 2020).

This cruise ship had an approximate capacity of 2,600 passengers and 1,150 crew members (Princess, 2021). It sailed from a port in Northern America to four stops in South America. According to Moriarty et al. (2020), the roundtrip from the

USA lasted from 11th – 21st February 2020. This trip is later referred to as Trip 1. 68 passengers and most of the 1,111 crew members from Trip 1 stayed on board for another cruise. The second voyage was planned to leave on 21st February and return on 7th March. While trip 2 was underway, a clinician in the USA reported two patients displaying COVID-19 symptoms (Moriarty et al., 2020). These two patients had previously been on Trip 1, and one of the two people tested positive for the Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2). The national public health agency notified the cruise company. Based on information from the confirmed cases, all group activities on Trip 2 were suspended. Following the first confirmed COVID-19 case linked to Trip 1, an additional 20 COVID-19 cases of passengers who left the cruise ship after Trip 1 were confirmed, including one death.

A rapid response team was transferred by helicopter to the ship on 5th March 2020 to collect samples from 45 people with COVID-19 symptoms. Out of the 45 samples, two passengers and 19 crew members tested positive for SARS-CoV-2.

Symptomatic passengers and crew were asked to stay in their cabins. Furthermore, public dining was replaced by room service until disembarkation. The ship arrived at the departure port on 8th March, and the cruise company started to disembark passengers and crew. Most passengers were from the USA, and these people entered a land-based site created for a 14-day quarantine. However, there were also non-US citizens on board. Governments around the world started to arrange repatriation flights in order to fly their citizens home. These flights were coordinated between the various governments and the USA.

4.4.3.2 Preparation and Planning

On 8th March 2020, the DfT contacted several UK commercial airports to scope if these airports could potentially receive a repatriation flight. The request included information that the flight would resemble a flight arriving from a heavily infected territory. For flights from countries like China, specific processes that included scanning passengers and contact tracing were already established. The airport expected all passengers to be tested for COVID-19, confirming that only people who tested negative were on the flights. In addition, the perception was that due to regular post-test swabs, the risk of COVID-19 issues might even be lower than flights from a less infected country. According to Participant 5314, the airport received the information that *“all the UK citizens have been swapped and checked and tested. So, you are very safe from a COVID perspective.”* Based on this information, the airport signalled its availability to take the flight and the planning and the required resources were based on the given details.

The airport was selected within hours after confirming its availability to receive the repatriation flight. It could not be determined if other airports also signalled their availability or why the airport was selected.

The airport expected *“just a normal flight”* (Participant 5314), similar to one from an infected region. The airport organised a phone call with the DfT and the cruise company and established an execution plan for the arrival of the passengers. The plan was to collect the passengers by bus after landing and take the passengers to a public car park. The airport owns the open-air car park, but a third-party company runs this. Around 80 taxis would wait at the car park to take the passengers and baggage home. *It is a high-profile flight, yes, so we made sure our comms people were switched on”* (Participant 5314). Due to the expected media interest around the event, the airport suggested an alternative place for the taxis, allowing better media control and protection of the passengers.

The airport contacted its primary handling agent company to conduct the ground operation of the repatriation flight, but the handling agency was unable to do so. Information about why the request was turned down could not be obtained. Instead, together with the cruise company, the airport selected a cargo handling agency, which was included in the further planning.

An official slot for the repatriation flight with the ATM services was booked on 9th March, which provided the airport with additional information. The aircraft was supposed to land at 2:45 pm on 11th March 2020 after a flight of around 14.5 hours. The flight plan also contained details about the aircraft and its registration. *“I looked at the registration of the aircraft, and I decided to do a bit of background work and check what the aircraft was. And it was at that point that we started to* *think, right, we might need to think about it differently"* (Participant 5314). The reason for reconsidering the situation is provided in the next paragraph.

When the planning team at the airport checked the registration, it was discovered that the aircraft for the repatriation flight was a freighter. A freighter aircraft is built to move goods and is not configured to provide a high level of comfort. The aircraft did not have windows, and the airport received the information that temporary seating had been installed and two portable toilets had been strapped into the aircraft. A long-haul flight with no windows and only two toilets for over 140 passengers may create a stressful environment. Furthermore, the *"typical demographic of people on a cruise ship tend to be the older people"* (Participant 5314). Therefore, it was expected that most passengers would be from the older demographic. The median age of the passengers on board this cruise was 68 years (Moriarty et al., 2020). Several online aviation databases contain publicly available information about airlines, airports, and aircraft. One of them is Flightradar 24, the largest aviation database with information about more than 1,000 airlines, 7,000 flights and 500,000 aircraft. This website was also used to determine the type of aircraft that would fly the people back to the UK.

The responsible airport's duty incident manager (DIM) on that day (9th March) contacted the LRF to inform the group of the repatriation flights and all the related activities. The LRF is a multi-agency partnership in the UK, consisting of representatives from emergency services, local authorities, the NHS, and others. The objectives of the LRF are planning and preparation for localised incidents and emergencies. This collaborative arrangement should help identify potential risks and develop plans and strategies to prevent or mitigate incidents and their impact on local communities (Civil Contingencies Secretariat, 2013).

On the evening of the 9th of March, the same DIM was approached by a member of staff from the Ministry of Housing, Communities and Local Government Resilience and Emergencies Division, giving an update on the latest development. The airport was informed that the cruise company would take the lead for the onward travel of the passenger. Following this conversation, the council's emergency planning team became engaged in the planning. The involvement of the council's emergency planning team proved to be a valuable resource for the planning and handling of the flight.

Being informed that the council's emergency planning was involved, the DIM and the airport manager decided to escalate the situation to a "*Major incident*". (*"I decided, quite a big decision really, now thinking about it, but it was the right one. I decided to escalate it to a major incident within the local resilience network*" (Participant 5314)). This decision triggered the Incident Management Centre (IMC) to be stood up, and it was agreed that several meetings would be held the next day. This IMC structure is designed to support the handling of an incident and provide tactical management and planning. The airport developed and implemented a general command structure that defines the governance during disruptive events and uses a *"three-tier process with clear, reasonably high-level objectives of aims for each [tier]"* (Participant 5314). Each tier describes a different rank order, with the operational level representing the bronze level, tactical the silver, and strategic the gold, the highest of all three levels. The command structure is based on roles rather than grades within an organisation. Each role is defined based on a person's expertise, location, skill, and competency. The gold-silver-bronze structure's purpose is to define a transparent chain of command in an incident (*"Everyone understands a three-tier piece and know where they link together, no one basically tries to shortcut it and go from gold down to bronze"* (Participant 5314)). The airport maintains a roster of responsible leads for each level in any given week to ensure that the IMC structure can be stood up quickly. The roster includes contingencies, and *"someone is always on call"* (Participant 5314).

Furthermore, the gold-silver-bronze structure is scalable, meaning that for less severe incidents, the bronze level may be sufficient to mitigate the situation. The IMC structure for the repatriation flight involved all three levels and was finalised on 11th March 2020 during the 9:00 am meeting.

On the evening of 10th March, the airport's DIM met with the council's emergency planning lead to assess the concerns related to the passenger's welfare. It was agreed that the British Red Cross would be asked to support the operation and supply welfare packs due to the long travel onboard a freighter aircraft and the older demographic. In addition, the council would be responsible for providing provision packs for the onward journey.

Furthermore, the information about the event was shared with the local Clinical Commissioning Group (CCG) and Public Health England (PHE). Due to this information sharing, the ambulance service and Port Health team at London Heathrow became aware of the repatriation flights and joined the planning team.

4.4.3.3 Day of repatriation flight

Despite thorough planning before the operation, heavy amendments to the plans and adaptation were required. The following section outlines how the operations team had to improvise and adjust its plans.

Leading up to the repatriation flight, the planning team at the airport had various meetings and conference calls with the DfT and Foreign and Commonwealth Office (FCO). At no point during the discussions with the DfT and FCO did the planning team at the airport receive any other information that the flight would be any different to a flight from a heavily infected area. Based on Participant 5314, the information from the FCO was *“rest assured; this is just a normal flight [from a highly infected area]”.* Therefore, the planning team expected that it would be a standard flight for which passengers underwent pre-screening and would be regularly tested during the journey.

One of the priorities was reducing passengers' stress during the arrival process. As the airport was expecting a normal flight, the planning team wanted to greet the passengers without wearing Personal Protective Equipment (PPE) to *“make them feel warmly welcomed back into the UK and to smooth the next steps for them”* (Anonymous Airport, 2020, p.5).

Contractors at the airport were hired to support passengers with reduced mobility and welfare packs supplied by the local council. The British Red Cross was ready to provide the passengers with the necessities during the arrival and coming days. Furthermore, the airport opted to have ambulances and a tactical advisor on standby if any passengers developed symptoms or tested positive during the flight. This process was in accordance with the PHE protocols for incoming flights.

The airport had been working with the cruise company to optimise the location of the aircraft and taxis to minimise the chance of press capturing the deboarding process. Therefore, the aircraft would be parked so the exit would face the airfield. The taxis were then parked airside between two hangars. The airport also established a specific vantage point for the press to control its position. The location was on top of a car park with a view of the airfield. However, buildings shielded the location of the parking position.

On the day of the expected arrival of the repatriation flight, the FCO sent two officials to the airport. During a discussion to establish their role, Participant 5314 discovered that the officials were sent to *"make sure that the flight goes on and the wrong people do not get off the flight".* At this point, the planning team became aware that the aircraft also carried passengers from Ukraine and Romania besides UK citizens. This fact had severe implications for the Border Force Team, and they had to put additional measures in place to ensure that only passengers who were entitled to enter the UK would disembark the aircraft. *"We started to see as Wednesday (the day of operation) carried on, this thing started to grow arms and legs*" (Participant 5314).

The initial flight plan had an arrival time of 2:45 pm and a five-hour turn-around time. The turn-around time describes the time between the arrival and departure of the aircraft. According to the event report, the FCO and Border Force were concerned about having the aircraft stationary at the airport for five hours and wanted to have the aircraft leave British soil as quickly as possible. Hence, the turn-around time was amended to 90 minutes. The aircraft was delayed on the day of operation and was expected to arrive at 4:55 pm. Apart from the last-minute change in arrival time, the planning saw effective coordination between the various stakeholders throughout the day, according to participant 5314. The result was that all of the planned resources were in place when the aircraft arrived shortly before 5:00 pm.

However, when the aircraft arrived, and the aircraft door opened, it became apparent that the airport was dealing with a Medical Evacuation (MedEvac) flight and not a repatriation flight. *“When they opened the door of the aircraft, and people on board looked like Spaceman frankly, you know in full white suits, and with masks, I think that woke a few people up.”* (Participant 5009). *“It looked like a scene from ET”* (Participant 5314).

This development meant heavy amendments to the original plan to deal with the situation. The situation demanded an urgent response, and the operations team had little time to develop a new plan. The immediacy of the situation required a swift adjustment of plans. Some of the following actions occurred at the same time. For clarity purposes, this section unpicks the multiple actions that went on in the five-and-a-half hours after the aircraft had landed.

The initial idea was to send the Chief Port Health Medical Officer (CPHMO), wearing a face mask, to board the aircraft and assess the situation. *“As soon as you see someone open that door in full PPE if you go onto that plane, you have to at least match that PPE”* (Participant 5314). The airport benefitted from the CPHMO bringing his PPE. Otherwise, there may have been a shortage of PPE. Together with representatives from the ambulance service and CCG, the CPHMO from Heathrow had to adjust the plans and communicate those changes to all airport operations staff. All the information was combined in IMC, and the people in the IMC could watch the group's action via live CCTV footage. The live footage allowed the team in the IMC to think about the next steps and provide tactical support to the people on the ground. Having been able to don additional PPE, the medical officer went on board to understand what the airport was dealing with. *“What he finds really shocked him because it was the very opposite of what we have been told”.* (Participant 5314). All the passengers on board the aircraft were wearing face masks (see photo 1 in Figure 4-18), and three aeromedical crew members were on the aircraft, wearing full PPE (photos 2 & 3 in Figure 4-18). There was a metal container towards the rear of the aircraft, and inside were six COVID-19-positive patients (photo 2 in Figure 4-18).

Figure 4-18 Scenes from inside the freighter (taken from Narain (2020))

One of the passengers showed COVID symptoms, and per the protocols, the ambulance service took the person to a local hospital. Later that evening, the passenger was taken back to the airport and completed travelling to Glasgow.

The airport was expecting a routine repatriation flight and adjusting the plans to deboard the passengers safely consumed more time than initially planned. Furthermore, reuniting the passengers with their luggage and transferring them onto taxis was another time-consuming task due to the limited number of personnel from the cruise company. During the deboarding of the British citizens, Border Force ensured that the passengers who went on to Romania and Ukraine stayed on the aircraft. The initial 90-minute turnaround time of the aircraft was extended by another hour. The aircraft eventually took off at 7:30 pm.

After the people departed the aircraft, one of the challenges was that many taxi drivers rejected the job and left. According to the airport, this was down to two factors. The primary factor was that the taxi drivers had not been briefed about the situation and now became aware of the event's magnitude and no longer felt comfortable transporting passengers from this flight. The passengers were wearing facemasks and were accompanied by nurses in PPE. The fact that the aircraft's arrival took longer than expected and increased the taxi waiting time further contributed to taxi drivers withdrawing their service. The withdrawal required a timely adjustment of the plans. The cruise company suggested booking hotel rooms for the remaining passengers and sorting out an alternative onward journey for the next day. Some hotels would not take the booking, but after a couple of attempts, the cruise company found a hotel for its customers. However, the hotel also heard the news about the state of the passengers. The hotel was concerned about the welfare of the other hotel guests and rejected the reservation. Participant 5314 recalls the chaotic situation: *“the doors are closed, the [hotel] manager comes to the door and says: Look, we know what’s going on here, no one’s coming in, we are cancelling your booking. It literally was like a Bethlehem moment; there was no room at any inn because they knew what’s happening here”.*

Fortunately, one of the hotels accepted the remaining passenger into their reception areas as it was raining outside. The reception area provided the passengers with a dry and warm place, and warm beverages were handed out. In the meantime, the airport’s communication teams worked with the local council on a solution for the onward journey.

Eventually, the CEO of the council got involved in the late evening and supported handling the incident. The event report described the council’s CEO as “*an experienced Gold Commander, who provided timely support and higher level command to the situation”* (Anonymous Airport, 2020, p.7). According to the airport, this helped organise the onward journey for the remaining passengers. The CEO’s support would have been crucial if no solution for the onward journey had been found and local assets and resources from other regions had been needed.

The withdrawal of many taxi drivers created logistical issues and welfare concerns. Due to the long waiting time, passengers needed the toilet, but no airport facilities were nearby. A local business jet hanger offered assistance and allowed passengers to use their facilities. A large number of people and the limited mobility of some passengers made this a rather lengthy process. During this time, the airport team used their relationship with its wider network to organise taxis for the remaining passengers.

Transportation for each remaining passenger was eventually organised, and the airport team completed the task late at night. As the disembarkation went on, a director of the PHE raised concern about the passengers' COVID conditions after arriving home. However, the initial plan to use the local NHS to follow up with the individual passengers was deemed sufficient. The Chief Nurse would coordinate the process using the Passenger Locator form's information.

4.4.4 Internal review of the event

The event report (Anonymous Airport, 2020) is based on wash-up meetings and debriefs. The report highlights factors that contributed to the successful outcome of the event. It also summarizes some of the critical lesson learnings of the event. The exact number of after-action meetings could not be determined.

4.4.4.1 Good practices during the event as listed in the report

According to the report, the IMC's local command and control structure worked well. The IMC structure allowed the operations team to swiftly respond to several challenges the team had to manage during the day. The command and control structure ensured that response plans were always aligned and improved the involved parties' situational awareness.

The successful outcome was also supported by all personnel working hard to cope with the dynamic situation. The report highlighted the work done by the cruise company’s team and the facilities management at the airport that *“went above and beyond their normal duties and shift times”* (Anonymous Airport, 2020, p.8). People and resources (e.g. taxis) that generally enter the controlled area of the airport had to be airside to allow an unabated transfer from the aircraft and their onward journey.

The security and planning team interface worked well, and the vehicles and people were escorted in a timely and efficient manner, allowing a seamless operation. The CPHMO from London Heathrow volunteered to be at the airport and support the local team. Having him on site and using his assistance benefitted the successful repatriation flight execution as he brought the necessary PPE and had previous experience from his role at London Heathrow airport.

Various working groups and forums facilitate existing relationships with stakeholders in the region. The LRF provided crucial additional resources for the repatriation operation, and prior relationships meant that stakeholders were familiar with the airport operation.

According to the review meetings, the decisions of the IMC around the "*orientation of aircraft, parking, location of taxis, and taxi gap filling were crucial and led to the overall success in terms of media profile of the event*" (Anonymous Airport, 2020, p.8).

4.4.4.2 Opportunities for improvement

The overall feedback was that if more accurate information about the nature of the flight had been known earlier, the plans could have been tailored more appropriately to the event. Due to the lack of information about the flight, PPE level and quantity on the ground were only just adequate. However, any further escalation of the incident would have created a shortfall of PPE, causing a potential loss of control over the situation

The team at the IMC requested to contact the flight deck crew of the aircraft one hour before the landing for additional details in preparation for the ground handling operation. Nevertheless, this request was never executed, and during the review, it became apparent that the ground handling agency could not speak directly to the flight deck crew. If known before, other communication channels could have been used to provide the personnel on the ground with more detailed information about the aircraft before its arrival. For example, it was unclear whether the luggage would arrive on pallets or as bulk cargo. Bulk cargo requires more workforce to unload it from a plane as it arrives in a net instead of on a pallet. Initially, the luggage would arrive as bulk cargo, but the information was revised, and the people on the ground prepared to unload palletised cargo. Eventually, it was bulk cargo which slowed down unloading the passengers' luggage.

Furthermore, transferring the suitcases from the aircraft onto the taxis could have been more efficient. The ground handlers used cargo pallet dollies to offload the bags from the aircraft and then put the bags onto coaches for the short transfer to the taxis. In their internal review, the airport appreciated that, ideally, the bags should have been put on baggage dollies. These dollies are ideal for bulk cargo, and the dollies should have also been used to take the suitcases directly to the taxis. However, the airport prepared the resources for palletised cargo. According to the airport, cargo pallet dollies were unsuitable for towing bulk cargo to taxis.

The report mentioned that the final briefing in the IMC may have been scheduled a bit too late. The late finish caused the teams to hurry to prepare for the aircraft's arrival. In hindsight, the meeting should have been scheduled earlier to allow the team sufficient time to get into position and account for any unexpected delays during the preparation.

Even though the discussion between the airport and cruise company took place, earlier and deeper engagement between the two companies would have streamlined a few processes. Only a few representatives from the cruise company were present to greet the passengers and support the operation. Although the report highlighted the great work of the team of the cruise company, it suggested that more resources from the cruise company may have helped with the execution of the repatriation flights. The report highlighted the examples that reuniting the passengers with the suitcases and transferring them onto a taxi could have been sped up with better and thorough communication and additional resources. Mobilising the cruise company's local care team or drawing on its global support network may have been an option. However, the report also suggested why this may not have been possible. In light of the cruise company dealing with a global crisis that affected their entire fleet, it is unknown whether the cruise company could support the incident with additional resources.

The entire repatriation operation on the ground took longer than anticipated and carried on into the darkness. The people in the IMC were using CCTV to monitor the situation on the ground and used live images to make decisions. Especially for PHE officials in the IMC, the *“visual prior to this was important information”* (Anonymous Airport, 2020, p.9). After sunset, the IMC team could not get any live images due to the lack of light. Had the operation been anticipated to continue into the night, temporary lightning could have been installed earlier. The longer duration of the operation meant that the IMC had to think about the welfare of the people on the ground. This welfare was not organised beforehand.

One of the challenges throughout the event was that no one understood who had primacy for the event (*“there was a conflict between (the cruise company) managing their guests, but the Chief nurse for the (region) saying, no they are my patients”* (Participants 5314)). A better alignment between the airport, the region’s chief nurse and the cruise company would have streamlined some processes and removed ambiguity over the primacy.

Furthermore, an earlier engagement of the airport with its security partner and more efficient use of the security personnel would have freed up additional airport operations staff to organise and coordinate the scene. However, the security was used to escort people not used to working on an active airfield.

Another area of improvement was concerning communication. During the day, the airfield radio channels were highly utilised. It has to be noted that the airport continued with its regular operation, and the communication about the arrival of the repatriation flight interfered with the handling of the ground handling operation of the other aircraft. The report suggested that *“consideration should be given to using an alternative radio channel, or using scan functionality on the handsets”* (Anonymous Airport, 2020, p.9) to separate the repatriation flight operation from normal flight operations. This high utilization was amplified because everyone working on the airfield must follow agreed communication channels. However, on that day, many involved people were not used to working on the airfield. All personnel had been briefed about the communication channels beforehand by the airport bronze commander, but sometimes these rules were not followed. This lack of experience posed risks to the entire operation at a vital time when clear communication was needed, and the channels were busy.

4.4.5 Discussion

"A resilient system must be proactive; flexible; adaptive; and prepared. It must be aware of the impact of actions, as well as of the failure to take actions" (Hollnagel and Woods, 2006, p.356). Several principles from the literature review could be observed in this case study. This discussion section analyses how the airport dealt with a unique and unprecedented situation and how proactive and adaptive actions led to a successful outcome of the event.

Using Westrum's (2006) classification, the discussed case can be best described as an irregular threat. The repatriation flight required special attention and the use of the IMC to deal with the situation. Such an incident would fall into the disruptive context, indicated in Hällgren's, Rouleau's and de Rond's (2018) matrix of contexts activities according to the event occurrences. Unlike an engine fire or plane crash, handling a potentially contaminated aircraft and avoiding the spread of the virus is unrelated to the regular operation of an airport. The airport had to develop unique plans and procedures for the arrival of this particular repatriation flight. Government guidelines for processing flights from highly affected areas reached their limits and were not applicable due to the nature of the flight and the demographics onboard. Participant 5314 mentioned that the airport was expecting the arrival of a regular flight from a highly infected region. However, it quickly escalated to handing a MedEvac flight with multiple suspected COVID-19 people onboard the aircraft. The situation could potentially cause severe disruptions at the airport if multiple airport members had been contaminated or if certain parts of the airport were closed until being classified as COVID-19 safe again. The short notice, uncertain nature of the flight and unavailability of procedures for handling this flight indicated that this case falls into the category of irregular threats (Westrum, 2006).

4.4.5.1 System Setup

The airport also benefitted from specific processes and mechanisms defined in the *System Setup* theme that implied the actions taken in the *System Preparedness* and *System Response* themes.

Table 4-24 matches high-level principles with practical examples. It further shows how the operationalised principles affected other themes. The connections with other themes highlight whether the principles were directly influenced by outputs from other themes or their results directly impacted other themes.

Table 4-24 System Setup principles observed in case study 4

High-level principle	Example	Result	Connection with other theme(s)
Sufficient resources are available to monitor operation	Position of Head of Fire and Emergency Planning	Capacity to monitor development of situation and do risk assessment	Input into System Checks
Flexible mode of operation	Availability of IMC	Predefined hierarchy, processes, and communication lines for disruption	Input into System Response
System is aware of interfaces with other systems	Established links with LRF	Predefined processes and communication lines	Input into System Response

<u>Principle: Sufficient resources are available to monitor operation</u>

The airport invested resources in employing an emergency planning manager. An emergency planning manager reviews existing emergency plans and prepares plans and procedures for emerging threats. The manager provided the necessary resources to monitor the situation very closely, and according to Hollnagel (2009a), this is one enabler for generating the potential for a resilient operation. Monitoring the situation and frequently reviewing the risk assessment based on the latest update directly affected the actions taken in the *System Checks* theme.

Principle: Flexible mode of operation

Another contributing factor to successfully handling the repatriation flight was the availability of the IMC. The clear hierarchy and defined responsibilities gave the airport a governance structure adapted for this event (Naderpajouh et al., 2018). A command structure that is flexible enough to be deployed at any event is a strong indication of a connection between the *System Setup* and *System Response*.

Principle: System is aware of interfaces with other systems

The existing relationship with the LRF also proved helpful in handling the repatriation flight. The LRF was designed as a partnership to support local communities in incidents and provide extra capacity to mitigate the impact. The airport system was aware of interfaces with other systems. Furthermore, existing relationships, pre-established contacts with local partners and a wider network contributed to the system's resilience as everyone has a shared cognitive structure and was familiar with the processes (Naderpajouh et al., 2018). Naderpajouh et al. (2018) also mentioned trust as an information mechanism leading to systems' resilience, which also works as an enabler for information sharing in the LRF. According to Participant 5314, the established links with the LRF were crucial for dealing with unexpected demands during the operation. Those pre-established links provide another example of a connection between the *System Setup* and the *System Response* theme.

4.4.5.2 System Checks

During the preparation of the arrival of the repatriation flight, a crucial step was to recognize the changing risks to the operation and proactively escalate the situation to a "*Major Incident*". Table 4-25 matches the observed high-level principle with a working example and highlights the consequence of the operationalised principle. It also shows the effect of the consequence on other themes.

Table 4-25 System Checks principle observed in case study 4

High-level principle	Example	Result	Connection with other theme(s)
Recognizing changing risks to operation	Risk assessment of flights determined severe threat to operation	Escalation to “*Major Incident*”	Input into System Preparedness

Principle: Recognizing changing risks to operation

When the DfT first approached the airport, the initial information suggested that the flight would be a regular flight from a highly infected area, for which the current mitigation strategies existed. The airport’s initiative and investigation changed the planning team’s perception of the arriving flight. Upon receiving the aircraft registration, the Head of Fire and Emergency Planning used the details to determine the aircraft type. Using details from the flight plan helped obtain new, crucial information about the nature of the flight, which supported the airport team with the planning. Pasman, Knegtering and Rogers (2013, p.25) argue that “*early warning is of crucial importance to prevent major hazard accidents by creating situational awareness in those parts and levels of the organization that can make corrective decisions*”.

Once the emergency planning manager discovered that the people would arrive on a freighter aircraft, he combined this information with the other known facts and assumptions. He concluded that having people from an older demographic arriving at the airport that have spent more than ten hours on a plane with no windows and proper facilities and coming from a contaminated cruise ship would require special attention and preparation. Being able to perceive weak signals and *“translate the signal[s] into something that could be seen as a safety issue with a potential to grow much larger”* (Axelsson, 2006, p.152) is a sign of a resilient operation.

During the interview, Participant 5314 mentioned that he previously worked in the oil and gas industry. He highlighted that most of the documentation on crisis management from major oil and gas companies stated that the principle and policy of overreaction as one of the core items (“*Because if you underreact, and* *you actually needed the staff two hours ago, it can be catastrophic. And that's the principle*" (Participant 5314)). During the interview, he reflected that the decision to declare the flight as a "*Major Incident*" proactively is *"something that I learned when I worked in oil and gas"* (Participant 5413). The emergency planning manager prepared plans for the flight's arrival. He anticipated specific threats and initiated proactive actions to mitigate the expected challenges (Palazzi et al., 2014). The airport emergency planning manager decided to proactively declare the arrival of the repatriation flights as a "*Major Incident*". This decision triggered actions taken in the *System Preparedness* theme.

4.4.5.3 System Preparedness

As described in the literature review (see section 2.2.4.2), resilience can be achieved through action in the *System Preparedness* theme. Some occurrences prior to the arrival contributed to the successful outcome of the operation. The action taken before the day of operation meant that the airport could plan and prepare for the repatriation flight.

Table 4-26 maps high-level principles from the literature review against practical examples observed in the case study. Table 4-26 also shows the consequence of the operationalised principles, and the data analysis considered whether the result added any connection to other framework themes.

Table 4-26 System Preparedness principles observed in case study 4

High-level principle	Example	Result	Connection with other theme(s)
Ability to anticipate bottlenecks	Anticipating poor physical condition of passengers	Realizing that additional resources are required and contacting LRF and CPHMO	Input into System Response/Output from System Checks
Temporarily increasing buffer capacity	Contacting LRF and stepping up additional resources	Increase in buffer capacity	Input into System Response
Temporarily increasing buffer capacity	Stepping up IMC freed up additional internal resources	Increase in buffer capacity	Input into System Response
Temporarily increasing buffer capacity	Involvement of CPHMO	Expert joined the team and supported the operation	Input into System Response
Preparing operation for expected disturbance	Anticipating high media interest	Stepping up communications team and parking aircraft at different part of the airport to shield location from inquisitive glances	Input into System Response
Preparing operation for expected disturbance	Stepping up IMC	Have appropriate Control and Command structure in place	Input into System Response
Preparing operation for expected disturbance	Sharing of plans with stakeholders	All stakeholders were kept up to date	Input into System Response

Principle: Ability to anticipate bottlenecks

The planning team expected the arrival of 136 people and assumed the people to be anxious and exhausted. The airport recognised that even a tiny percentage of these people needing medical attention would overwhelm the airport's resources. The recognition that the airport's resources may be insufficient triggered one of the critical actions during this event, resulting in the creation of additional capacity (Woods, 2011). The airport expected a bottleneck due to the lack of resources. Therefore, the IMC was stepped up, and the LRF was contacted. As mentioned in the literature review, anticipating bottlenecks is one of the principles of the *System Preparedness* theme.

Principle: Temporarily increasing buffer capacity

Proactively declaring the COVID-19 repatriation flight as a "*Major incident*" and stepping up the IMC structure freed up internal resources. Those extra resources provided additional buffer capacity to the system to meet any unexpected and potential additional demand. Resources further extended the buffer capacity brought in through the LRF. The proactive involvement of the CPHMO can also be considered a temporal increase in buffer capacity. The CPHMO provided expertise and played a crucial part in dealing with unexpected challenges during the event.

Taking on these additional resources can be seen as "*sacrifice judgments*" (Woods, 2006b). Sacrifice judgements are trade-off decisions that may lead to *"a local slowdown in production operations to avoid risks as complications build up."* (Woods, 2006b, p.32). The decision to step up the IMC, have the local Chief Nurse and CPHMO onsite, and ambulances on standby was a sacrifice judgement. One of the challenges with sacrifice judgements is that hindsight could reveal that the sacrifice was not necessary (Woods, 2006b). For example, if it had been a routine flight, as indicated by the DfT, using the additional external resources would have been an unnecessary sacrifice as they could have been of better use elsewhere. However, as the event's outcome showed, it was appropriate to step-up the additional resources as the situation could have overwhelmed the airport's resources if the precaution measures had not been implemented. Using the lead time to step up additional resources and prepare for the event shows that action *System Preparedness* directly impacted the operation in the *System Response* theme.

Principle: Preparing operation for expected disturbance

During the planning phase, the airport team immediately realised that "*this was probably going to be the highest-profile flight on that day*" (Participant 5314). Therefore, the emergency planning manager informed the communications team at the airport about the flight to ensure that information before and during the event could be shared swiftly and efficiently. One day before the flight, the airport received the plans from the cruise company for how they were planning to execute the transfer of the passengers. Aware of the potential high media interest, the airport "*proposed an alternative location for the taxis, which would have enabled easier control of the press*" (Anonymous Airport, 2020, p.4). These actions show anticipation and preparation (Hollnagel, 2009a).

As soon as the operation was declared a "*Major Incident*", the airport's command structure for handling major incidents was stepped up. A day before the flight's arrival, the IMC was activated. Stepping up the IMC triggered the external and internal processes for handling an incident at the airport. The IMC provided the governance structure during the operation and helped coordinate the various stakeholders during the evolving situation.

Another contribution to the successful operation was constantly revising the plans during the *System Preparedness* theme. The planning team reviewed their plans during the days leading up to the event, and as soon as new information became available, the plans were updated. Furthermore, alternative solutions were suggested to other stakeholders, such as the positioning of the aircraft. The "*ability to modify understanding of a situation either because the situation has changed or evolved over time, or because the initial assessment of the situation was flawed*" (Sutcliff and Christianson, 2013, p.3) contributed to a successful outcome. The airport team constantly checked for new or updated information to ensure the plans were sufficient and adjusted or optimized them accordingly. This behaviour can be described as being of unease, and according to Hollnagel and Woods (2006, p.356), "*resilience requires a constant sense of unease that prevents complacency*". As the plans evolved, the airport used its IMC structure to share the latest plans with all stakeholders. This connection improved the situational awareness and common workflow expectations of all involved parties (Bechky and Okhuysen, 2011). The creation of foresight, using multiple sources, and the trust and communication between the stakeholders influenced the successful operation (de Vries, 2017).

4.4.5.4 System Response

The unexpected nature of the flight created additional challenges during the day. Multiple occurrences from the *System Response* theme contributed to the system's resilience during the operation.

Table 4-27 lists the analysis findings that identified high-level principles from the literature review and linked them with practical examples. The table also shows the consequences of the actions.

Table 4-27 System Response principles observed in case study 4

High-level principle	Example	Result	Connection with other theme(s)
Governance structure for coordination and communication	Flexible Command and Control Structure	Supported the coordination of the operation	Output from System Setup
Use of additional resources	Availability of internal resources	Providing internal additional capacity for handling increased demand	Output from System Preparedness
Use of additional resources	Availability of resources from LRF	Providing additional capacity for handling increased demand	Output from System Preparedness
Agile adjustments	Ability of CPHMO to respond to upgrade his PPE	Adjustments of PPE allow a screening of passengers onboard the aircraft	–
Agile adjustments	Ability of IMC to adjust its plan to mitigate various challenges	Adapted plans help mitigate challenges during the handling the luggage and finding a suitable solution for accommodating passengers	–
Agile adjustments	Council’s CEO supporting onward journey	His support allowed the onwards journey of the passengers	–

Principle: Governance structure for coordination and communication

During the arrival of the COVID-19 repatriation flight, the predefined command structure of the IMC proved crucial in handling the incident as "*fostering resilience needs a governance structure that supports collective actions and integrates fragmented fields with different institutional frameworks.*" (Naderpajouh et al., 2018, p.306). According to the interviews with Participants 5009 and 5314, the IMC governance structure supported the coordination during the operation. The coordination ensured efficient use of the available resources and agile adjustments

Principle: Use of additional resources

As mentioned in the *System Preparedness* theme (see section 4.4.5.3), stepping up the IMC structure also provided the airport team with additional resources to handle the unprecedented situation. According to Participant 5314, "*all the people that were out there, my Incident Management Centre was busy. We had a lot of people in there, and we needed them all. They all had a role".* This process and the additional resources induced additional buffer capacity and enhanced the resilience of the operation.

The arrival of the repatriation flight required more resources than initially anticipated, moving the operation closer to the boundary of unacceptable workload and operational boundary, as seen in Figure 4-19. Supported by the sacrifice judgement, proactive actions created additional resources during the day, leading to a more significant buffer capacity. Taking on additional resources relaxed the situation as the boundary of unacceptable workload was extended, creating a larger space of possibilities (Rasmussen, 1997).

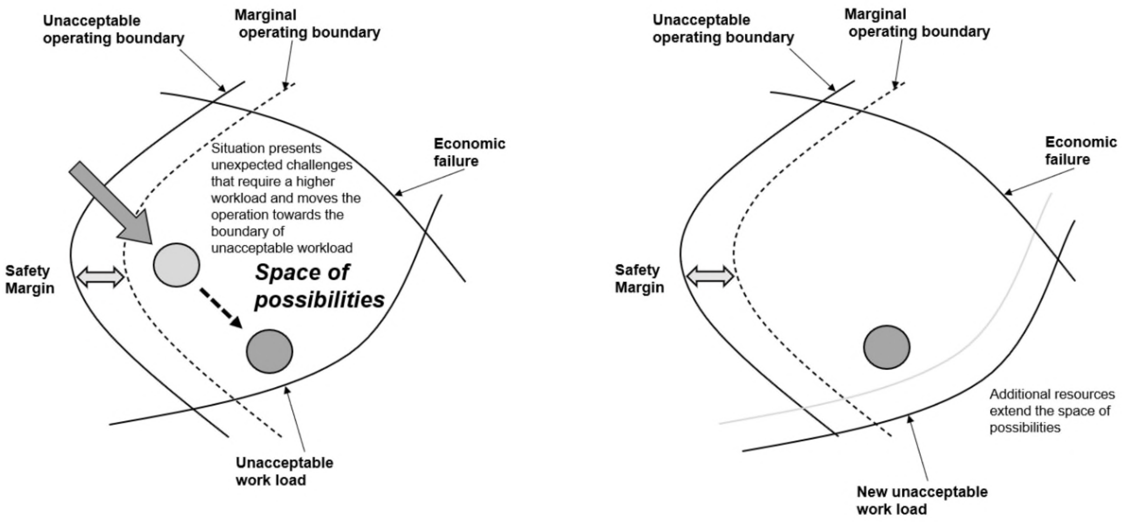


Figure 4-19 Mitigation strategy to handle an increase in workload

The airport used additional internal and external capacity that is not available during regular operation. The command and control structure provided the governance to facilitate the deployment and coordination of the resources during the operation. This structure provided the system with the flexibility to handle the unprecedented nature of the flight. The effect of the flexibility and redistribution of resources were visualised in the stress-strain model (see Figure 4-20). The non-uniform region was extended by using additional resources and flexible processes. The result moved up the failure point to a higher demand value. A higher demand value gave the system more space to stretch non-uniformly to avoid failure and a control loss. Cook (2006) described this observed adaptative behaviour with his second resilience pattern.

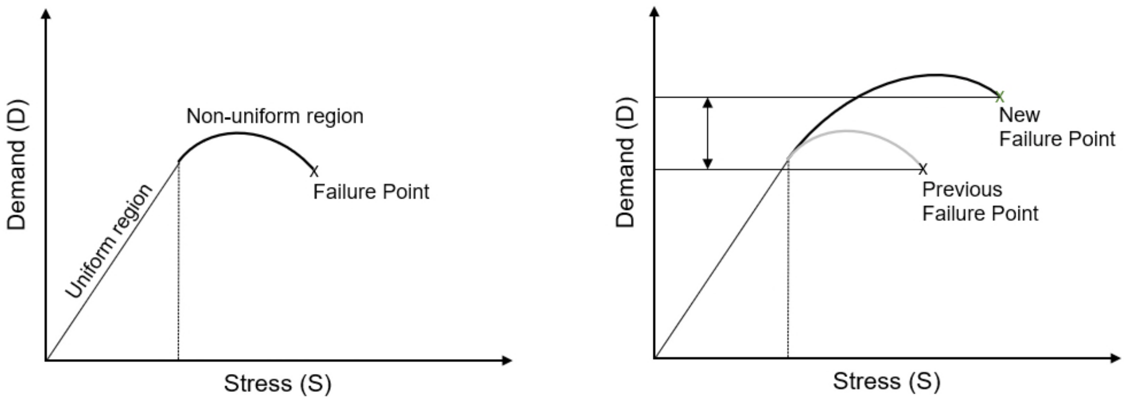


Figure 4-20 Extension of the non-uniform region

Principle: Agile adjustments

Although the CPHMO joined the operation due to some fortunate circumstances, his presence was vital for the successful outcome. From his role at London Heathrow airport, he had already been familiar with the flight processing from highly infected regions and health protocols for dealing with COVID-19 suspected passengers. On the day of the repatriation flight, the team intended to meet the passengers wearing no PPE to welcome them back to the UK warmly. After the aircraft door opened, the team was confronted with a different situation than anticipated and had to improvise (Lundberg and Johansson, 2015). The team at the airport was unprepared for a situation that required full PPE. However, the CPHMO compensated for the lack of PPE by using his own PPE. Therefore, it was possible to board the plane and assess the situation before allowing the passengers to leave the aircraft.

The team at the airport was able to make quick adjustments to develop solutions to handle various challenges. These challenges included handling the cargo, reuniting the luggage with the passengers, or finding a suitable shelter for the passengers, while they waited for the onward journey. Those adaptations can be seen in what Lundberg and Rankin (2014) described as improvisation to situations that are different to the original plan. Those improvised actions supported the successful handling of the repatriation flight.

Another positive impact was the support of the council’s CEO. With him, another expert joined the team and supported the operation at the gold level. He brought in additional resources and was able to help with the onward journey of the passengers.

4.4.5.5 Integration of the findings

The case study showed how several high-level principles from the literature review were applied before and during the operation concerning the COVID-19 repatriation flight. Practical examples of the high-level principles were found in the *System Setup*, *System Checks*, *System Preparedness*, and *System Response theme.*

The outputs from sections 4.4.5.1 – 4.4.5.4 were used to refine the PRF by adding additional connections.

- Connection between *System Setup* and System Response:
  As shown in section 4.4.5.1, the high-level principles of *Flexible mode of operation* and *System is aware of interfaces with other systems* improved the operation during the *System Response* theme.
- Connection between *System Checks* and *System Preparedness*:
  Section 4.4.5.2 demonstrated that the frequent checks of the situation allowed the system *Recognizing changing risks to operation*, which started actions in the *System Preparedness* theme. Therefore, this connection was added.
- Connection between *System Preparedness* and *System Response*:
  The case study showed how proactive actions in the *System Preparedness* theme positively affected the *System Response* (see section 4.4.5.4). The system moved into a state of alertness by *Temporarily increasing buffer capacity* and *Preparing operation for expected disturbance*, which provided more resources during the disruption and more effective coordination and communication. Hence, a connection between *System Preparedness* and *System Response* was shown.

Figure 4-21 visualises how the findings from case study 3 were used to refine the PRF. The figure explains the content of each theme and highlights the connections between the themes, using practical examples.

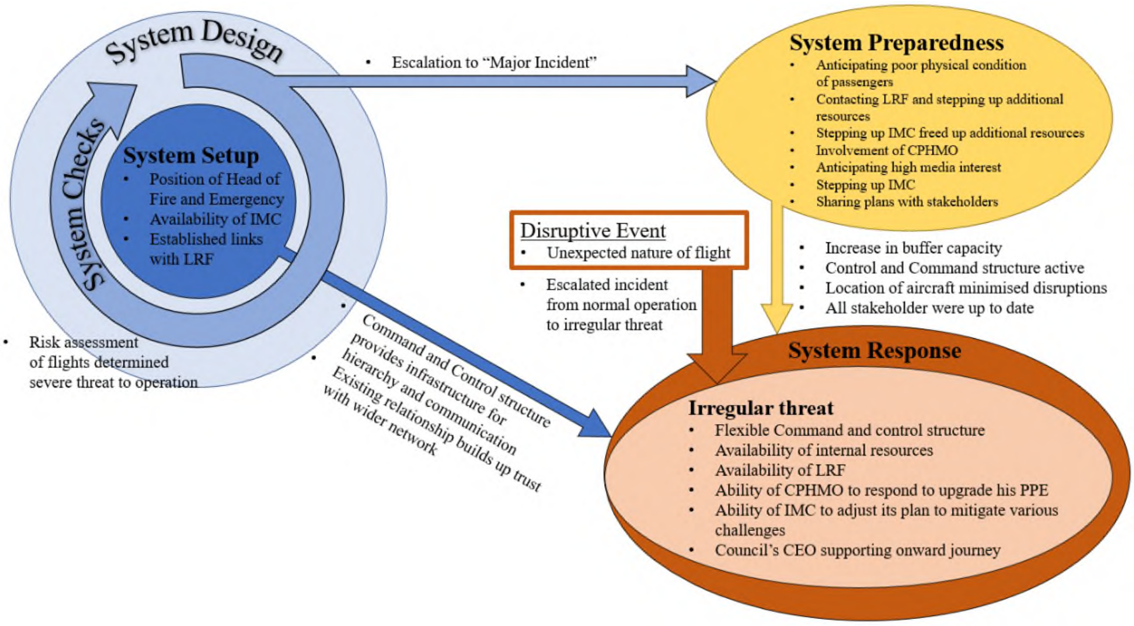


Figure 4-21 Integration of findings from case study 4

This case study highlighted the importance of the *System Preparedness* theme. It showed that actions in this theme supported the system's dealing with an irregular threat in the *System Response* theme.

4.4.6 Closing remarks

This case study investigated a unique event. It was the first COVID-19 repatriation flight for passengers from a cruise ship that arrived at a commercial airport in the UK. Using multiple sources and access to detailed information provided rich insight into the proceedings before and during the arrival of the repatriation flight at the airport. The level of detail allowed a thorough analysis of how a resilient operation was achieved.

The repatriation of passengers from a contaminated cruise ship arriving on a freighter aircraft represents an irregular threat to the operation. There were no existing plans for handling such a flight, and the airport planning team could not rely on past experiences. The case study captured actions taken before and during the operation that contributed to a successful outcome. It was shown that proactive behaviour and the principle of overreaction were crucial for handling the situation. This case study demonstrated that the resilience of a system could be generated through the *System Preparedness* theme. Furthermore, evidence of how the *System Setup* contributed to the resilience when responding to an unusual event was collected. Having the appropriate resources available and existing relationships with the broader network was beneficial. The proactive actions freed up resources that helped compensate for the additional workload required to handle the operation. The unexpected nature of the flight required flexibility and improvisation during the arrival of the passengers. The flexible governance structure proved crucial to managing and coordinating the adaptive behaviour during the *System Response* theme.

However, some limitations are associated with this case study. As this study investigated a unique event, there was no baseline scenario available to compare it against and assess the actual effectiveness of the actions. The interviews were conducted over six months after the event. Due to the significant delay, it can be argued that the interviewees were affected by hindsight bias. Hindsight bias describes the "*tendency for people with outcome knowledge to believe falsely that they would have predicted the reported outcome of an event*" (Hawkins and Hastie, 1990, p.311).

Furthermore, the data collection primarily looked at the event from an airport's perspective. Further research could engage with other stakeholders, such as partners from the LRF or the cruise company, to integrate their experiences into the analysis of the proceedings. This additional information could enhance the research by adding a more holistic view of the event.

The research could also not determine if similar repatriation flights into commercial airports occurred after this incident. It may be worthwhile to investigate if the findings and lessons have been shared with other stakeholders and deployed elsewhere.

4.5 Case study 5: UK aviation response to COVID-19

Certain events are so severe "*they require a shift in mental framework. It may appear impossible that something like the event could happen*" (Westrum, 2006, p.57). The COVID-19 pandemic has often been described as an unprecedented situation (e.g. Sun, Wandelt and Zhang, 2020) and is an example of Westrum's (2006) third situation, the unexampled events.

4.5.1 Introduction

The pandemic caused a closure of borders and brought significant changes to the air transportation industry. Kingsley-Jones (2020) stated that over two-thirds of all 22,000 passenger aircraft were grounded by mid-April 2020 due to the COVID-19 outbreak. A situation of this magnitude required a mental framework shift. This case study investigated the role of the IRG and ODLG in the UK aviation response to COVID-19 from January 2020 until June 2020. The study highlighted challenges that stakeholders experienced, summarized the role of the IRG and ODLG and the resulting benefits and collected ideas of additional potential for the role of the IRG. The case study used the pandemic to analyse if high-level principles from the literature review were used by the IRG and ODLG before and during the initial phase of the COVID-19 pandemic. The outputs from the case study were also used to refine the PRF and determine connections between the various themes and subthemes.

The planet-wide spread of COVID-19 had a tremendous impact on people's lives and caused over six million deaths worldwide by February 2022 (Rizzo and Nirappil, 2022). In the initial spread of the pandemic, countries closed their borders and went into lockdown. As a result, people could not travel to foreign countries due to lock-down measures. However, countries took action at different times, creating a jigsaw puzzle of different rules and measurements and according to Sun, Wandelt and Zhang (2020, page not identified), this was done in "*a highly uncoordinated, almost chaotic manner*". As airlines connect the world and allow people to fly from one country to another, this fast-evolving situation was challenging for the aviation industry, as the imposed regulations of the individual countries create a randomly changing regulatory landscape.

4.5.2 Data sources

Out of all the five case studies, the study capturing the role of the IRG in response to COVID-19 in the UK aviation industry was the most complex and challenging one. The fast-evolving situation meant that industry contacts became unavailable due to the increasing workload or being furloughed, which was a challenge for the data collection. Furthermore, the research was challenged by a multi-dimensional situation. Multiple, parallel discussions occurred at various levels, and the researcher had to make sense of a somewhat confusing situation. In order to address these challenges, various information sources and interview techniques have been used to accumulate data and develop a comprehensive picture of the situation, as shown in Table 4-28.

Table 4-28 Data sources used for case study 5

Primary data source(s)	Secondary data source(s)
Interviews between 23rd July 2020 and 12th August 2021 • Participant 3313 • Participant 3314 • Participant 3413 • Participant 4012 • Participant 4110 • Participant 4112 • Participant 4715 • Participant 4913 • Participant 5009 • Participant 5010 • Participant 5314 • Participant 5412	Two industry reports • EUROCONTROL (2020a) • EUROCONTROL (2020b)
Observations and meeting minutes from 29 teleconferences and meetings between 04th February 2020 and 16th September 2020 • 22 teleconferences were attended by the researcher • Seven meeting notes from other teleconferences and meetings were forwarded to the researcher	Three websites • Institute for Government analysis (2021) • Aspinall (2022) • Dunn et al. (2022) OAG data base

The data contained unstructured and semi-structured interviews, observations, meeting minutes from various IRG and ODLG meetings from December 2019 until June 2020, industry reports, and news articles.

- **Interviews**

  The outputs from interviews with twelve IRG members conducted between 23rd July 2020 and 12th August 2021 were used for this study. The interviewees represented ten different organisations. The organisations included five airports, one airline, a slot coordinator, ATC, the UK regulator, and the chair of the IRG. The time for each interview ranged between 31 minutes and 63 minutes. The people were interviewed using a semi-structured interview technique with eight pre-planned questions. A list of the semi-structured question can be found in Appendix D. The outputs from the interviews were later categorised into challenges experienced by stakeholders, the role of IRG/ODLG and resulting benefits, and additional potential for IRG/ODLG work, and thoughts on how to improve the IRG/ODLG. The interviews were recorded on an encrypted recording device and transcribed for analysis.

- **Meeting minutes**

  Meeting minutes from 29 meetings have been analysed for this case study. The researcher has attended 22 meetings, and the data set was complemented by five additional meeting minutes from ODLG meetings. The researcher did not attend all ODLG meetings as he only became a permanent ODLG member in November 2020. Instead, personal summaries of an ODLG member from the COVID-19 meetings was forwarded to him.

- **Industry Reports**

  One valuable source of information was the European Network Operations Plan – 2020 Recovery Plan (NOP2020RP) published by EUROCONTROL. The European NOP2020RP "*is a special version of the NOP supporting aviation response to the COVID-19 Crisis. It provides for a consolidated European network view of the evolution of the air traffic and facilitates the planning of the service in the recovery phase by ANSPs and* *airports to match expected traffic demand in a safe, efficient and coordinated manner*" (EUROCONTROL, 2020a, p.iv). The European NOP2020RP was the output of the EUROCONTROL's European Aviation Crisis Coordination Cell (EACCC). This cell is explained in a later section of this case study (see section 4.5.4.3).The document provided a rolling outlook and was updated weekly. The outlook included a forecast for traffic numbers, Enroute capacity, airport capacity and expected evolution in member states. Access to the weekly updates provided insight into the fast-evolving situation in Europe, which helped put some of the findings into context.

- **News articles**

  This type of secondary data helped add additional information to the data set and was also used to cross-check some of the outputs from the interviews.

- **Database**

  The OAG database was used to build the narrative and look at how COVID-19 affected the flight movements in China and the UK.

4.5.3 Narrative

The following sections build the narrative and summarize key events that create the case study context. The list mainly focuses on events relevant to the aviation industry in the UK and includes some global milestones during the first theme of the COVID-19 crisis. The focus was on the initial outbreak of the coronavirus and the spread of the disease during the first wave in the UK. The chronology is supposed to help understand the challenges and issues of the UK aviation industry in the time from January 2020 until June 2020.

The following information for writing section 4.5.3.1 was collected and mainly used from the Institute for Government analysis (2021), Aspinall (2022) and Dunn et al. (2022).

4.5.3.1 Chronology of key events

The coronavirus was first detected in the Chinese Hubei province in Wuhan. The World Health Organization (WHO) was informed on 31st December 2019 that the Chinese health authorities identified a cluster of pneumonia cases with an unknown source and were detected in Wuhan. A sample from a patient contained a novel coronavirus named SARS-CoV-2. According to the WHO, the first SARS-CoV-2 confirmed cases outside China were detected in Thailand, South Korea and Japan on 20th January 2020.

On 22nd January 2020, PHE moved the risk level from the novel SARS-CoV-2 to the British public from *"very low*" to "*low*". PHE used to be England's health agency before being replaced by the UK Health Security Agency and Office for Health Improvement and Disparities on 1st October 2021. On 22nd January 2020, London Heathrow airport started screening all arrivals from the Wuhan region.

One day later, on 23rd January 2020, the Chinese government decided to stop all in- and outbound traffic from Wuhan, resulting in a closure of the Wuhan Tianhe Airport. All planes and trains departing from Wuhan and the city were locked down to contain the spread of the virus. However, the Chinese Railway Administration calculated that an estimated 100,000 people had left the region through the train station before the lockdown was imposed.

Evacuation flights repatriating UK nationals from the Wuhan region left Wuhan and arrived on 29th January 2020 at the Royal Airforce Base in Brize Norton. All passengers had to stay in a hospital for a 14-day quarantine. On 29th January 2020, the UK recorded the first two positive COVID-19 cases. The number of infections in China kept increasing, and more cases had been confirmed outside Asia. As a result, the WHO announced in a press statement on 30th January that COVID-19 had met *"the criteria of being a Public Health Emergency of International Concern"* (WHO, 2020). The following day the UK Chief Medical Officer recommended increasing the UK risk level from "*low*" to "*moderate*". The UK government issued a statement on 4th February 2020 and directed all UK citizens to leave China.

The 11th of February 2020 marks the day the virus was officially named COVID-19. The name stands for coronavirus disease 2019. The first confirmed coronavirus death in Europe was recorded in France on 14th February 2020.

Italy was the first European country that saw a significant increase in COVID-19 cases, and on 23rd February, government officials locked down ten towns in the Lombardy region. Strict measures were imposed, and almost 50,000 people were locked down to contain the spread in Italy.

The first UK citizens died abroad due to a COVID-19 infection onboard the cruise ship Diamond Princess on 28th February 2020. UK authorities also confirmed that COVID-19 had been transmitted inside the country. On the same day, the WHO raised its coronavirus alert to the highest level.

On 3rd March 2020, the UK government announced its COVID-19 action plan consisting of four phases; containment, delay, research, and mitigate. In the containment phase, infected people should be identified, and all close contact identified early enough to avoid the spread of the illness. Should the containment phase not work, the country would move into the delay phase, using tighter restrictions to delay the spread of the disease. Assuming the delay phase would also not work against the virus, the government would intensify its focus on research to find out how the virus spreads and how to treat infected people. The government hoped to take the pressure off the healthcare system by delaying the peak. The fourth of the phase (Mitigate phase) would be issued if the government considers the virus widespread. Containing and delaying the virus had failed, and the NHS could be closed to all but critical care. This phase would aim to protect the most vulnerable people.

On 4th March 2020, Italy decided to shut down all schools and universities, and on 9th March 2020, the British Prime Minister (PM) confirmed that the UK remained in the contain phase.

The WHO officially declared the virus a pandemic on 11th March 2020, and the US government suspended flights from all European countries other than the UK for 30 days. The UK risk level was raised from “*moderate*” to “*high*” on 11th March 2020, and the UK switched into the delay phase.

Italy was the first European country to impose a localised lockdown and the first to enter the first national lockdown on 12th March 2020. Switzerland and Spain followed shortly afterwards, imposing the first national lockdown on 13th March 2020 and 14th March, respectively.

Although pubs and restaurants stayed open, the British PM urged the public to avoid pubs and restaurants and work from home on 16th March 2020 to avoid an overload of the NHS. The announcement marked the start of the PM’s daily press conferences.

France announced its plan on 17th March 2020 to impose a national lockdown immediately, only allowing people to go out for walking and breathe fresh air. The EU bans almost every travel into the EU for 30 days on the same day.

On 20th March 2020, the UK government closed all schools across England until further notice and instructed all gyms, restaurants, pubs, and other social venues to close. In his daily briefings, the UK PM announced on 23rd March 2020 the first national lockdown in the UK. People in the UK were urged only to leave their houses to buy groceries, exercise once a day or go to work, and the measures legally came into force on 26th March 2020.

The UK government confirmed on 30th March 2020 that £75 million would be spent on charter flights and airline tickets to fly home almost 30,000 UK citizens from abroad. These people were stranded when countries closed their borders to contain the spread of COVID-19. By 15th April 2020, Denmark became the first European country to relax its COVID-19 measures and allow children under eleven to return to nurseries and schools. The number of confirmed cases globally reached two million on the same day.

Having had almost no quarantine rules before, the UK government announced on 10th May 2020 that people arriving in the UK by plane must go into a mandatory 14-day quarantine. During the daily briefing, the PM also announced a conditional plan for gradually lifting the lockdown measures. Furthermore, people who could not work from home were allowed to return to work.

The first national UK lockdown ended on 1st June 2020 when the requirement to stay at home was replaced with the rule to be home overnight. Outside gatherings of groups of up to six people were also allowed.

From 8th June 2020 onwards, everyone arriving in the UK had to self-isolate for 14 days. The UK government made wearing a mask on public transport compulsory from 15th June 2020, and all non-essential shops, places of worship and zoos were allowed to reopen in the UK. Almost three weeks later, pubs, restaurants and hotels were allowed to reopen on 4th July 2020.

On 26th June 2020, the UK government announced changes in the quarantine rule upon arrival to allow people to go on holiday over the summer. A week later, on 3rd July, the UK released a list of 50 reduced-risk countries to which people can go on holiday and do not have to quarantine after arrival. This list became active on 10th July 2020.

4.5.3.2 How did the outbreak of COVID-19 affect the traffic numbers?

The detection and outbreak of the new coronavirus first impacted the aviation sector in Asia. Figure 4-22 shows all of the scheduled flights at commercial airports in China from 16th December 2018 until 3rd August 2019 and from 16th December 2019 until 3rd August 2020. The flight schedule shows all the flights scheduled for a specific period. The data were extracted from the OAG database and contained 3,070,000 flights for the first period and 2,309,361 flights for the second period.

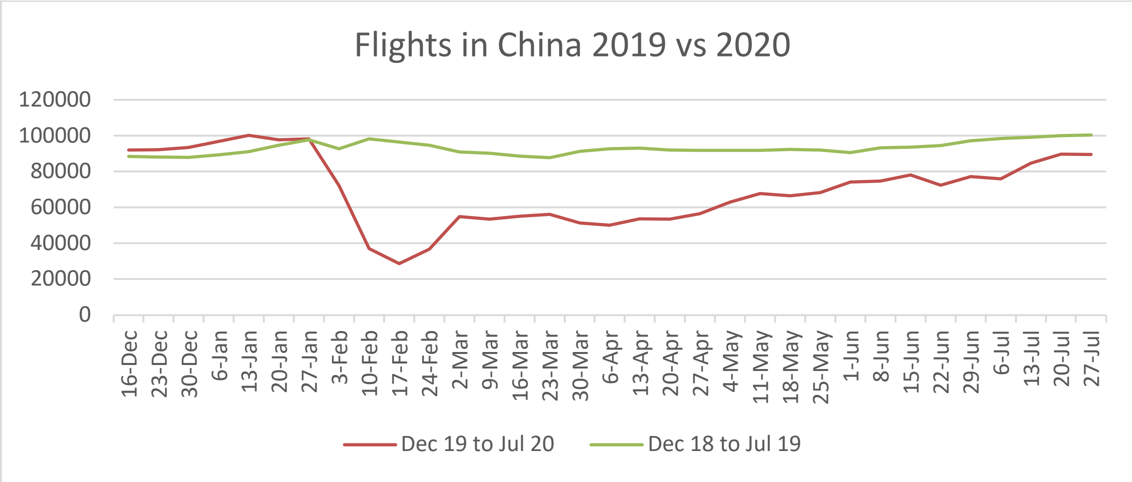


Figure 4-22 Year-over-year comparison of commercial flights schedule in China between December and July

Whereas traffic numbers in Asia plummeted in January 2020, the number of flights in the UK remained close to 2019, as shown in Figure 4-23. For Figure 4-23, the OAG database was analysed for the same periods, counting all the scheduled flights at commercial UK airports. In the first period, 686,242 flights and 311,564 flights were scheduled to arrive at UK commercial airports in the second period.

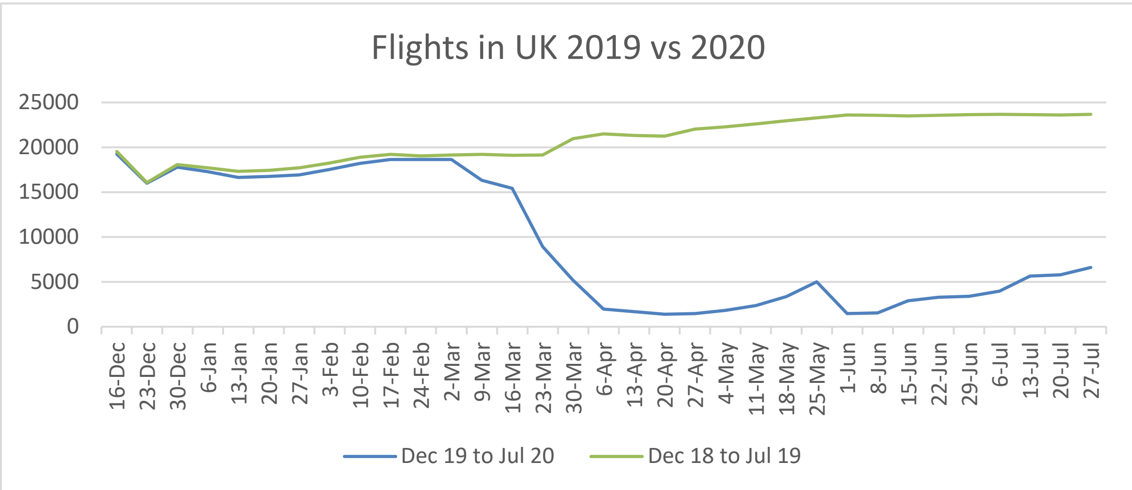


Figure 4-23 Year-over-year comparison of commercial flights schedule in the UK between December and July

COVID-19 started as an Asian problem and made travel between Asia and the rest of the world challenging. Due to the Chinese containment measures, Wuhan Tianhe Airport was the first Chinese airport closed to commercial passenger flights. The airport witnessed a sudden drop to almost zero aircraft movements on 23rd January 2020.

As the virus continued spreading in China, the air traffic movement in China plummeted. At this point, the UK still had several daily connections to and from China. However, the cancellations of some of these connections were insignificant regarding the total flights in the UK network.

As the spread of COVID-19 reached Europe, traffic numbers in the European network started to fall significantly. The traffic numbers in the EUROCONTROL network went down as far as -93% of 2019 figures on 12th April 2020 (EUROCONTROL, 2020b).

These numbers show the magnitude and severity of the crisis and what impact the pandemic had on the aviation industry.

4.5.4 UK aviation response to COVID-19

The first time the coronavirus was officially discussed at the IRG was in an ad-hoc call between the IRG and the government on 4th February 2020.

4.5.4.1 The period until the "freefall"

This period describes the time between detecting the new disease in China and European countries moving into lockdown. During the first two months of 2020, the traffic numbers in Europe remained relatively stable and were almost 2019 level until 1st March 2020 (EUROCONTROL, 2020b). The day Italy went into lockdown (12th March 2020), traffic numbers in the European network were only 17% down compared to 2019 figures. However, after the 12th of March 2020, the aviation industry entered the "*freefall*" period, and the numbers by EUROCONTROL (2020b) showed that traffic numbers decreased dramatically.

Until that point, most airlines were operating according to routine operations, and the UK government had regular teleconferences to discuss the process of handling passengers from highly infected regions.

4.5.4.1.1 Ad hoc teleconferences

The meeting invite sent out to the IRG members for a meeting on 4th February 2020 included that *“the DfT have requested a call with industry to discuss the on-going situation. They are keen to discuss the current government response and to listen to any comments or issues the airports are facing, the aim being to improve the cross-government response”* (Mail from 4th February 2020).

Representatives from various major UK airports and airlines attended the call, and some senior managers up to the COO level were dialling in.

Each of the airports on the call was sharing their perspectives. One major UK airport highlighted the need to streamline communication as they had multiple parallel conversations about the topic. The aim was to find an efficient way to align with PHE. Furthermore, they sought advice on the right PPE for handling passengers from high-risk countries and handling passengers in general. One UK hub member questioned whether the stakeholders had enough resources if the virus were to get to the next level. Changing masks every hour for 4,000 members of staff meant that commercial resources were running low. The question was raised if government resources were available to support the aviation industry with resources. This additional supply could be critical if the guidance changed.

The common message was that stakeholders were doing business as usual, but that could change quickly. Therefore, it would be crucial to have an aligned response from the government as airports could become quickly overwhelmed if there is no guided process. This process included support and advice on how and what to expect and prepare for changes.

The IRG members were interested in whether there were any plans for an escalation policy as there was no insight from an airport perspective. One of the critical interests was when they had to prepare for the next steps. Chinese carriers were still operating between China and the UK, and airports wanted to know how to track people passing through the airport and what the policy was. They requested a consistent message from PHE and DfT.

This fact was echoed by multiple airports, especially the need for a consistent message to be sent out to the entire aviation community, including Border Force and ground handlers. One airport that did not receive direct flights from China mentioned that it is crucial to monitor indirect flights.

Although no immediate challenges were reported on that call, it was emphasised by one major airport that if the guidance changed, it would be crucial that all airports would be doing the same thing and move simultaneously. This joint approach would be crucial for maintaining the level of customer confidence. Airports already pointed out that guidance was expected to be changed, and there was a need to ensure common communication channels were set up.

Participants representing airlines on the call reiterated the need for clear guidance on what one should and should not do. Connecting multiple countries, airlines also mentioned that they experienced challenges in keeping on top of all the various travel restrictions and advice. They said they would welcome a central source of all the frequently updated restrictions.

Another point discussed on the call was the 80/20 rule and the potential suspension of the rule for flights between Asia and Europe.

4.5.4.1.2 The 80/20 slot rule

Airports with limited or constrained infrastructure capacity are managed by airport coordination. This airport coordination uses a set of rules based on the Worldwide Slot Guidelines (WSG) (IATA, 2019) to maximise the efficiency of the airport infrastructure. The WSG define three different levels of airports. Level 1 describes airports that have sufficient capacity to meet the demand of the users at all times. At the next higher level, airports may run into capacity issues during a particular day, week, or season peak. Eleven UK airports are classified as Level 2 airports (IATA, 2022). However, Bristol airport is considered a Level 3 airport during the summer season (IATA, 2022). A level 2 airport appoints a facilitator that facilitates the operation planning between the airport and airlines.

Level 3 describes *“airports where capacity providers have not developed sufficient infrastructure, or where governments have imposed conditions that make it impossible to meet demand”* (IATA, 2019, p.42). Seven UK airports are coordinated airports during the winter and summer season. The list includes Birmingham, London-City, London-Gatwick, London-Heathrow, London-Luton, Manchester and Stansted (IATA, 2022). A coordinator is appointed to manage the airport coordination by allocating airport slots to the aircraft operators. The coordinator for airports in the UK is ACL (Pickett and Hirst, 2020). ACL was founded in 1991 to coordinate the five largest airports in the UK and the airport in Bermuda. Today, ACL is responsible for 46 airports worldwide, including the coordination of 14 Level 3 airports (ACL, 2021).

A *slot “is a permission given by a coordinator for a planned operation to use the full range of airport infrastructure necessary to arrive and depart at a Level 3 airport on a specific date and time”* (IATA, 2019, p.42). A series of slots refers to at least five slots for the approximately same time on the same weekday.

Slots are only allocated at a Level 3 airport, and an aircraft operator must hold a slot for operating at a coordinated airport. Once a slot is allocated, an aircraft operator must not intentionally operate a flight at a time or in a significantly different way than allocated. All slots have been allocated at certain highly utilized airports and can only be swapped or transferred between airlines. Slots are crucial to airlines, and according to EUROCONTROL (2016), one slot was sold for $75 million in 2016. However, slots are only allocated per season. Therefore, airlines are interested in retaining the slot for the next equivalent season. The WSG regulates the retention of the slots with historical precedence. The historic precedence refers to the so-called *USE IT OR LOSE IT RULE*. This rule states that if an aircraft operator can demonstrate that a series of slots was used at least 80% of the time during a season, it can retain the slot for the next equivalent season.

The spread of the coronavirus in Asia meant that certain flights between China and the UK were cancelled. Airlines were concerned that not operating these flights could have potential implications for the retention of the slots for the next equivalent season. Airlines were calling for alleviation for those flights, meaning the *USE IT OR LOSE IT RULE* would be suspended on specific routes.

However, there was a conflict on who would have the authority to make the alleviation, and the *"regulation did not give us the flexibility to give alleviation on the 80/20 rule to airlines at an early enough date (…) we had a lot of airlines coming to us for a request for alleviation from the 80/20 for that period in the winter"* (Participant 5010).

The DfT did not feel responsible, and ACL, the slot coordinator for the UK, did not have the authority to make their own decision. The issue was that *"if you look at the criteria by which the regulation is laid down, it does not give us, it does not put a pandemic or anything similar to that. There is everything from weather-related, or there is geopolitical kind of elements that you consider, but certainly not a crisis of this nature"* (Participant 5010). ACL was waiting for guidance and advice from the European Union (EU) on changes to the 80/20 rule. The topic remained an issue until the EU granted alleviation on 30th March 2020.

The first telecon seemed to be appreciated by industry and government, and the chair of the IRG offered the IRG's help to facilitate more calls and meetings. The research is aware of twelve more telecons between 7th February 2020 and 3rd March 2020.

The following meetings allowed the PHE to provide the industry with an overview and update on the latest response and scenario planning. It was stated that Heathrow airport was the first airport where public health monitoring would occur and cascade to other airports.

One of the challenges early on was the so-called case definition. PHE defined the case, which included guidance on the flights that had to be monitored and passengers monitored upon arrival. The industry shared concerns that the number of affected flights could overwhelm PHE resources. In order to stay ahead and manage the increasing workload, PHE augmented a team called Port Health at Heathrow airport. This team would also be responsible for all other UK airports.

During the phone call on 7th February 2020, a significant airport raised issues about the availability of specialist ambulances for public health monitoring of passengers arriving from high-risk countries. Furthermore, issues were already concerning the communication from the government, and it was agreed that the frequency of IRG teleconferences would be increased. In addition, a routine phone conference between the government and the airport would be set up. Another action was the integration of representatives from the Border Force in the calls.

One of the PHE actions was to train additional Port Health crews to deal with the increasing number of flights that had to be monitored.

In one of the following meetings, various people voiced concerns about the protocols published on the triage and how to get more effective enforcement of reporting by airlines. One major airport mentioned that if an aeroplane from an infected region carrying a passenger with fever, cough, or shortness of breath, there is an urgent need for better communication and notification. Communication between airlines and airports would avoid a situation where passengers arrive at the airport and have to self-present themselves to the authorities. This concern resulted in a letter sent to all airlines operating from this hub, and the DfT and CAA provided support to distribute the letter to other airlines.

In addition, the DfT and Home Office issued an action to work with PHE on a system to allow traceability of passengers who were on a flight from an infected area and who presented symptoms. At that time, IATA required passenger locator forms to track passengers sitting in the two rows behind and in front of the symptomatic passenger. These forms were paper-based.

PHE set up a helpline for airports if questions arose or clarification was required. During a call on 11th February 2020, the feedback from the airports on this helpline was positive. However, one of the shortcomings was that the helpline was only available during working hours and the airports asked for 24/7 support.

The following day, PHE reported to the IRG that out-of-office hours would be covered and available for certain people in the industry. They indicated that this service would be ready by 16th February 2020.

Furthermore, one airport reported that the guidance was sometimes contradicting and that there is a need for consistency in the guidance. The airport mentioned that the PHE guidance was contradictory on appropriate detergents that had to be used for areas in which symptomatic passengers had been. PHE took action to update and re-issue the guidance to resolve the issue.

The need for better visibility on indirect passengers was brought up during a meeting on 12th February. Especially smaller airports in the UK, which did not receive direct traffic from affected regions, raised concerns over this issue.

During this meeting, a major UK airport announced that it would work with two airlines to identify symptomatic passengers. The airport would send a Notice to Airmen (NOTAM) message that all arriving airlines comply with PHE guidance.

A NOTAM contains information about the condition, change, or establishment in any facility, service, hazard, or procedure of the aeronautical flight operation (ICAO, 2001). This information is vital for all personnel involved in the operation and is issued by national authorities. Examples could include airspace restrictions, closed runways, or notification about hazards such as parachuting activities or temporary obstacles near airports (ICAO, 2001).

The NOTAM message was sent out on 13th February 2020 and contained the following information: "*Crew operating from China, Thailand, Japan, Republic of Korea, Hong Kong, Taiwan, Singapore, Malaysia and Macao are advised to comply with United Kingdom Department for Transport Coronavirus protocol regarding notification for direct arrivals"* (NOTAM message shared in email to IRG members). The NOTAM also listed six bullet points about steps to be taken before arrival at the airport. These steps included the provision of an information leaflet to the passengers, broadcasting an inflight message, and notifying the airport about symptomatic passengers and what other information had to be shared prior to arrival.

Later that day, the IRG members discussed whether public health advice should be shared on indirect flights. An action was taken to explore how many passengers were arriving in the UK on an indirect route. However, it was reported that a scale-up of the response to indirect flights would not be possible with the available resources.

The concerns over the lack of availability of ambulances were first raised on 7th February 2020; by 14th February 2020, this was still a major concern. The ambulances were necessary to take symptomatic passengers to the hospital. The question was who would wait with the passengers if there was a delay with the hospital transfer. One airport reported the experience of a passenger who had to wait for 14 hours before an ambulance was available to take them to the hospital. An action was taken that the Department of Health and Social Care would ensure adequate availability of ambulances for transporting symptomatic passengers to the hospital within a reasonable time.

Heathrow airport reported 16 call-outs from 12th February 2020 until 17th February 2020. Two other London airports reported that a NOTAM was also issued for General Aviation traffic.

4.5.4.2 The “freefall” period

The “*freefall*” describes the time when the SARS-COV-2 reached Europe, and many countries on the European continent went into lockdown. The weekly arrivals in the UK went from 15,432 for week 12 to 1,971 for week 15.

During this time, the IRG had three short teleconferences during which the individual members shared the situation of their organisations. There was some anxiety in the industry as nobody knew how low the traffic would get. The aviation industry was challenged by the number of repatriation flights taking place and ramping down the operation simultaneously.

There was no fundamental governance structure within the IRG and ODLG to facilitate any coordinated approach. The online meetings were mainly used to check-in and share experiences. However, there seemed to be no capacity left to do anything else apart from the regular information exchange. People retracted and were preoccupied with the operation of their organisation. According to Participant 3313, the industry looked to the daily announcement and responded to the latest guidance accordingly.

4.5.4.3 The European Aviation Crisis Coordination Cell

One of the organisations that tried to provide an overview of what was sometimes a somewhat confusing situation was EUROCONTROL. The 2010 eruption of the Icelandic volcano Eyjafjallajökull showed how vulnerable the European aviation system is when faced with a crisis and the difficulties in achieving pan-European coordination between states. As one learning from the volcanic eruption in 2010, EUROCONTROL set up the EACCC. The EACCC purpose is to support a coordinated response to a network crisis. It attempted to provide a demand picture and give an overview of the situation for the European stakeholder. Each of the EUROCONTROL member states had an appointed State Focal Point (SFP), who fed information about the situation in the individual state into the EACCC. Situations for previous EACCC activations included the shootdown of the Malaysian Airlines flight MH17 in 2014 and the Brussels terrorist attacks in 2016. The EACCC was activated for the COVID-19 pandemic on 31st January 2020, after the member states and SFP were first notified on 22nd January 2020. The SFPs were feeding information into the EACCC, which was summarized in factsheets.

After the traffic numbers bottomed out in March and April 2020, and the European network experienced a slight uptick in traffic movement, the first NOP2020RP was published. The NOP2020RP contained information about *"the evolution of the traffic demand and of the planning of the service delivered in the recovery phase by ANSPs and airports to match the expected air traffic demand in a safe, efficient and coordinated manner"* (EUROCONTROL, 2020b, p.3). The NOP2020RP was published every week and contained a rolling four-week outlook. It contained information about the traffic demand in the European network, the situation at the control centres and airports in the network, sector capacity, and information about changes in entry requirements of the individual countries.

4.5.4.4 The period until the end of the 1st UK lockdown

According to the OAG data, the numbers for scheduled arrivals in the UK reached their lowest point in the calendar week 17 of 2020 (20th - 26th April), with only 1,403 scheduled arrivals. The UK was still in lockdown at that point, which remained in place until 1st June 2020. However, the schedule was increasing again, for the first time since the sharp decrease in calendar week 12. In week 22 (25th May), the weekly schedule arrival hit 4,986. The industry was awaiting information about reopening borders, and the first discussions about "*airbridges*" took place. However, the numbers were compared with the CAA database. The database revealed that the actual number of flights stayed at a low level and did not spike in arrivals between 26th April and 1st June 2020. Usually, the number of scheduled data is similar to the actual number of flights. One possible explanation for the significant difference in schedule data is that airlines expected an improvement in the situation. However, as the situation did not improve, the schedule data were not updated. This lack of synchronization may have been due to the volatility of the situation. After the initial spike in scheduled flights in week 22 (25th May), the schedule was adjusted, and the weekly scheduled arrival decreased again to 1,464 in week 23 (1st June). This adjustment in schedule may be related to the public briefing on 22nd May 2020, during which a mandatory 14-day quarantine for people arriving in the UK was announced.

4.5.4.5 UK governance structure

As far as this research is concerned, there has not been a clear governance structure to coordinate the aviation industry during the "*freefall*" period. The first time a clear governance framework was presented to the aviation industry was during a meeting on 6th May 2020. Figure 4-24 shows the governance structure shared with the industry on 6th May 2020 to tackle the challenges for the expected traffic recovery.

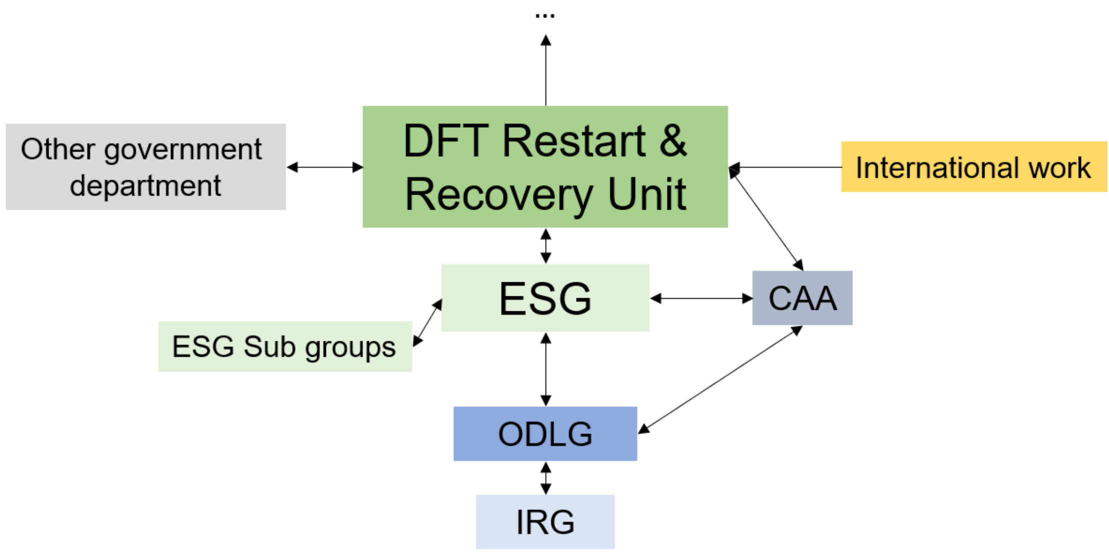


Figure 4-24 UK Covid-19 Aviation Recovery Governance

4.5.4.5.1 DfT Restart and Recovery Unit

In order to define a UK position in response to the COVID-19 pandemic, the government set up a Restart and Recovery Unit (RRU) within the DfT. The RRU would be supported by a government-led working group called the Expert Steering Group (ESG). It was also supposed to work closely with the CAA to align with the UK aviation regulator. The RRU also had links to other government departments and agencies, such as Department for Health & Social Care, PHE, Home Office, Border Force and FCO. Furthermore, it would consider international work, including work done by ICAO, EASA and EUROCONTROL.

Once the UK position was defined, it would be shared with DfT Ministers and DfT cross-modal groups.

4.5.4.5.2 Expert Steering Group

As mentioned earlier, one crucial input into the RRU was the ESG. The ESG brought together parties from across the industry and government. It had representation from DfT officials, CAA, NATS, ground handlers, airports, airlines, trade associations, unions, and other government departments.

The purpose of the ESG was to receive input from the industry and use it as a form of intelligence gathering. Representation from government bodies and industry would also provide an opportunity to road test ideas and drive consensus for the UK-wide approach to redesign the aviation customer journey during the pandemic.

The objective should be achieved using DfT science and analysis combined with industry insight. The work was accompanied by expert health advice and social and academic feedback. This framework was the theoretical description of how the DfT was planning to formally engage with industry to respond to the COVID-19 pandemic and deliver a UK position. The ESG later formed certain subgroups to address specific challenges, such as defining and reviewing an appropriate testing regime.

4.5.4.5.3 Relationship between ESG, ODLG and IRG

In the hierarchy presented on 6th May 2020, the ODLG was seen as a group that would support the ESG and share information. During the "*freefall*" period, the ODLG and IRG effectively merged into one group (*"and I think within COVID, to be honest, IRG and ODLG just merged into one*" (Participant 3412)). They were driving the information exchange within the industry. Some of the ODLG members were also represented at the ESG. However, one major remark three interviewees made was that the IRG chair was not on the ESG. They mentioned that the chair could have provided the government with an impartial view of the industry.

As described in section 4.2.4, the IRG met every month before the pandemic, whereas the ODLG only came together on two or three occasions a year. During the "*freefall*" period, the ODLG came together and held weekly or biweekly meetings as more senior people were represented in this group. People felt that the COVID-19 challenges felt more appropriate to discuss on an ODLG level. The IRG still met monthly, but the ODLG essentially drove most of the cross-industry conversation. Effectively, the IRG was supplanted by the ODLG. Since the IRG and ODLG are part of the same cross-industry working group construct, the rest of the subchapter discusses the entire construct and refers to it as the IRG/ODLG.

Section 4.5.5 summarizes some of the high-level challenges stakeholders of the UK aviation industry experienced.

4.5.5 Challenges experienced by the aviation stakeholders

The UK aviation industry faced numerous challenges during the initial phase of the COVID-19 pandemic; some of the challenges were specific to the operation of the individual stakeholders. The case study summarises all the collected challenges at a high level (see Table 4-29). The challenges were part of a summary sent out to the ODLG members, and the feedback was that "*this is a good, concise summary*" (Comment from one of the ODLG members).

Table 4-29 Summary of experienced challenges

Challenges experienced by stakeholders
• Sudden impact on operation • Maintaining safe and compliant operation • No indication about next steps

4.5.5.1 Sudden impact on operation

One of the reoccurring themes was that COVID-19 caused severe disruptions to the operation of airports and airlines.

As soon as the virus spread reached Europe, the impact of COVID-19 on the operation was sudden, and organisations had to quickly adapt to a new reality handling the dramatic and sudden change within a very short timeframe (Participant 4913). *"I do not think anybody knew the scale. I do not think anybody, anywhere, really predicted the scale of this or the duration of it. I think we thought that we may be facing potentially a few weeks of constraint"* (Participant 4112).

The interviewees described the changes as sudden, dramatic, and substantial, as seen in the following comments. *"We were keeping on top of what was happening, but I do not think we thought it was going to affect the UK until probably early March"* (Participant 3413) and *"the pace of change, the volume of reading and an interpretation of guidance, legislation, regulation within that space, whilst trying to run a business at the same time*" (Participant 5412). These changes created an unfamiliar situation. The industry had to deal with the volume of reading and interpretation of the guidance and *“everyone I think gets frustrated in terms of the changing advice and the timelines and timeframes that we get to work on”* (Participant 4715).

“*There is the challenge of changing the way you operate your business to meet the UK's changing requirements, and government abroad in terms of what they want from their outbound flights*” (Participant 4112). The aviation industry is global, and *“the main challenges are understanding the new regulations in place of operating across the globe and the differences that are out there”* (Participant 4715). It was frequently mentioned that the pace of change and updated guidelines were challenging.

Furthermore, stakeholders had to maintain a safe and compliant operation while dealing with a severe financial impact and drop in revenue (e.g. *“from an airside operation, I still need to provide safe and compliant operation...We were seeing x percentage fall in our traffic numbers and our passenger numbers, and we expected to see the same level of reduction in our staff overhead”* (Participant 3314). The sudden decrease in demand meant the organisation was trying to reduce the number of employees and estimate the required staffing level. With the reduction in traffic also came a drop in revenue (Participant 4913) and stakeholders had *“that dilemma of trying to right-size your business”* (Participant 5412). Stakeholders were trying to assess the minimum amount of staff required as *“right from the off, we were looking at what’s the minimum numbers because we were expected to lose people in the first instance, because of testing positive”* (Participant 3313).

This action was necessary to ensure a safe and compliant operation under the aerodrome licence terms. In order to be compliant with the relevant legislation and regulation, the airports had to make sure they had enough staff to do so (Participant 4913). As the aviation industry entered the “*freefall*” period, it was a significant challenge to forecast traffic numbers, as this comment emphasises: *“They [airlines] would wait until the last minute to cancel anything. So we were then not looking at the right information”* (Participant 3413). According to

Participant 5010, *“the lead times cancellations were about 16 days in the first three months of summer”.*

4.5.5.2 Maintaining safe and compliant operation

The COVID-19 pandemic generated numerous new guidelines the aviation industry had to comply with. A frequently raised challenge was the pace of changing guidelines, and that industry had relatively short notice to implement these guidelines. *“We were adhering to the guidelines, but the guidelines were changing”* (Participant 3313) and *“some of those were very, very short notice changes, you know, tomorrow we have to do something different”* (Participant 4112).

Moreover, these guidelines and regulations were sometimes not operationally possible. This fact is shown in the following comment: *“Some of these people are very well educated civil servants who do a fantastic job and what they are doing, but they are introducing regulations, where there is no way in the world, they are going to understand the detail of what that means”* (Participant 5412). People raised the concern that introducing new regulations was sometimes issued without understanding what it meant to the operation and the obstacles that had to be overcome before they could be implemented.

“A single call to say, you know, not we have issued some guidance, we are about to issue some guidance that says this, this and this. Operationally, airports, does that work for you? Can you make that work? What do you think about it? Rather than issuing health guidance from government policy that was not operationalizable, that does not work on the ground” (Participant 3314).

The new regulations created bottlenecks in the system that had to be solved. Overall, there appears to have been a lack of practicality and comments were also made that the response and initial airport guidance were too London Heathrow specific. *“We really needed to rally Public Health England and get them in a good conversation to recognise that it is not just Heathrow, and there is a lot more we need to consider”* (Participant 3314).

Certain airports had to deal with scenarios that were not considered in the guidelines. *"We had some scenarios which they never considered, people can just jump on a private business jet and fly….the process they came up with worked for passengers and airlines but did not work for business jets"* (Participant 3313). There was also confusion about the different guidelines and harmonization of guidelines, especially in the early stages of the COVID-19 crisis. Specific guidelines left room for interpretation, such as *"when one guideline mentions a face mask, and another one mentions a face covering. Just a really small play on semantics there, but the difference in interpretation of those two really small changes are quite big in an organisation"* (Participant 3314).

The sudden change also caused much anxiety in the industry, and in *"those early days, nobody really had any idea about how deep it was going to be or how long it was going to last"* (Participant 5412).

The lack of transparency caused another challenge. Stakeholders received information from different sources in the early days of the crisis. Participant 5009 mentioned that it was challenging to ensure that their organisation gathered the current information, especially at the beginning of the pandemic. One main issue was that stakeholders did not understand their part in the response process and where they fit in during the response process (Participant 5009). This breakdown caused policymakers a lack of feedback mechanism about the challenges observed at the sharp end.

4.5.5.3 No indication about next steps

Observations were made that appeared to show the lack of government support in clarifying some of the processes and creating better transparency. Industry highlighted that no indication about the next steps was made, and rapid changes in the guidelines created surprises for the aviation industry. There was *"frustration of getting a decision at short notice without having been consulted on things*" (Participant 3413). There *was "frustration that they were not making more decisions and bringing for sort of actions that they have done….I think there was frustration from the airlines on, you know, what is happening with corridors, what is happening with testing"* (Participant 3413).

In addition, the response from the government to the COVID-19 crisis was sometimes perceived as slow (e.g. "*I think it will be fair to say at the start, it was slow*" (Participant 4715)). Due to the slow initial response, some stakeholders mentioned that they were well ahead of the government's lockdown announcement (Participant 5009). This slow response hampered the industry's unified approach as stakeholders proactively introduced safety measures before official government guidelines were issued. Furthermore, *"I do not think they have done things in a coordinated way, and I certainly do not think they have done it in a consultative way"* (Participant 5010).

Particular stakeholders became aware of the potential magnitude of the crisis early on *"13th January first flagged this as a risk to our business…we were putting mitigation, probably a good month or six weeks ahead of most other UK airports. So we had Perspex screen up and all that kind of stuff. We increased our cleaning in line with what we thought would be appropriate, even though there were no guidelines at the time"* (Participant 3314).

4.5.6 Role of IRG/ODLG and resulting benefits

The first time the coronavirus appeared on the agenda of the IRG was on 4th February 2020.

Having an established working group with representatives from the regulator, airports, airlines, and other aviation and non-aviation stakeholders brought some benefits to the response to the COVID-19 crisis.

Table 4-30 summarizes the resulting benefits of the IRG/ODLG. The following section investigates the role of the IRG/ODLG and what benefits its existence had for industry and government.

Table 4-30 Summary of resulting benefits

Resulting benefits of IRG/ODLG
• Enabling cross-industry discussion and work • Engagement with non-industry stakeholders

4.5.6.1 Enabling cross-industry discussion and work

The IRG/ODLG allowed stakeholders to come together and break down silos, and *"the IRG gave a huge amount of support by creating that platform for conversation between airlines and airports but (…) I am not sure if I look at the agenda for the IRG over the last three or four weeks if in itself has delivered a huge amount other than the platform for that conversation"* (Participant 5010).

However, the discussion allowed the IRG/ODLG members to share good practices and allowed participants to follow up offline after a teleconference. Over the years, *"the IRG has developed lots of those relationships"* (Participant 5010) and trust across the industry, which became helpful during the pandemic (*"I have got much stronger relationships with other airports now"* (Participant 5412)). Based on statements from interviewees, people had already been comfortable working together with members from other stakeholders as part of this group. (e.g. *"He knows that I pick up the phone to him, and we can have an exploratory, informal talk about some of the problems. You know, I am not going to start lording that information over him commercially; it is going to be cool between us"* (Participant 4112)). Having had these prior connections allowed an open information exchange, which improved the situational awareness of other stakeholders. Following teleconferences, stakeholders would sometimes contact other organisations for a one-to-one discussion if they felt it was necessary (Participant 5009).

Furthermore, the IRG/ODLG gave its members access to cross-industry information, which allowed *"gleaning information that we would not necessarily get any other way"* (Participant 3413). The information exchange also gave organisations a feel for where other stakeholders were during the initial "*freefall*" and *"understanding airports next best intentions, in terms of what are they going to do from an operating perspective, and having eight airports in the line, I think, is a really good insight"* (Participant 4715).

The IRG/ODLG could link different information sources by combining multiple channels and information sources. This information gathering was also shown by the SFP joining the ODLG to provide the industry with a European network update. *“So from the IRG, we get quite a few of the outlying airports that can impact the operation when your traffic is low…..So having that input from those people on the IRG and the ODLG has been invaluable”* (Participant 3413). This aspect allowed the IRG/ODLG to work as an industry sounding board.

By hosting the cross-industry conversations, the IRG/ODLG also gave a holistic view of the challenges and enabled some cross-industry work, even though this work was minimal. The purpose was to enable work in uncommercial but good common ground, which included conversations about safety and potential bottlenecks in the system. As mentioned previously, members of the industry felt that the response to the initial spread of the virus was not unified. The IRG/ODLG brought the right stakeholders together, which *“is essentially what the organisation is set up to do, is to bring harmonisation to the industry and bring other bodies in”* (Participant 3314). This platform allowed stakeholders to speak to counterparts in other organisations and receive a sense-check of how other stakeholders were implementing guidelines.

4.5.6.2 Engagement with non-industry stakeholders

The IRG/ODLG allowed the industry to come together and create a safe discussion space. *“Things like phone calls with PHE and DfT were very, very useful”* (Participant 4112). It also provided a platform to engage with the government and share a single message of industry. Stakeholders felt that the information and experiences at the sharp end eventually influenced the policy-making (Participant 5009). This government feedback created a sense of urgency and an element of pace. This communication channel was perceived as a potential route into the ESG (*“especially initially when the public health response was being formalised, the IRG did do an awful lot of kind of that bridge building and the patchwork to make it happen”* (Participant 4112)).

The close link between the IRG/ODLG and the regulator also allowed discussion of where to go next, even though part of the discussion was limited.

4.5.7 Additional potential for IRG/ODLG

Although the IRG/ODLG brought some benefits to the industry during the COVID-19 pandemic, some remarks were made that the IRG/ODLG did not use its full potential during the crisis (see Table 4-31).

Table 4-31 Summary of additional IRG/ODLG potential

Additional potential for IRG/ODLG
• Improved governance • Improved communication

4.5.7.1 Improved governance

All of the interviewees highlighted the lack of transparency of the response process and a disconnect between the various working groups (e.g. *"I think there seems to be a little bit of no clarity how you escalated up. And really what each area was there to look after, there were some quite complex, organic rounds at the start"* (Participant 4715)). Participant 5412 saw the lack of clarity as *"why people were clamouring for information*".

As far as this research is concerned, there was no formal crisis governance structure before 6th May 2020, and according to Participant 5412, *"we need a better hierarchical system of reporting up and getting all that information so it can get fed out".* "*The bit that was missing is that they were getting views and opinions and ideas and stuff from the IRG and ODLG. Whether that was being taken into the ESG and into government actually is a bit of a mystery. It is certainly a mystery to me*". (Participant 3413). According to their experiences, the industry did not see much information coming back from the ESG.

Although the industry was trying to feed in as much as possible into the ESG, they did not see much output. The discussion was perceived as a one-way instead of two-way communication. Much information was shared in the ESG, but *"I would say, we have not seen much information coming back from the ESG* (Participant 3413). *"I think we probably could have got in earlier and used the IRG as the framework for that, representing everybody…If you have got individual airports lobbying government for their own reasons, there is always an* *interpretation of what each organisation wants, it is not impartial, and I think that is where the IRG for me plays a part in its impartiality"* (Participant 3314).

This lack of feedback loop caused frustration, and some interviewees would have liked to have more transparency for the decision making and issuing action as *"you could certainly feel frustration from the rest of the industry on the fact that they were not necessarily been consulted…..they probably sometimes felt they were not listened to and then just decisions were made and not thought about"* (Participant 3413).

Remarks were made *"whether or not the IRG or ODLG could have a stronger voice as an entity at something like the ESG (…) Jon [the chair of the IRG] should be a strong voice around the ESG, and unfortunately, he is not"* (Participant 5010). Changes and updates in guidelines were communicated on short notice. Industry members would have liked to see an advanced sharing of information, which had limited the potential for surprise. The absence of two-way communication was perceived as a missing link between strategic decision-making and operational implementation. People felt that there was a disconnect between IRG/ODLG, ESG, and ESG sub-groups. People offered their view and suggested that the industry and government should define a better governance structure (e.g. *"the ESG, the ODLG and to get those groups in the right order and get representation (..) I mean we have been there before, you could go to gold, silver, and bronze, couldn't you?". "I can imagine that there might have been a, you know, a weekly or twice-weekly bulletin, you know, setting out current status across the group of the airports and organisations involved"* (Participant 4112)).

Some of these challenges were related to the fact that there is no formal or contractually binding structure of the IRG, and *"maybe it is a question about defining the roles of the group in these types of circumstances"* (Participant 4112). The formal structure could have been used to inform the government about operational issues earlier, and stakeholders felt that the escalation process needed to be formalised as a lesson from this pandemic (Participant 5009).

Furthermore, without a clear structure, it was difficult to move things forward and achieve more than an open discussion about the challenges experienced by the various stakeholders. Suggestions were made that it needs *“almost like a charter of airlines and airports, someone saying to you if you are going to be part of this because clearly there are massive benefits for you as an entity and as a result of it, you need to divulge information to the best of your ability, and clearly, there will be terms and conditions around it”* (Participant 4715). This lack of progress was supported by the fact that *“there are no minutes, there is no real attendance piece. (...) It was not really a meeting you prepared for”* (Participant 5412).

The IRG/ODLG is currently not contractually governed, and *“I am a bit worried that the IRG seems to be as strong as its chair”* (Participant 3313). *“I think unless you have a core set of people who can deliver work around the clock at the pace at which this crisis has moved, I do not think we were ever going to get anything major from the IRG because it just was not the time in place to actually try and actually do that work for the IRG.”* The non-contractual concept meant that the IRG/ODLG never moved beyond the information exchange and the UK industry was passive during the crisis and only reacted to changing guidelines.

Although stakeholders openly discussed challenges they experienced, better visibility of stakeholders’ regeneration plans would have been helpful. These plans could have been used to see how other areas in the industry were doing their planning and what the demand picture was likely to be. One of the lessons learning was *“that there is not really a lot of action that has come out of the ODLG during COVID. It is more of a facilitation of information as opposed to, you know, somebody coming out with actions at the end of it*” (Participant 3413). Furthermore, *“if anything that this sort of pandemic has made clear, hat working together is definitely a benefit*” (Participant 4715).

4.5.7.2 Improved communication

The interviewees commented on various communication channels that could be improved, and *“there has got to be a process and a learning about sharing of information*” (Participant 5412). The first communication challenge concerned enhanced communication between government and industry. In their view, the industry did not feel consulted and listened to. This point goes back to the earlier comment that the industry was feeding much information into ESG but barely saw any output. In addition, they felt that IRG/ODLG could have had a stronger voice at ESG (e.g. *"I do still think there was a missing link between information and opinions going up and not necessarily being taken into account"* (Participant 3413)). They felt there should have been a stronger desire for discussions on future policy and communication about what is operationally possible. *"I think if we cannot directly influence, we could certainly inform. And you know, what I liked in the past was having the DfT there, listening first-hand about some of the issues we experienced...I think that would have been really useful in this to get an industry sense"* (Participant 3313).

Based on outputs from the interviewees, another channel that could be improved was the communication between health agencies and the industry. This enhanced communication could have helped with the clarification of guidance. Moreover, upfront discussion about making guidelines and regulations operationally feasible would have been possible with a more vital link between health agencies and industry. This link would have allowed health agencies to receive industry feedback before issuing new guidelines.

Additionally, it *"could have been more useful to find out what the regeneration plans were in other areas….we were doing it within our (organisation) and how we were bringing together the forecast and the traffic and relating that to our staffing and furloughing and all of that. I think it would have been interesting from a lesson learning point of view to hear how other areas in the industry were doing their planning…..one of the big things of the IRG is to learn lessons and to kind of gleaning information from others within the industry so that we can help each other collaboratively"* (Participant 3413).

4.5.8 Discussion

This case study highlighted principles from the literature review shown by the IRG/ODLG in response to COVID-19. The collected data were analysed, and the benefits of enabling cross-industry discussion, work, and engagement with non-aviation stakeholders were matched with the identified principles. The discussion section analyses how this working group contributed to the system's resilience.

For the analysis, the identified principles in section 2.2.4 were used. The analysis outputs were used to refine the PRF and add connections between the themes.

4.5.8.1 Introduction

The COVID-19 pandemic was the first time the European aviation industry had to deal with a significant disease outbreak. Therefore, resilience in this context is "*the ability to deal successfully with unexpected events*" (Furniss et al., 2011). Dealing with a pandemic created an unfamiliar environment, and *"this level of threat cannot be anticipated neatly enough to permit construction of a response algorithm. Instead, the basic qualities of the organization, its abilities to self-organize, monitor and formulate a series of responses, will determine whether it can react effectively"* (Westrum, 2006, p.58). Considering the type of event and the impact it has caused on the aviation industry, COVID-19 would fall into the third category of Westrum's (2006) classification, the unexampled event. The aviation system had to respond to an event without a pre-made response plan and quickly adapt to the new environment. The unavailability of procedures and the devastating impact on the operation indicate that this case study describes an unexampled event (Westrum, 2006).

COVID-19 affected everyday lives and had detrimental effects on aviation, with traffic numbers in the UK plummeting to as low as ~ 6% compared to the year before. Given this research, this disruption was severe enough to push the system towards failure (Cook and Rasmussen, 2005). Although the recovery from this crisis was still the overriding goal, the priority for many organisations during the initial theme of the pandemic was survival (Barker, Ramirez-Marquez and Rocco, 2013) and achieving a stable state (Hollnagel, 2006). The aviation industry had to deal with a crisis it had never had before.

Aviation experts worldwide referred to this situation as "*unprecedented*" (e.g. Busvine, Rucinski and Freed, 2020; D'Souza, 2020; MacGregor, 2020), which was a new situation for the European aviation industry. Airlines converted their passenger aircraft to cargo aeroplanes to provide cargo capacity and generate ad-hoc revenue (Albers and Rundshagen, 2020).

The challenge with COVID-19 was that this threat was unrelated to the core activities of the aviation operation. On the contrary, storm events and volcanic ash eruptions directly affect the core operation's safety – flying an aircraft during COVID-19 was still safe. However, crossing borders was not the norm, and the government's announcement to only allow essential travel meant almost everyone had to stay at home. According to Hällgren, Rouleau, and de Rond (2018, p.135), organisations *"can be ill-equipped to handle disruptions, particularly when wholly unrelated to their core activities*". The case studies analysed what of the identified principles the IRG/ODLG showed to enhance the potential for a resilient response of the UK air transportation system during the initial phase of the COVID-19 pandemic.

The following sections examine how resilience was generated during the *System Setup, System Changes*, *System Preparedness*, and *System Response* theme.

4.5.8.2 System Setup

Case study 5 found one example of an operationalised high-level principle from the *System Setup* theme, as shown in Table 4-32. It further explains the result of the operationalised principles and connection with other themes.

Table 4-32 System Setup principle observed in case study 5

High-level principle	Example	Result	Connection with other theme(s)
System is aware of interfaces with other systems	Availability of IRG and ODLG, created relationship with wider network	Creation of platform for collaboration and trusted environment	Input into System Response

<u>Principle: System is aware of interfaces with other systems</u>

As argued in the literature review (see subchapter 2.2), resilience can be achieved through the *System Setup*. The cross-industry working group, with its communication channels and processes, had been set up before the pandemic and, based on the output of the interviewees, was beneficial to the UK aviation industry.

When the IRG was set up, the expectation was that the industry *“should work together to achieve much improved “network level” coordination to enable appropriate resource planning, conflict resolution and continuous improvement review”* (IRG, 2018a, p.1). Since its launch in 2018, the IRG/ODLG had brought together the CAA, DfT, airlines, airports, and other aviation stakeholders on several projects. The group was chaired by Jon Proudlove and held monthly meetings regularly. The IRG/ODLG construct created a platform for the industry and government to come together and collaborate, highlighting the need for an appropriate governance structure (Naderpajouh et al., 2018).

The IRG functioned as a quick access point to the aviation industry for the government. This communication channel was first used in the COVID-19 pandemic to set up a call on 4th February 2020 through the IRG chair. The initial teleconferences brought the main UK aviation stakeholders together and allowed a discussion between PHE and the industry.

Besides building a platform for collaboration, the IRG/ODLG created new relationships within the aviation industry. By having the cross-industry working group in place since 2018 and facilitating monthly meetings and workshops for specific topics, the IRG/ODLG created a feeling of community. People had a chance to meet people from other organisations in similar roles and work collaboratively on topics concerning the resilience of the UK air transportation system. Some interviewees mentioned that relationships were also made outside the IRG/ODLG. However, the IRG/ODLG supported the creation of a trusted environment where sharing information was the norm. This fact aligns with de Vries’ (2017) research, which lists communication and trust as factors for successful operation. Sharing information also improved situational awareness (Le Coze, 2019).

4.5.8.3 System Checks

As highlighted in section 2.2.4.1.2, the potential for resilience can be generated through the *System Checks* theme. Case study 5 found one operationalised principle, and Table 4-33 layouts the practical examples, resulting consequences and connection with other (sub-)themes.

Table 4-33 System Checks principle observed in case study 5

High-level principle	Examples	Result	Connection with other theme(s)
Identify changes in environment	IRG members doing internal risk assessment	Identified developments in Asia as an area that needs to be looked at	Input into System Preparedness

<u>Principle: Identify changes in environment</u>

As mentioned in case study 2 (see subchapter 4.2), the IRG does not have the resources to do any risk assessment. Instead, the IRG was used as a platform to share internal risk assessments done by the individual IRG members. The situation in Asia was discussed at a meeting on 26th February 2020, and airline representatives mentioned that they were monitoring the situation. This discussion can be seen as an empirical example of Hollnagel (2014a), who described identifying environmental changes as a sign of resilience.

Due to the identified changes, the situation in Asia was closely monitored, which led to some actions taken in the *System Preparedness* theme.

4.5.8.4 System Preparedness

As highlighted in section 4.5.4.1, some actions took place before the traffic numbers sharply decreased in March. Table 4-34 lists the observed high-level principle and links it with the empirical examples. It also shows the result of the operationalised principle.

Table 4-34 System Preparedness principles observed in case study 5

High-level principle	Example	Result	Connection with other theme(s)
Ability to anticipate bottlenecks	Developments in Asia as potential risk to borders	Engagement with government and PHE	Output from System Checks
Ability to anticipate bottlenecks	Developments in Asia as potential risk to operation	Concerns over 80/20 rule	Output from System Checks

Principle: Ability to anticipate bottlenecks

The first telecon between the DfT and the IRG was held on 4th February 2020. At that point, flight numbers in China had already dropped to ~78% of 2019 levels (calendar week 6), and parts of China had been put in lockdown. The DfT used the IRG as a quick access point to receive an overview of the challenges experienced or expected by the stakeholder. This meeting triggered the discussion between PHE and IRG/ODLG to define measures to protect the UK population through appropriate screening measures. The industry received information about the appropriate communication channels and how to contact PHE with questions about the measures. These teleconferences followed principles of proactiveness (Costella, Saurin and de Macedo Guimarães, 2009), anticipation (Hollnagel, 2009a) and preparation (Wreathall, 2006).

Although protocols for handling passengers from highly infected regions were developed and shared, the issue of indirect flights from highly infected regions arriving in the UK was never solved, as far as the research is concerned.

As early as the beginning of February, industry stakeholders highlighted operational issues they were expecting. One IRG member airport highlighted concerns over the supply of adequate PPE as commercial resources were expected to run low should the guidance require changing the masks everyone hour for all their staff.

Another critical issue was flagged by airlines and airports. They were calling for clarification on the 80/20 rules as the industry had not received any information on alleviation. A pandemic was not explicitly listed in the criteria that would give alleviation for airlines. The 80/20 rule works well for a highly-efficient system but does not provide any flexibility to cancel flights because of an epidemiological situation. Flexibility is one of the enablers of resilience frequently listed in the RE literature (e.g. Azadeh et al., 2014b; Ranasinghe et al., 2020; Wreathall, 2006; Zarrin and Azadeh, 2019). By having the 80/20 rule in place effectively until 1st April 2020, airlines in the UK and EU were forced to fly their aeroplane to protect their slots for the following season. As soon as the EU drafted a proposal on 13th March 2020 that would give alleviation to all European airlines, the traffic numbers plummeted to as low as 7% of 2019 traffic levels in the European network (EUROCONTROL, 2020b). Earlier suspension of the 80/20 rules may have also alleviated the "*ghost flight*" discussion (Sillers, 2020). The term ghost flight refers to flights with no or almost no passengers on board that were only conducted to use slot capacity.

Even though the IRG/ODLG identified the developments in China as a risk to the operation, it is questionable if the stakeholders were aware of the scale of the potential issue. This observation can be seen best by the statement from participant 5412: *"if you stand up there and say, look, there is going to be a global pandemic, if you stood up in the middle of February and said, right, we need to start thinking about downsizing, we are not going to have a summer…in February, someone would look at you and thought you were stupid".* The ODLG had one of their regular meetings on 26th February 2020, during which the developments in China were only briefly discussed. During the two weekends before the meeting, the UK aviation industry was severely impacted by two storm events, and this topic received much more attention during this meeting. Focusing on the two recent storm events during the meeting on 26th February 2020 may indicate that people saw the preparation for a potential impact on UK aviation not as one of the top priorities. Individual stakeholders may have prepared their internal operations for the expected disruption, which was outside the scope of this research. However, at an IRG/ODLG level, no actions that triggered active preparations at a system's level could be observed. Although the discussions indicated some signs of anticipation and preparation, the outputs from the discussions were not used to effectively prepare the system for a sharp decrease in traffic numbers.

4.5.8.5 System Response

As mentioned in Westrum's (2006, p.58) definition of an unexampled event, the *"level of threat cannot be anticipated neatly enough"*. Therefore, the *System Response* theme is vital as not all treats cannot be proactively mitigated through the *System Preparedness* theme. This section investigates which operationalised principles of the *System Response* theme were observed by investigating the role of the IRG/ODLG through the initial phase of the COVID-19 pandemic. The section also provides empirical examples of the high-level principles, shows the resulting consequences and explains the connection with other themes (see Table 4-35).

Table 4-35 System Response principles observed in case study 5

High-level principle	Example	Result	Connection with other theme(s)
Governance structure for coordination and communication	Cross-industry discussions and work	Access to cross-industry information and holistic view of challenges	Output from System Setup
Governance structure for coordination and communication	Engagement with government	Build framework for cross-industry discussion	Output from System Setup

<u>Principle: Governance structure for coordination and communication</u>

Having the IRG/ODLG in place was possible for cross-industry discussions and work. Van der Beek and Schraagen (2015) study mentioned cooperation in building resilience as an essential part. Although the study looks at the work of a team, they concluded that *“cooperation with other teams, a defining characteristic of multi-team systems, is more important than ever, given that teams no longer work in isolation”* (van der Beek and Schraagen, 2015, p.34). Following the principle of cooperation, the IRG brought stakeholders together, which broke down silos and made collaborative work possible. The industry could use the IRG’s framework to share experiences and best practices during the COVID-19 pandemic. Although the IRG/ODLG is not contractually governed, it provided some sort of informal governance structure for communication (Naderpajouh et al., 2018)

As mentioned by the interviewees, the working group gave a platform to exchange information and insight into other stakeholders' operations. This information exchange provided access to cross-industry information. Operations Directors or people in similar positions could hear first-hand about the situation and challenges other stakeholders were facing, which supported the creation of awareness (Shirali, Shekari and Angali, 2016; Wreathall, 2006). One of the IRG members came forward on 26th March 2020 and presented a detailed description of their situation, including staffing level and regeneration plans for the coming weeks, which helped to understand the dependability between system-of-systems (Bukowski, 2016). This kind of open sharing was only possible because of the trusted environment the IRG has created over the years. However, as mentioned by interviewee 3413, it would have been beneficial if more stakeholders had shared their regeneration plans.

The IRG/ODLG brought some harmonization to the industry by exchanging information and regular discussions. People could check if the various stakeholders heard the same things, which provided the platform for a united approach. This reassurance process was essential in the early stages of the pandemic when the guidance rapidly changed, and stakeholders struggled to stay on top of the latest updates. Reichardt, Ulfarsson and Pétursdóttir (2018) touched on this point when investigating how the aviation industry struggled to stay on top of the latest information during the volcanic ash eruption in 2010. They concluded that *“while information is important in times of crisis, the amount of information and scattered sources of information can cause confusion and hinder efficient risk management. The multi-sector partnership would benefit from a designated single point of information during a crisis”* (Reichardt, Ulfarsson and Pétursdóttir, 2018, p.110). One of the solutions discussed in their paper is a website platform that the EACCC coordinates during a crisis.

The platform for discussion provided by the IRG/ODLG had an additional benefit. People felt comfortable sharing experiences, and the trusted environment generated a form of a venting system, leading to openly discussing issues.

The IRG/ODLG also facilitated the engagement between the industry with the government via the DfT. As initially described in the request for a teleconference on 4th February 2020, the DfT could hear first-hand about the situation at the sharp end. This operational feedback system is essential for resilience (Owen, Healey and Benn, 2013). As stated by the interviewees, the information shared through the IRG/ODLG forum eventually seemed to influence policymaking. The industry saw the IRG/ODLG as a perceived link to the ESG.

The interviewees saw the ESG as an exclusive government-led group, and the DfT managed the membership. The IRG/ODLG, on the other hand, was inclusive, and interested members could and did join throughout the pandemic. The direct dialogue between DfT and industry helped create situational awareness and help bridge the gap between sharp-end users and policymakers. This link supported the creation of domain knowledge for policymakers. According to Rankin, Dahlbäck and Lundberg (2013), the lack of domain knowledge can severely hamper the resilience of a system.

Furthermore, the discussions created a sense of urgency that specific actions needed to happen, which was perceived as beneficial by three interviewees.

4.5.8.6 Integration of the findings

The case study has highlighted that the potential for resilience was generated with *System Setup, System Checks*, *System Preparedness*, and *System Response* principles. The occurrences and conditions that led to a resilient operation were visualised in Figure 4-25. The figure highlights the content of each resilience theme and shows the connection between the themes. The outputs from sections 4.5.8.2 – 4.5.8.5 were used to refine the PRF by adding additional connections.

- Connection between *System Setup* and *System Response*
  Section4.5.8.2 demonstrated that the principles of *System is aware of interfaces with other systems* improved the potential for resilience generated through the *System Response* theme. The availability of the IRG/ODLG created relationships between air transportation stakeholders, which created a trusted environment. Furthermore, the cross-industry working group provided a platform for collaboration
- Connection between *System Checks* and *System Preparedness*
  In section 4.5.8.3, it is shown how the principles of *Identifying changes in the environment* in the *System Checks* theme led to actions taken in the *System Preparedness* theme through the principle of *Ability to anticipate bottlenecks*. The IRG/ODLG was used to share concerns over the situation

and development in Asia and how the development may impact the UK's borders and air transportation operations.

Figure 4-25 visualises how the findings from case study 5 were used to refine the PRF. The figure explains the content of each theme and highlights the connections between the themes, using practical examples.

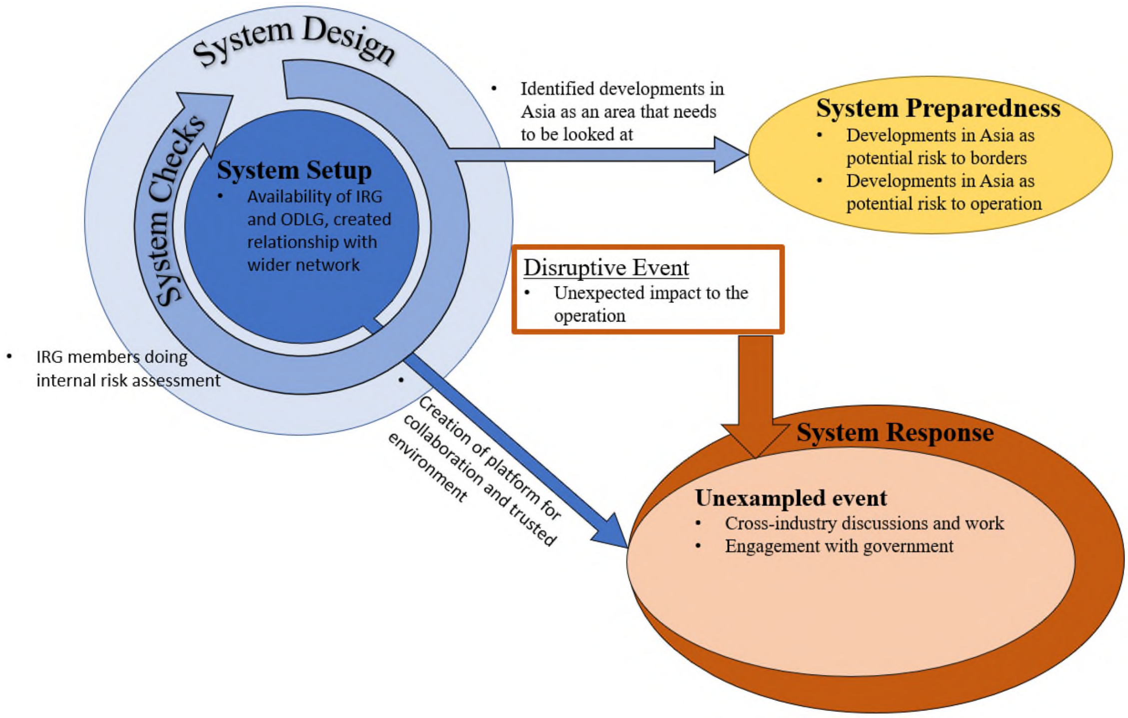


Figure 4-25 Integration of findings from case study 5

One explanation for the gap between *System Preparedness* and *System Response* theme and why the system was never really prepared for the crisis could be that people may have been biased by the events in 2003. In 2002 and 2003, Asia had to deal with the so-called Severe Acute Respiratory Syndrome (SARS) outbreak in Southern China in November 2002 (Chan-Yeung and Xu, 2003). However, the spread of the SARS in 2003 was contained in Asia and never significantly impacted the aviation industry in Europe.

During the interviews, some people reflected on the preparation *"and now I guess, could we or should we know it with what everybody knew what was going on in China? People know that the world is globally connected. Perhaps when you put two and two together, but I think it was very quick. Yeah, and I guess we* *looked at it now, and it happened again, we would be all worried a lot earlier*" (Participant 5412).

4.5.8.7 Potential for higher resilience

All interviewees mentioned that they benefited from having the IRG/ODLG during the COVID-19 pandemic. However, comments were also made about the additional potential and how the IRG/ODLG work could be improved.

Having a structure that supported the development of future construct could have put the IRG/ODLG in a more proactive outline that could have been used to inform the government about future concepts developed by the aviation industry (Naderpajouh et al., 2018). One country in which the aviation industry came together and collaboratively developed a 20-point concept paper in April 2020 for handling operations during COVID-19 was Germany. This concept paper was proposed to the German government as a foundation for a safe restart of aviation. The Bundesverband der Luftverkehrswirtschaft e.V. (BDL), a trade association for the entire German aviation industry, facilitated the discussions and development. The BDL provided facilitative leadership. Unlike the IRG/ODLG, it provided full-time staff members and a framework for the discussions with the industry and the development of the concept paper. All this information was collected during a 45-minute interview with a senior manager of the BDL.

One of the main remarks about the IRG/ODLG was the lack of structure and formalized processes, characteristics mentioned by Naderpajouh et al. (2018) for a successful governance structure. Interviewees highlighted that there were no minutes of meetings and no attendance record, which made it challenging to generate action points and follow up on them during the next meeting (e.g. Participant 5412). The role of the IRG/ODLG was not defined for crises, and without a clear structure, it was difficult to progress with actions and achieve something other than an open discussion (e.g. Participant 5412). Even though the DfT used the IRG/ODLG as an industry sounding board, the absence of formalized processes also meant no formal engagement. It took until 6th May 2020 for a formal governance structure to be shared with the industry. Therefore, stakeholders were unsure about their role in the response process and where they would fit in, and this caused concerns over the transparency of the response process.

Even after the ESG was set up, certain issues were still unresolved based on the interviewees' outputs. The interviewees felt that they were feeding a lot of information into the ESG but did not see much information coming back from the ESG. Owen, Healey, and Benn (2013) highlighted the importance of two-way communication and interviewees perceived that this link was missing during the COVID-19 crisis. The interviewees felt a disconnect between the IRG/ODLG, the ESG and the ESG sub-groups. This missing link meant that the industry did not feel consulted or being listened to and did not understand the responsibilities of each group. The industry members also felt upfront discussions would have ensured that guidelines and regulations were operationally possible. It would have also meant that the government had a chance to receive feedback from the industry.

Four interviewees highlighted that a formalized process right from the start would have benefitted the collaborative response from the UK aviation industry. The alignment between the IRG/ODLG and a government-led group in response to a national crisis could potentially be something that could be formalized to achieve a clear hierarchy and avoid confusion (Naderpajouh et al., 2018).

Some stakeholders shared in the interviews that they started as early as February with their internal preparations (e.g. Participant 3314). However, no coordination on a network level could be observed during all the attended meetings. Furthermore, airlines could not take out any capacity and downsize the operation proactively as the *USE IT OR LOSE IT* rule was still in place until March. The rule was flagged as a potential issue early on, but it took over six weeks until the framework was adjusted, and the airlines could cancel flights on a large scale because of COVID-19. It is difficult to conclude whether airlines would have taken out any capacity from their initiative to soften the decrease in traffic numbers and potentially slow down the spread of the virus. However, the fact is that airlines were not able to prepare for the sharp fall in traffic numbers without risking losing their slots for the following season.

4.5.9 Closing remarks

This case study benefitted from a rich and unique data set. The case study attempted to cover a complex situation and looked at the events in the UK aviation industry from January 2020 until June 2020 in an IRG/ODLG context. It was the first time the air transportation industry had to deal with a global pandemic. The case study focused on how the existence of a cross-industry working group benefitted the UK air transportation industry during the particular time frame. The research also looked at certain limitations of this group and highlighted further potential this working-group construct could explore. The findings from the case study showed some novel findings.

The case study showed how resilience can be generated through the *System Setup* and how the existence of the IRG/ODLG benefitted the industry during the *System Response* theme. Through the triangulation of data, using multiple interviews, meeting minutes and documents, it was possible to highlight the benefits the IRG/ODLG brought to the aviation industry during the *System Response* theme to cope with an unexampled event.

The IRG/ODLG also showed elements of *System Preparedness,* but the UK air transportation industry failed to prepare the system effectively for this crisis. The 80/20 rule also meant that the system did not have the flexibility to adjust proactively, but it is unclear if the airlines would have done it if the rule had not been in place.

Overall, the IRG/ODLG proved to be a beneficial concept that supported industry during the pandemic. However, the construct became less and less effective due to the lack of formal structure and processes as the crisis unfolded.

Even though various sources of information were used for this research, which generated a rich data set, the case study had some limitations. Observations by the researcher were only made for the IRG discussions, and the researcher had to rely on external meeting minutes from the ODLG meetings. However, it was impossible to determine the content between all the offline conversations and the government's direct involvement with the individual stakeholders.

Although the researcher interviewed twelve people from ten different organisations, this data set also had certain limitations. During the "*freefall*", people became extremely busy looking after the organisation's operation and were not available for interviews. The interviews were conducted between 23rd July 2020 and 12th August 2021. Due to the significant time delay, it is arguable whether the participants remembered all of the details or were affected by the hindsight bias (Hawkins and Hastie, 1990).

The research attempted to look at similar events in the past. However, due to the unprecedented impact on the aviation operation in Europe, it was impossible to look at comparable data. Therefore, comparing the study results directly with a similar event in the past was not feasible.

Finally, the case study did not investigate elements of *System Changes*. Although longitudinal data were used, the research did not investigate if changes in the governance structure occurred after the "*freefall*" period and if learning had been implemented for the next lockdown period in December 2020. However, this was not the focus of this research. Further research would be advisable to determine if learning to handle traffic during lockdowns occurred over the summer of 2020 to prepare for the following winter.

More research is necessary to investigate more elements of the UK air transportation industry response to the COVID-19 pandemic and compare the response to other countries to determine the actual value the IRG/ODLG has brought to the UK aviation industry.

5 DISCUSSION

The discussion chapter draws on collected evidence and aims to answer the last objective from chapter 1, which was conducting a synthesis across multiple case studies to refine the basic framework and develop an ICRF that explains resilience in the UK air transportation system context. The following section's goal is to combine the various findings from the case studies and enhance the framework developed from the literature (see Figure 2-15).

Furthermore, the discussion chapter defines a way forward in resilience research and what benefits the developed ICRF can provide to practitioners. The discussion chapter concludes with the limitations of the research and recommendations for additional work.

5.1 Introduction

The research goal was to analyse the RE literature and use examples from the UK air transportation industry to identify how the concept can be operationalised. The literature reviews highlighted that there is not a one-size-fits-all definition of resilience. Resilience has been interpreted differently, leading to a blurred vision of resilience. As a result, Son et al. (2020, page not identified) identified that in previous reviews, *"limited attention to documenting constituent dimensions of resilience ('what makes a system resilient?')"* was given.

Therefore, one of the research objectives was to propose a conceptual framework that outlines what makes a system resilient and how resilience can be operationalised. The developed ICRF aims to bring order to the RE literature and show that the sometimes-contrasting views on resilience are related and can be combined in a framework. The research also followed Pettersen's and Schulman's (2019) suggestion for clarification of the concept of resilience and moving away from an abstract level. Instead, the concept should be "*analytically differentiated into formal types each of which should be understood empirically in relation to specific organizational functions and requirements*" (Pettersen and Schulman, 2019, p.467)

In order to structure the RE literature, a PRF was proposed in the literature review (see Figure 2-15.). The PRF was then applied to the UK air transportation system to investigate the resilience of this particular industry. Multiple case studies were conducted, and the research used a synthesis across the case studies to collate evidence that helped develop the ICRF.

Furthermore, the output from the case studies added more details to each of the proposed resilience themes of the framework. By highlighting specific connections between the themes, it was possible to merge the outputs and develop the ICRF.

5.2 Rationale for Integrated Conceptual Resilience Framework

One of the best examples from the case studies highlighting the need for a holistic view of resilience was collected during the second case study (see subchapter 4.2). The primary driver for the formation of the IRG was enhancing the resilience of the day-to-day operation of the UK air transportation system. The discussions were mainly driven by optimizing the performance of a system, and the parameter the stakeholders were most concerned about was the delay minutes of the system (CAA, 2017b). However, delay minutes became irrelevant during COVID-19 (subchapter 4.5) as the system's utilisation percentage dropped to single digits during the pandemic's peak. Discussions were mainly about regaining a stable state and recovering some of the traffic. Dealing with such a dramatic situation indicates that a different kind of resilience was required, one that could not be measured by delay minutes.

The word resilience was used in both a highly utilised system and for the operation with low traffic numbers during COVID-19. Using the term resilience in such extreme situations raises the question of whether a system can be resilient towards one event but not another. Westrum (2006, p.65) answered the question by saying that "*a resilient organization under Situation I will not necessarily be resilient under Situation III*". Therefore, this research takes a holistic view and outlines a framework that allows a system to maximise the potential for resilience in any situation.

The UK air transportation system can be seen as a well-oiled system that works well during normal operations. The system is driven and maintained by processes and seasonal planning cycles. However, the system struggles to cope with disruptions that would fall out of its usual performance envelope. Examples of this claim were the volcanic ash eruption in 2010 (Reichardt, Ulfarsson and Pétursdóttir, 2018) or case study 5 (see subchapter 4.5). The developed ICRF accounts for different events by integrating Westrum’s (2006) classification of regular and irregular threats and unexampled events. The ICRF highlights the need for a system to respond to all three situations to be truly resilient. Responding to various disruptions leads to the proposition that resilience can be generated through the *System Response* theme. The developed framework visualises how the scope of the resilience of a system can be extended.

As highlighted by Dinh et al. (2012) and seen in all case studies, the potential for resilience can also be generated in the *System Setup* theme. Subchapter 4.1 showed that the setup of the operation and definition of the buffer capacity and safety margins directly affect the system’s resilience. Review processes in the *System Check* theme to ensure these defined safety margins are maintained over time (subchapter 4.1). Furthermore, the *System Preparedness* and *System Changes* themes are ways to improve the system’s resilience.

As shown in the SLR (see chapter 2), resilience is indeed a novel and valuable concept. Another significant finding of the literature review was the conclusion that various views on resilience exist. Authors in the RE had already attempted to develop a framework for RE. Madni’s and Jackson’s (2009) is, with 310 citations, a highly-cited framework in the resilience literature. Their framework links the variables of *System Attributes*, *Methods*, *Disruptions*, and *Metrics* with *System Resilience*. The framework operates at a high level and shows some connections between the variables. For example, Madni and Jackson (2009) argue that *System Attributes*, such as organisational infrastructure, system performance, or system breakdown structure, enable *System Resilience*. *System Resilience* is also associated with *Methods* that include proactive risk management and safety/schedule trade-offs. *Metrics* can be used to measure

System Resilience. *Metrics* examples are time/cost to restore operation, potential disruptions circumvented, or successful adaptations within time and cost constraints. In their framework, *System Resilience* is affected by disruptions (e.g. natural/man-made or short-lived/enduring), and disruptions affect *System Attributes*. However, one major limitation is that the framework does not show how the concept of resilience can be operationalised during various stages of the operation. The four faces were avoid (anticipation), withstand (Absorption), adapt to (Reconfiguration), and recover from (Restoration). The four faces share some overlaps with the four themes of resilience identified in the literature review.

However, similar to the PRF of the SLR in subchapter 2.2 (see Figure 2-15), Madni's and Jackson's (2009) figure of the four faces failed to identify the links between the faces and how the faces may interrelate. Therefore, this was taken as the rationale to develop the ICRF and highlight the connections between the themes.

5.3 Development of ICRF

The outputs from the literature review in chapter 2 indicated that resilience could be generated through four themes, and some of the themes were divided into subthemes. For each of the (sub-)themes, 26 high-level principles were defined that support a system to generate resilience, as shown in Table 5-1.

Table 5-1 Summary of all 26 high-level principles

System Design

System Setup

- Buffer capacity is incorporated
- Built-in redundancies
- Sufficient resources are available to monitor operation
- System is aware of interfaces with other systems
- System is aware of bottlenecks and critical parts of the operation
- Error-tolerant design
- Flexible mode of operation

System Checks

- Recognizing adaptations in operation and drift correction
- Identifying changes in environment
- Recognizing changing risks to operation

System Changes

- Creation of lesson learning
- Anticipation of future challenges
- Safe integration of long-term changes

System Preparedness

- Ability to anticipate bottlenecks
- Preparing operation for expected disturbance
- Temporarily increasing buffer capacity

System Response

System Robustness

- Early detection of disturbance
- Ability to minimise and contain failure
- Use of internal buffer capacity
- Use of redundancies

System Rebound

- Use of additional resources
- Restoring functions and repair rate/Rapidity
- Governance structure for coordination and communication
- Agile adjustments

System Extensibility

- Ability to avoid overload by shifting to emergency configuration
- Ability to restore critical linkages between systems

The goal of investigating five cases was to identify empirical examples of the high-level principles and, more importantly, establish connections between the different (sub-)themes. The COVID-19 pandemic has limited the option for suitable cases, and the five cases were selected on the criteria described in subchapter 3.5. The cases provided numerous practical examples of operationalising the identified high-level principles. Empirical pieces of evidence for 19 out of the 26 high-level principles were identified by studying the five cases.

Although each case considered a different system as the unit of analysis, it was demonstrated how the operationalisation of high-level principles affects other themes, establishing connections between them. Therefore, it may be possible to generalise the outputs of each case study and merge all the findings to develop an ICRF.

The basic structure of the PRF (see Figure 2-15) was used. A synthesis of all the findings of the various cases was conducted. Figure 5-1 explains the process of merging the PRF with the findings of the five cases to develop the ICRF.

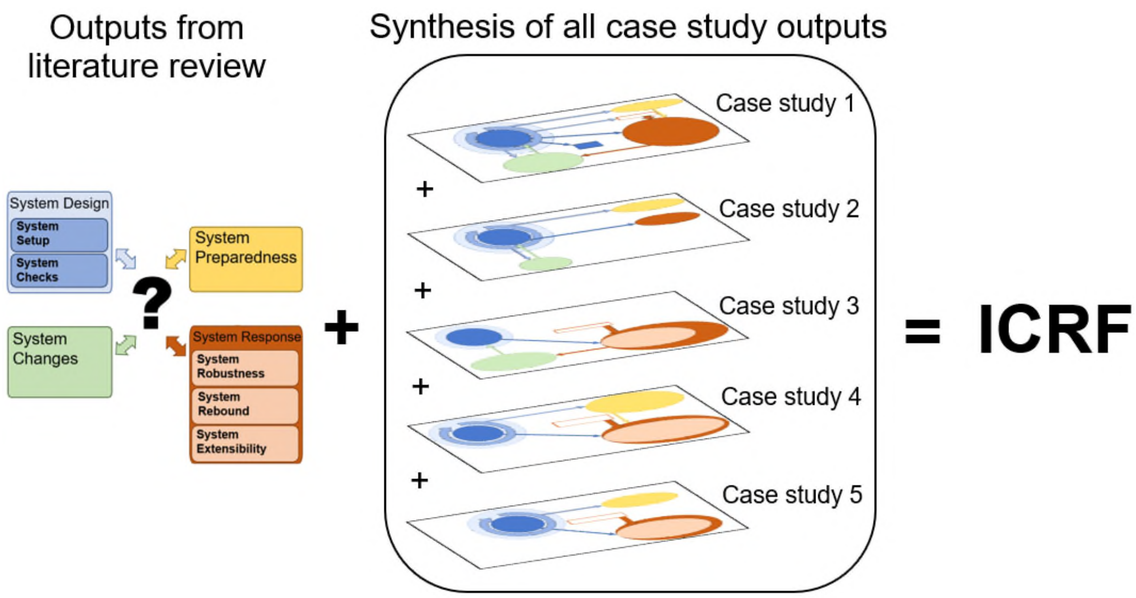


Figure 5-1 Methodology for development of ICRF

5.3.1 Synthesis of case study findings

This section explains the process of generalising the outputs of the case studies and establishing connections between the (sub-)themes.

5.3.1.1 System Setup

As shown in Table 5-2, empirical evidence for six principles was found in the case studies. The table also shows how the operationalised principles added connections to the PRF.

Table 5-2 Outputs relevant to the System Setup theme

Case study	Observed high-level principle	Added connections
1 & 2	Buffer capacity is incorporated	Decreases likelihood of internal disruptions
1 & 4	Sufficient resources available to monitor operation	Input into System Checks
1 & 3	Buffer capacity is incorporated	Input into System Response
1, 2, 4 & 5	System is aware of interfaces with other systems	Input into System Response
1	Build-in redundancies	Input into System Response
1 & 4	Flexible mode of operation	Input into System Response

All five case studies found evidence that the *System Setup* theme contributes to the resilience of a system.

Case studies 1 and 2 provided practical examples that sufficient safety margin by incorporating buffer capacity can decrease the likelihood of internal disruptions. It was concluded that a sufficient safety margin in operation improves the potential of resilience by minimising the likelihood of internal disruptions. Therefore, the connection between *System Setup* and *Disruptive Event* was added with the description: *Increases reliability and minimises likelihood of internal disruptions.*

Case studies 1 and 4 gave practical examples of how sufficient resources to monitor the operation improved the level of resilience. The allocated resources became helpful in the *System Checks* theme as the system could identify internal and external changes to the operation.

Another principle concerned the connection between *System Setup* and *System Response*. Case studies 1 and 3 showed that buffer capacity incorporated in the system's operation was used during the *System Response*, adding another connection to the framework. Awareness of the system of interfaces with other systems proved essential in achieving resilience, as highlighted in case studies 1, 2, 4, and 5. The interaction between (sub-)systems created a situational awareness (e.g. case study 2) and trust (e.g. case study 5) among stakeholders, which improved the performance during the *System Response* theme. Furthermore, built-in redundancies and defining flexible modes of operations in the System Setup increased the level of resilience generated in the *System Response* theme. These examples emphasised the connection between the *System Setup* and *System Response* theme in the ICRF. The connection between System Setup and *System Response* was generalized as *Defines back-up strategies and governance structure*.

5.3.1.2 System Checks

Table 5-3 summarizes which high-level principles were observed in the various case studies and how the findings influenced the development of the ICRF. The five case studies found practical examples for two of the three identified principles.

Table 5-3 Outputs relevant to the System Checks theme

Case study	Observed high-level principle	Added connections
1, 2 & 4	Recognizing changing risks to operation	Input into System Setup (case study 1), System Preparedness (case study 1 & 2 & 4), and System Changes (Case study 1 & 2)
5	Identify changes in environment	Input into System Preparedness

Empirical evidence in case studies 1, 2, and 4 showed how essential the recognition of changing risks to the operation was in achieving the system's resilience. NATS' systematic review process of the maximum sector capacity (see case study 1) aimed to identify early indications of risks and mitigate them immediately. In this example, the *System Checks* updated the *System Setup* by adjusting the maximum sector capacity. The close link between *System Setup* and *System Checks* is visualised in the ICRF by the fact that the *System Checks* theme surrounds the *System Setup* theme to ensure that the defined safety margin does not erode over time.

In addition, in case studies 1, 2 and 4, the outputs from the *System Checks* were used to operationalise principles of the *System Preparedness* theme. The recognition that the COVID-19 repatriation flight (see case study 4) triggered proactive actions in the *System Preparedness* theme highlighted the connection between the two themes. Therefore, the connection between the *System Checks* and *System Preparedness* was added, and a general description was added (*Identifies changes that may lead to short-term disruptions*).

A third connection, leaving from the *System Checks* theme, was made to the *System Changes*. The establishment of ACOG (see case study 1) and IRG (see case study 2) highlighted how outputs from the *System Checks* theme led to the generation of resilience in the *System Changes* theme. In both examples constraining factors in the operation were identified that informed the development of plans in the *System Changes* theme. Hence, the connection between the two themes was named: *Identifies constraining factors that may require long-term changes*.

Case study 5 mentioned that the IRG noticed environmental changes as the virus spread in Asia. The development was first not seen as an immediate risk to the operation, but outputs from the operationalised principle were used for actions in the *System Preparedness* theme (see section 4.5.8.4). This example re-emphasised the connection between the *System Checks* and *System Preparedness* theme.

5.3.1.3 System Preparedness

All of the three in the literature review identified principles were observed in the case studies. Table 5-4 shows in which of the case studies the operationalised principle was identified and what connection was added based on the findings of the case studies.

Table 5-4 Outputs relevant to the System Preparedness theme

Case study	Observed high-level principle	Added connections
1, 2, 4 & 5	Ability to anticipate bottlenecks	Input into System Response (not in case study 2 & case study 5), Output from System Checks
1 & 4	Preparing operation for expected disturbance	Input into System Response/ Output from System Checks
4	Temporarily increasing buffer capacity	Input into System Response

Practical examples of the principle that describes the ability to anticipate bottlenecks were found in case studies 1, 2, 4, and 5. All of the examples relied on outputs generated from the *System Checks* theme. The IRG did not have a process to use the outputs from the *System Preparedness* theme to prepare the operation for expected bottlenecks, which is different from what was observed in case studies 1 and 4. Case study 4 showed how the airport anticipated bottlenecks and used the knowledge to temporarily increase the buffer capacity to be in a better position to mitigate the expected additional demand.

Proactively issuing flow restrictions (see case study 1) or stepping up the IMC (see case study 4) are examples of how the operation was prepared for the expected demand. Those measurements ensured the system was put in a state of alertness for the expected disturbance in the *System Preparedness* theme.

Due to findings from case studies 1 and 4, the connection between the *System Preparedness* and *System Response* theme was added. This connection is crucial for maximising the resilience potential, and a missing connection may compromise the system's resilience. *Prepares system for expected short-term disruption* was the label that was added to the link between the two themes.

5.3.1.4 System Response

The case studies identified several practical applications of the identified principles of the various subthemes. Table 5-5 outlines how the findings from the case studies influenced the development of the ICRF.

Table 5-5 Outputs relevant to the System Response theme

Case study	Observed high-level principle	Added connections
3	Early detection of disruption	–
1 & 3	Use of internal buffer capacity	Output from System Setup
1	Use of redundancies	Output from System Setup
1 & 4, 5	Governance structure for coordination and communication	Output from System Setup
4	Use of additional resources	Output from System Preparedness
4	Agile adjustments	–

As mentioned in the literature review (see subchapter 2.2), the *System Response* theme is divided into *System Robustness*, *System Rebound*, and *System Extensibility* subthemes. The subthemes follow Westrum's (2006) classification of regular threat, irregular threat, and unexampled event. Those three categories describe different magnitudes of events, and an arrow was added to the ICRF to visualise the escalation level.

Case study 3 specifically looked at an incident that would fall in the category of a regular threat, therefore describing an event in the *System Robustness* subtheme. Results showed how the principles of early detection of the disruption helped mitigate the event. No connection with any of the other themes could be determined based on this principle. However, a second principle, the use of internal buffer capacity, was identified in the same case study. The analysis showed that this buffer was available due to decisions taken in the *System Setup* theme (e.g. combination of standby slots at airports). This case reinforced the connection between the *System Setup* and *System Response* theme.

A response to an irregular threat was investigated in the fourth case. The event indicated how the principle of using additional resources prevented an overload of the system and helped keep the operation within the functional limits. The additional resources mainly became available due to actions taken in the *System Preparedness* theme, highlighting the importance of connecting the *System Preparedness* and *System Response* theme. A predefined governance structure supported the coordination and communication during the event. The *System*

Setup defined the governance structure, showing the link between the two themes. A third principle, agile adjustments, was also observed in case study 4. However, investigating the case could not determine any connection with other themes of the ICRF. Case study 5 looked at the role of the IRG/ODLG during the COVID-19 case study, which falls into the *System Extensibility* subtheme. The analysis identified that the governance structure, although not contractually agreed, provided a platform for information exchange in the *System Response* theme. The case study also highlighted the connection between the *System Setup* and the *System Response* theme as the coordination benefitted from the awareness of interfaces between the systems. Although case study 1 did not specifically look at a disruptive event, an additional principle from the *System Response* theme could be identified. Standby facilities at other control centres were considered an empirical example of the principle that describes the use of redundancies. Redundancies are established in the *System Setup* theme. Hence, it is another example of the link between *System Setup* and *System Response*.

5.3.1.5 System Changes

Examples for all of the *System Changes* principles were found in the case studies. Based on the findings from the case studies, new links between the themes could be established (see Table 5-6).

Table 5-6 Outputs relevant to the System Changes theme

Case study	Observed high-level principle	Added connections
1 & 2	Anticipation of future challenges	Outputs from System Checks
1 & 3	Creation of lesson learning	Output from System Response
1, 2 & 3	Safe integration of long-term changes	Input into System Setup

The case studies have demonstrated that the generation of resilience in the *System Changes* theme can be achieved reactively and proactively. Therefore, the ICRF splits the *System Changes* theme into a *Proactive* and *Reactive* element. With the formation of ACOG (see case study 1) and IRG (see case study 2), practical examples for the principle of anticipating future challenges were identified. The operationalisation of this principle was achieved proactively, using outputs from the *System Checks* theme. On the other hand, case study 1 and case study 3 showed how the *System Changes* theme could be achieved reactively, following a disruption, based on outputs from the *System Response* theme through the creation of lesson learning. In case study 3, it was shown how previous mass diversion events highlighted the need for better management of these events, which resulted in the collaborative work of a mass diversion protocol. Therefore, the *System Response* theme connects with the *System Changes* theme. This connection was visualised by adding an arrow between the two themes to the ICRF with the label *Provides material for identifying lesson learnings*.

As mentioned in the literature review, long-term changes must be created safely (du Plessis and Vandeskog, 2020). Case studies 1, 2, and 3 provided empirical data that showed how this principle could be operationalised. The work of ACOG (case study 1) is to determine trade-offs of changes to the airspace infrastructure and assess potential side effects. This example indicates how the potential can be achieved through the *System Changes* theme as changes are assessed before they are implemented in the *System Setup*. As a result of these examples, a link with the description *Safely updates the setup of the operation* was added between the *System Changes* and *System Setup* theme.

5.4 Description of ICRF

As mentioned in the previous section, the ICRF is a combination of the findings of the SLR and a synthesis of the outputs from the case studies. The case studies' outputs were generalised, adding more information to each proposed resilience theme. Furthermore, the outputs also enhanced the understanding of the connection between the themes and how the themes interrelate.

The ICRF explains the concept of resilience in an UK air transportation industry context. The ICRF comprises four main resilience-generating themes: *System Design*, *System Preparedness*, *System Response*, and *System Changes*. Figure 5-2 displays the proposed ICRF, and each element is explained in a separate section. In order to avoid a repetition of subchapter 2.2, only the main principles of each theme are mentioned.

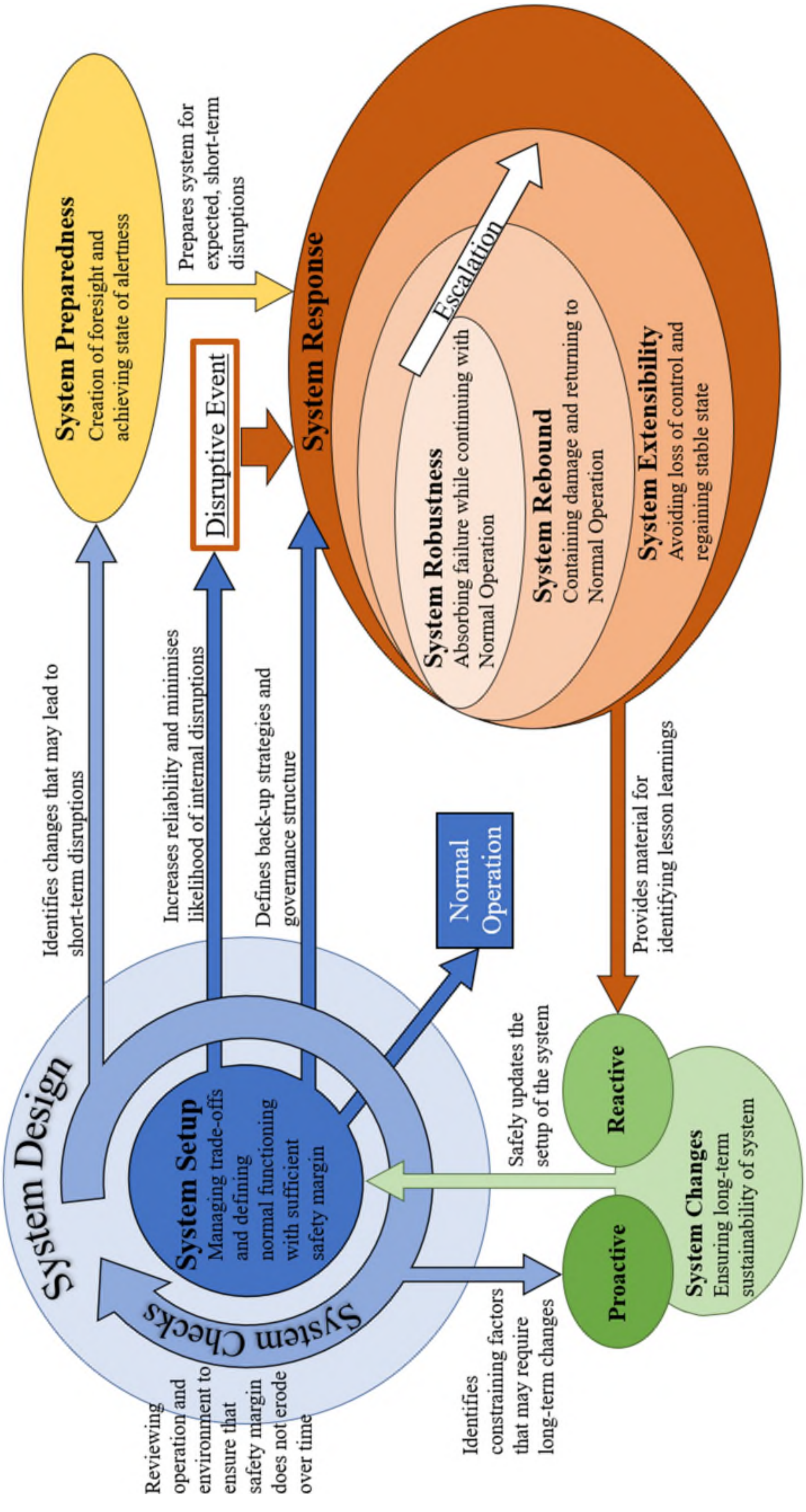


Figure 5-2 The Integrated Conceptual Resilience Framework

5.4.1 System Design

The design of a system influences the system's resilience. The *System Design* theme consists of the *System Setup* and the *System Checks* subthemes.

5.4.1.1 System Setup

Maximising the potential for resilience heavily depends on the setup of the operation and how the resources are allocated to define the normal functioning. The *System Setup* deals with trade-offs as the system has limited resources available (Hoffman and Woods, 2011). Therefore, as Woods et al. (1994) argued, a system needs to have a mechanism integrated that allows it to balance multiple goals and make trade-offs. Woods and Hollnagel (2006) suggested that a resilient system takes safety as a core value. However, safety may compete with other system goals, which creates trade-offs. One example of these trade-offs was found in case study 2 (see subchapter 4.2) and how the IRG defined delay minutes as a trade-off between higher costs and more flights (see Figure 4-13). One model that helped to explain these trade-off challenges is the one by Rasmussen (1997). The space-of-possibilities from Rasmussen's (1997) model (see Figure 2-8) provided a visualisation of the trade-offs between efficiency and safety in a system. The *System Setup* defines the *Normal Operation* of a system, which is shown by the arrow between *System Setup* and *Normal Operation*. The *Normal Operation* describes a baseline performance that the system is trying to achieve during the day-to-day operation. Once the normal functioning with its safety margin is defined, a system needs to have sufficient resources to monitor the operation (Hollnagel, 2009a).

NATS' sector capacity in case study 1 (see subchapter 4.1) is an example of how resilience can be built into a system by leaving sufficient buffer capacity to mitigate minor variations without compromising the normal operation. Redundancies also offer a way to improve the potential for resilience. NATS standby capabilities at each centre are a practical application of how the concept of redundancy can be operationalised (see 4.1). Using barriers is also a way to safeguard the operation (Hollnagel, 2014b). The standby capabilities are also examples of how the *System Setup* defines backup strategies for handling a disruption. This relationship is shown by the connection between the *System Setup* and *System Response* theme. Furthermore, during the risk assessment, a system also defines some of the plans and procedures for disruption management. Defining a governance structure and a command and control framework in the *System Setup* that could be stepped up during the response to disturbances has also been proven helpful in case study 4 (see subchapter 4.4), providing a flexible mode of operation.

The term RE was first used by Woods (2003) as a way to engineer resilience into complex socio-technical systems and manage the safety of these systems. By having multiple components and actors in a system, new safety challenges arise; therefore, the link between cause and effect is not always visible (Hasan, Chatwin and Sayed, 2020). A system needs to be aware of interfaces between parts of the operations and how they may influence each other. Case study 2 (see subsection 4.2) and the formation of the IRG is an example of how the UK aviation industry tackled the challenge of creating better situational awareness. By creating a platform for collaboration, stakeholders were encouraged to come together, build new and strengthened relationships with the broader network, improve the interfaces, and enhance the system's resilience. Hollnagel's (2012) FRAM or Leveson's (2004) STAMP offered techniques to visualise underlying connections or interdependencies and how variables in a system can lead to different outcomes. Those techniques can also help a system identify bottlenecks and critical parts of the operation, improving the awareness of the system (Westrum, 2006)

5.4.1.2 System Checks

The drive for more efficiency and utilising every available resource could compromise the system's safety (Patterson and Wears, 2015). In order to maintain a resilient operation, Tjorhom and Aase (2011) argued that safety goals need a higher priority over production goals. Therefore, *System Checks* should review the operation and ensure that the safety margin does not erode over time. A practical application of Qureshi, Ashraf, and Amer (2007, p.1889) interpretation of RE as the "*ability of organizations, groups and individuals to anticipate* *changing shape of risk before failures and harm occurs*" is NATS SPWG meetings for reviewing the sector capacity in case study 1 (see subchapter 4.1). Regularly assessing whether the sector load needs to be adjusted is a sign that NATS is aware that the operation or environment could change, requiring an adjustment in the operation. This review process is a strong indication of monitoring, one of Hollnagel's (2009a) four cornerstones. NATS' PERL process from the same case study fell into a similar category and showed how a constant review process keeps the system safe and supports the system with dynamic trade-off decisions.

Dekker (2006) argued that small changes in the operation could be slow and potentially occur unnoticed by the system. Regular audits support the system to make changes in the operation and environment visible. This system's ability is related to awareness and opacity (Wreathall, 2006). The goal is to avoid becoming brittle by leaving sufficient buffer capacity in the system in order to be able to deal with internal and external variations in performance. In case study 2 (see subchapter 4.2), the CAA audited the capacity at the busiest airports in the UK and recognized that the high runway utilisation at most airports has eroded the safety capacity and change was needed. This example showed that a system needs to be regularly monitored to maintain the level of resilience (Woods and Hollnagel, 2006). Woods and Cook (2006, p.72) argued "*one part of assessing a system's resilience is whether that system knows if it is operating near boundary conditions*". Therefore, *System Checks* surround the *System Setup* to ensure that the operation is kept within the safe boundaries of the system.

NATS monitoring of the sector load and workload of the ATCO in case study 1 (see subchapter 4.1) is a practical example of how *System Checks* can be operationalised. Once the workload exceeds a certain threshold, mitigation strategies such as sector splitting or flow restrictions are implemented. This active monitoring keeps the operation within the system's boundaries and recognizes changing risks to the operation.

Constantly checking that the system stays within its boundaries and monitoring the environment can also bring the following benefit. By recognizing environmental changes, the system can pick up early indications, foresee short-term disruptions, and prepare for these events through the *System Preparedness* theme. The ICRF captures this process by connecting *System Checks* and *System Preparedness*.

System Checks may not only foresee short-term disruptions but can also help to anticipate future challenges. A changing environment could mean that the system needs to change in the long term, causing significant changes to how a system operates. This interrelation is visualised by the connection between *System Checks* and *System Changes*. These sustained adaptabilities are explained in section 5.4.4.

5.4.2 System Preparedness

As mentioned in the previous section, outputs from the *System Checks* can be used to foresee short-term disruption and opportunities. The goal is to create foresight and achieve a state of alertness. Anticipation is one of Hollnagel's (2009a) four cornerstones, and short-term disruptions or bottlenecks do not require a permanent operational adjustment. Instead, close monitoring of the operation and environment allows the system to transition into a state of alertness and maybe momentarily increase the buffer capacity (Nemeth, 2019) and prevent the system from becoming brittle. As visualised by the connection between *System Preparedness* and *System Response* in Figure 5-2, the outputs from the *System Preparedness* theme prepare the system for expected short-term disruptions and opportunities. These preparations help maximise the potential for resilience that can be generated in the *System Response* theme. The concept *System Preparedness* can predominately be used for known and expected events.

Case study 1 (see subchapter 4.1) provided a practical example of how *System Preparedness* can be used to increase the potential for the system's resilience. NATS develops a seasonal outlook at the beginning of each year and list all the main events that add stress to the system. By being aware of the expected additional workload, the planning department can develop mitigation strategies and opt to split sectors or proactively add ATCOs to the operation.

Another example was given in case study 2 (see subchapter 4.2). The Met Office used the IRG channels to give weather updates to the IRG members and inform the stakeholders about volcanic activities. Woods (2011) described compromising the performance of a system as a mitigation option for identified and anticipated bottlenecks. Pre-tactical cancellation of flights is a practical example of how a system can transition into a state of reduced functioning (Hollnagel and Sundström, 2006). However, sacrifice decision-making may be required to generate resilience through the *System Preparedness* theme.

The IRG also picked up early indications for the COVID-19 pandemic in case study 5 (see subchapter 4.5). The 80/20 rule was immediately flagged as a matter of concern, and the engagement with PHE was started to provide regular updates to the UK aviation industry. However, as concluded in section 4.5.8, there was a missing link between the *System Preparedness* and *System Response* theme as the system has never been prepared for what happened in March 2020.

One example of where the connection between *System Checks* and *System Preparedness*, and *System Preparedness* and *System Response* worked was given in case study 4 (see subchapter 4.4). During the preparation of regular updates on the arrival of the repatriation flight, specific problems and challenges were anticipated. Early indications, such as the older demographic being transported on a freighter aircraft, were translated into safety hazards, and needing more emergency resources. The phenomenon of overreaction was observed in this case study, which significantly increased the buffer capacity of the system (Woods, 2011). The benefit of constantly revising the plans and sharing the latest updates with the other stakeholders to increase the situational awareness of everyone involved was also demonstrated.

5.4.3 System Response

The *System Design* and *System Preparedness* theme describe actions and conditions that generate resilience through the prevention of or preparation for disruption. In contrast, *System Response* describes a reactive theme that generates resilience by responding appropriately to disruptions. However, the generation of resilience in the *System Response* theme also relies on the *System*

Setup, as shown in the ICRF. The backup governance for dealing with disruptions and the backup strategies, such as buffer capacities and redundancies, can be defined in the *System Setup* theme.

The *System Response* theme uses these resources to handle a variety of disruptions. The disruptions can vary in frequency and magnitude. The *System Response* theme is divided into three subthemes. *System Robustness*, *System Rebound*, and *System Extensibility* are used to describe responses to Westrum's (2006) classification of regular threat, irregular threat, and unexampled event, respectively.

5.4.3.1 System Robustness

One of Woods' (2015) four resilience concepts was using robustness as a synonym for resilience. The concept of robustness extended the system's capability to absorb disruptions without leaving the functional limits (Miller and Xiao, 2007). The system's goal is to keep the operation within the system's functional limits while continuing with the normal operation.

Case study 3 demonstrated that early detection of disturbances helped enhance the response process. Build-in redundancies, providing barriers to stabilize the system, developing mitigation procedures, or use of internal buffer capacity are ways to improve the system's robustness (Woods, 2011).

The example investigating this part of the ICRF is case study 3 (see subchapter 4.3). Plan 39 showcased how the UK air transportation system improved its resilience by increasing the buffer capacity of the system. All the slack resources of the individual airports were collected and combined in a structured mass diversion protocol. This efficient use of internal buffer capacity increased the system's resilience as the ability to absorb disruption was increased. Clear procedures, communication lines and a governance structure enhanced situational awareness and supported the UK air transportation system during the event (e.g. see case study 4).

5.4.3.2 System Rebound

Unlike in the *System Robustness* theme, the system's performance in the *System Rebound* theme is significantly affected. The system's goal is to contain the damage and restore the operation (Shiraki et al., 2017). The objective of the system changes to mitigating the damage and returning to normal operation. This capability is frequently referred to as the ability to bounce back (Woods, 2015). The event falls outside the design envelope of the system, and there are no detailed procedures that help to mitigate the disruption and return to normal operation.

An example of such a case was described in case study 4 (see subchapter 4.4), which investigated a repatriation flight during the COVID-19 pandemic. Handling the flight that brought back passengers from a cruise ship with COVID-19-infected people onboard represented an irregular threat (Westrum, 2006). The *System Preparedness* theme helped put the system in a state of alertness. The airport benefitted from additional resources for handling the unusual situation (Madni and Jackson, 2009). Early engagement with the LFR and the CPHMO prevented the situation from spinning out of control. The CPHMO also provided the necessary expertise and domain knowledge to handle the challenges associated with the nature of the repatriation flight. Agile adjustments made during the response also supported the successful outcome (Lundberg and Rankin, 2014).

One crucial element for the successful outcome of the event was the availability of a clear command and control structure, as it allowed the airport to have clear lines of communication with other supporting stakeholders and coordinate the response. This response structure became significantly important when new developments in the situation required a swift response and coordination of the involved stakeholders. With the necessary domain knowledge and organisational response structure, the airport could dampen the effects of the event and quickly return to normal operation (Rankin, Dahlbäck and Lundberg, 2013).

5.4.3.3 System Extensibility

Certain events seem so unlikely to happen or lie beyond what people think is possible that these events or the effect of the events come as a surprise. During such events, the boundaries of the system are severely challenged, and the system is pushed towards failure (Cook and Rasmussen, 2005). Woods (2015) referred to the system's capability as the concept of extensibility. The goal is to avoid a loss of control and regain a stable state. The system tries to avoid brittleness and escape failure by taking on additional resources, severely compromising the operation or reconfiguration. Hollnagel and Sundström (2006) described this situation as the disturbed functioning in their Resilience State Space model (see Figure 2-10).

Elements of *System Robustness* and *System Rebound* also support the system in a situation that requires resilience through the *System Extensibility* theme. However, instead of trying to return to normal operation, the immediate focus of the system is on not losing control over the situation and regaining a stable state. The system may run a skeleton operation to provide essential services. After compensating for the initial shock, the system slowly develops an exit strategy. Mendonça and Wallace (2015) also mentioned that in the event of this magnitude, it is essential to restore critical linkages of the system.

COVID-19 provided an environment in which the *System Extensibility* theme features took place. Case study 5 (see subchapter 4.5) captured some of these elements. The IRG provided a platform for collaboration and information exchange to the UK aviation industry. A forum where stakeholders could come together, share, and check certain information proved helpful. Knowing a more comprehensive network and adding additional information can be beneficial during extreme events (Miller, 2011).

Furthermore, the IRG supported the engagement between government and industry. This link helped bridge the knowledge gap and bring policymakers and experiences from sharp users closer together. Reichardt, Ulfarsson, and Pétursdóttir (2018) highlighted the importance of a crisis management infrastructure in a multi-sector partnership.

5.4.4 System Changes

The drive to achieve a resilient system in the long term defines the concept of *System Changes*. The *System Changes* theme aims to ensure the system's long-term sustainability.

The *System Changes* themes deal with the development of fundamental changes. This system update is visualised in the ICRF by connecting *System Changes* and *System Setup*. These changes must be evaluated before they are implemented, as they may contain unintended consequences at a different part of the system or generate new risks (du Plessis and Vandeskog, 2020). As a result, achieving resilience through *System Changes* requires extensive knowledge about the system and its interfaces and how changes may affect these. The potential for resilience in the *System Changes* theme can be generated reactively and proactively, and the ICRF split the theme into *Reactive* and *Proactive System Changes*.

5.4.4.1 Reactive System Change

The connection between the *System Response* and *Reactive System Change* theme highlights that output from the *System Response* theme can generate potential in the *Reactive System Change*.

Analysing incidents may lead to lessons being learned, and Gajek (2019) pointed out the need for learning to foster resilience. Learning was also highlighted by Hollnagel (2009a) as one of the four cornerstones of resilience. Instead of using the concept of resilience to *bounce back* to normal operations, the aim is to *bounce forward* and be better prepared for similar future disruptions (Nagenborg, 2019). Furthermore, reviewing accidents allows a system to identify and mitigate uncertainties in the operation (Yazdi et al., 2019). It is also important to mention that "*learning from the experience of others is sacrosanct for continuous improvement*" (Yazdi et al., 2019, p.1532).

A practical example of the *Reactive System Change* theme was given in case study 3 (see subchapter 4.3). Fuel emergencies of multiple flights during past mass diversion events led to the realisation that a more structured approach for handling similar events in the future was required. The so-called Plan 39 was developed and shared across the network to better prepare for similar disruptions. The first enactment of the developed protocol proved a successful implementation with no recorded fuel emergencies (NATS, 2019c).

5.4.4.2 Proactive System Change

Another option for ensuring long-term sustainability is proactively implementing permanent changes to the system (Burbidge, 2018). The connection between the *System Checks* and *Proactive System Change* theme visualises that the regular checks of the operation and environment can be used to identify changes in the environment or future challenges that would require changes to the operation and system setup. Benn, Healey, and Hollnagel (2008) argued that it is important to move away from a purely retrospective approach (e.g. *Reactive System Change*). "*Developing resilience means focusing upon the capability for effective systems control and renewal of processes through the anticipation of future vulnerabilities and adaptation to operational experience* (Benn, Healey and Hollnagel, 2008, p.325). Folke (2006) highlighted that these changes must adapt to the ever-changing environment.

Case study 1 (see subchapter 4.1) included elements of how the concept of *Proactive System Change* was operationalised. Together with the UK government, the UK air transportation industry realised the urgency to modernise the UK airspace system, as the system is based on the 1950s design. It was anticipated that the current design would not be able to cope with the expected future demand and challenges. Therefore, ACOG was initiated to develop strategies for updating the current system and integrating proposed changes safely.

Another practical example was given in case study 2 (see subchapter 4.2). The CAA conducted a study (CAA, 2017b) and concluded that the UK air transportation system was slowly running out of infrastructure capacity. There was no collaborative action to address the identified resilience challenges. As a result of the report, the VIRG was launched and later rebranded as the IRG.

In both cases, the UK air transportation system was confronted with challenges. However, the *Proactive System Changes* may also be used to identify and address future opportunities that require a change in the system.

5.5 Definition of Resilience

One of the things the research highlighted is that the concept of resilience has many elements and facets. Therefore, a one-sentence description of resilience would not do the concept justice. However, what is possible is to highlight the high-level principle for each resilience-generating theme. This research defined resilience as an outcome of actions and conditions that lead to a resilient system. The research defined a list of 26 high-level principles (see Table 5-1) required to maximise the potential for a resilient system. A system is considered resilient if it is capable of utilizing all of the identified themes and subthemes. The following paragraph states the thesis' definition of resilience.

A resilient system can define, monitor, and maintain the operational limits to avoid becoming brittle and proactively achieve long-term sustainability in the absence of an event. The system can adjust its function to prepare for expected disruptions or handle disruptive events. It knows when to change its structure during disturbances to sustain required operations and avoid failure under both expected and unexpected conditions. Following disruptions, a system can integrate change safely and adopt sustained adaptability to maximise the potential for resilience.

5.6 Recommendations for the UK air transportation industry

The ICRF is a way to visualise how resilience can be operationalised in a system. Splitting down the concept into themes that generate resilience implies that different forms of resilience exist. Therefore, the research follows authors like Woods (2015) or Pettersen and Schulman (2019), who argued that there are different forms of resilience. However, this research went one step further. It used case studies to visualise how these different forms of resilience can relate to and influence each other and integrated the findings into the ICRF.

One of the framework's strengths is that it shows multiple ways to improve the overall system resilience. The ICRF was presented to the Technical Risk and Resilience Committee of the IAPH during the 2022 World Ports Conference. The feedback was positive, and the committee showed high interest in using the ICRF as a baseline for the IAPH Resilience Guidelines. The committee appreciated that the ICRF makes the concept of resilience "*tangible*" (comment from one of the committee members). By breaking down the concept, it is possible to define small pockets of work that can be conducted, contributing to the system's overall resilience.

Another advantage of the ICRF is that it shows the connection between the different themes. Therefore, the ICRF can generate justification for investment in plans and redundancies of the system in the *System Setup* theme that help improve the potential for resilience in the *System Response* theme.

The description of the ICRF combined with the literature review findings offers a detailed guideline for systems to maximise their resilience potential. Based on the high-level principles and experiences over the past three years, certain recommendations for the UK air transportation system were developed to maximise the potential of resilience in the system. The following paragraphs should by no means be seen as detailed instructions for the UK air transportation industry, but more of a reflection of the studied cases.

Recommendation 1: Strengthening cross-industry collaboration

To achieve resilience on a system's level, the various stakeholders must understand the interfaces with other parts of the operation. The IRG (see case study 2) created a platform for various industry stakeholders to come together and share information. Most of the key UK aviation stakeholders are represented at the IRG, and it is crucial that sufficient resources are deployed by the stakeholder for a successful collaboration. Furthermore, a more substantial engagement with the ground handling community or Border Force could create a better understanding of how the operation at other parts of the system may lead to unexpected effects.

Recommendation 2: Improving situational awareness

Better collaboration may also lead to better information exchange between stakeholders and early notification. For example, issues at the border may result in long queues at the airport, slowing down the deboarding process and leading to longer turn-around times. In general, more information sharing between stakeholders is a way to strengthen resilience by creating better situational awareness among the various players. NATS regular network calls (see case study 1) are one example of how enhanced situational awareness can be achieved.

Recommendation 3: Identifying bottlenecks and defining safety margins

Another enabler for generating a high resilience potential is ensuring that a sufficient safety margin is left in operation. A safety margin helps to avoid disruptions as deviations in the operation do not cause ripple effects in the system. The need for sufficient buffer capacity was recognised when the CAA undertook a study to determine the runway utilisation at the major UK airports (CAA, 2017b). However, runway capacity may only be one limiting factor in the system's maximum capacity and incorporated buffer capacity. Airspace infrastructure, ground handling capability, throughput at the border or security may be other limiting factors. Therefore, a system needs to determine what the bottlenecks of the system are. Reviewing other parts of the operation besides the runway utilisation may be one way to understand the various system bottlenecks. Determining the maximum capacity of the various parts of the operation could help define safety margins to account for fluctuations in the operation. Furthermore, understanding the essential parts of an operation also helps protect these elements during normal operations and disruptions. The use of buffer capacity may be one option to increase the safety margins and the system's robustness, such as running the operation below the maximum runway utilisation.

Recommendation 4: Supplying sufficient resources for monitoring

The academic literature (e.g. Hollnagel, 2009a) highlighted that a system needs to supply sufficient resources for monitoring the operation. An understanding of the pinch points of the operation, such as queues at security or approaching maximum airspace sector capacity, allows the system to monitor those parts of the operation closely. This close monitoring allows the system to define thresholds, identify deviations early on and mitigate them immediately. NATS' monitoring of the sector load is one example of how this principle was operationalised. Should the maximum sector load exceed a certain threshold, new sectors can be opened, or flow restrictions could be implemented to prevent an overload in one sector.

Recommendation 5: Review of interfaces and safety margins

It is important to regularly review the operation and ensure that the defined safety margins do not erode over time. Reviews like the one by the CAA (2017b) help determine the system's current state and assess whether the conditions have changed. Especially following the COVID-19 pandemic, during which many people were made redundant, and expertise has been lost, reviewing various parts of the operation could make sense to identify if the processes still align and the interfaces with other stakeholders remained the same or need to be updated. Frequent reviews also support the system in recognizing risks or identifying environmental changes. NATS' monthly SPWG meetings for the internal assessment of the maximum sector capacity is a suitable example of how these reviews can be operationalised as it determines if the maximum sector capacity needs to be adjusted. A frequent review of the diversion capability of airports could be another example that investigates if the safety margins of the system remain the same over time.

Recommendation 6: Creating foresight and preparing for expected disturbances

Monitoring and reviewing the operation can also be used to create foresight and prepare for expected disturbances. Case study 4 provided an example of how an airport used the ability to anticipate bottlenecks for an expected disruption to a temporary increase in buffer capacity. This particular airport benefitted from its close links with its surrounding community through the LRF. Those relationships were used to add additional resources to the operation of the COVID-19 repatriation flight, which increased the buffer capacity. This example should encourage other airports to maintain a close relationship with members of the LRF as they may provide crucial additional resources for disruptive events.

Case study 2 identified that sharing detailed weather forecasts through the Met Office creates foresight in the operation. In order to use the provided information, it is essential to translate early signs of danger (e.g. gusts of wind) into safety hazards (e.g. potential reduction in landing rates may need a reduction of schedule). However, as far as the research is concerned, there is currently no process in the UK air transportation system to coordinate a proactive reduction in flight movements for an expected severe weather event across the network. Defining a process for collectively preparing and coordinating flight reductions in anticipation of a disruptive event may be one way to strengthen resilience during severe weather events.

Recommendation 7: Early detection of failures and deviations

Once a disruption happened, case study 3 showed that early detection of the failure improved the response to the event, reinforcing the need for closely monitoring the operation and defining performance indicators. As soon as the failure of the EFPS system was detected and the cause and timescale for the disruption could not be determined, the airport informed the NATS control centre. As soon as NATS received the information, Plan 39 was immediately activated to prevent ripple effects in the system and keep the workload of the ATCOs within reasonable limits. Therefore, it is advisable to have early indications of failure and define a mechanism for how the information is quickly shared across the network.

Recommendation 8: Increasing the buffer capacity

Plan 39 (see case study 3) is a prime example of using internal buffer capacity to protect the network during a mass diversion event. The use of redundancies, such as standby aircraft or personnel, may be other options to support the system remain functional without compromising the network's performance. However, the IRG recognized that the effect of Plan 39 may be limited for a disruption that requires more standby slots than defined in Plan 39. The system could explore other means to provide buffer capacity for the system in order to strengthen the system's resilience and extend the additional capacity provided by Plan 39.

Recommendation 9: Governance structure for wider aviation crisis events

Discussions about extending the work of Plan 39 and defining protocols for more sustained crises may help improve the potential for the system's resilience. The researcher became aware of the NACME protocol that is aimed at providing a governance structure for severe ATM incidents. NACME provides a platform for executive management to work collaboratively with military, regulatory, and government representatives. However, NACME is defined explicitly for ATM-related crisis scenarios. Case study 5 highlighted that there is no formalized or contractually-agreed governance structure for wider aviation crises, allowing two-way communication between industry and government. It took two months after the start of the COVID-19 pandemic to define a governance structure that allowed a formal information exchange between governance and industry. A permanent governance structure, similar to NACME, that can be stepped up in a crisis event and is flexible enough to be adapted for wider aviation crises may be one possible solution to improve the potential for a resilient operation during major disruptions. Such a governance structure may help bridge the gap of domain knowledge between the sharp end users and policymakers, improving communication and coordination during disruptions. Furthermore, a formal process of ensuring that efforts and regeneration plans are joint-up could also enhance the resilience of the system. In general, an appropriate governance structure for disruptions is useful as it may help coordinate agile adjustments required to mitigate irregular threats. Case study 4 showed how the IMC of an airport was used to support the coordination of various stakeholders and how it helped to facilitate agile adjustments.

Recommendation 10: Creating opportunities for improvements

After-action reviews can help identify good practices and lesson learning after a disruption. Plan 39 (see case study 3) was the result of experiences during and review of previous mass diversion events, and the need for better managing these events was recognized. NATS debriefing calls are another way to bring together the network, discuss previous incidents and create lesson learning. The establishment of ACOG (see case study 1) and the formation of the IRG (see case study 2) showed that anticipation of future challenges could also be used to ensure the long-term sustainability of the system. Reviews of the existing infrastructure may identify that long-term changes are required. New technologies and modes of transportation may require fundamental changes to the system. ACOG is an example of how necessary changes to the airspace system are identified and trade-offs mitigated.

Recommendation 11: Safe integration of changes

Once changes are identified and concepts for those changes are developed, it is essential to conduct a thorough analysis to determine the potential side-effects of those changes, as described by the objectives of ACOG. Safe integration of changes also requires the involved stakeholders to be aware of it. In the case of the implementation of Plan 39, the IRG wrote a briefing note to the industry explaining the principles and process of the new protocol. In addition, NATS hosted a tabletop exercise to ensure that all involved stakeholders were familiar with executing the mass diversion protocol. It is crucial that any changes done to the network are assess beforehand and clearly communicated to the various stakeholders before being implemented. Cross-industry collaborations such as the IRG could be used as a vehicle to drive change and ensure the safe integration of adjustments to the system.

The previously described examples and principles are a selection of different ways to strengthen the resilience of the UK air transportation system. However, there may be other means to improve the potential for resilience in the operation. The next section explains some limitations of the thesis and how further research could expand and add strengths to the findings.

5.7 Recommendations for further research

As mentioned in the SLR (see subchapter 2.2), research in RE has been diverse, and while some authors used the concept of resilience in a reactive form (e.g. Hale and Heijer, 2006a), others saw resilience as a continuous process (e.g. Grabowski and Roberts, 2019). This research untangled the concept and categorised the RE literature into themes. By splitting the concept of resilience into sub-concepts, it was possible to bring the different views together and show how they could be combined.

Researchers in the space of RE may want to use the ICRF to categorise what part of the framework their research addresses. Using the ICRF as a baseline framework may help future studies define in what theme future research lies. Using the ICRF as a baseline framework would make it easier to understand what resilience means in the context that the corresponding authors investigate. For example, if a future case study were conducted to analyse what factors and actions help an airport to return to normal operation after a prolonged runway closure, it would be clear that this research operates in the *System Rebound* theme. This definition would clarify that the research mainly looks at the concept of resilience as a way to return to normal operation following a disruption.

Although the research has used five case studies and a synthesis of the findings to develop the ICRF, there are certain limitations associated with this research.

Ideally, the research would have used the same system for multiple case studies without changing the system and system boundaries. Instead, case study 1 (see subchapter 4.1) defined the system predominantly as the operation within NATS and touched on the overlaps between NATS and the other stakeholder when managing the air transportation operation in the UK. Case study 2 (see subchapter 4.2) investigated the formation and work of the IRG that led to the development of a protocol to handle mass diversion events, which was investigated in case study 3 (see subchapter 4.3). Case study 5 (see subchapter 4.5) also used the IRG as a system and looked at how the working group structure supported the aviation industry during the COVID-19 pandemic. The system in case study 4 (see subchapter 4.4) could be considered an outlier as it analysed the operation of an airport and how it engaged with its wider network. Changing systems during the case studies was a compromise that had to be made due to the pandemic and re-adjustments of the research structure. People and data were not as readily available, and the researcher had to use what was available. However, as shown in section 5.3.1, the breadth of available data should allow a generalisation of the high-level principles from the various case studies to the UK air transportation system.

The ICRF offers new insights into how resilience could be operationalised in the UK air transportation system. However, further research is recommended to build on the research findings and enhance the research outputs in multiple ways.

First, further research would generate more data for the ICRF, which expands each resilience-generating theme and adds additional elements. Achieving this goal requires studying more cases in the UK air transportation industry. The thesis found empirical examples for 19 out of the 26 identified high-level principles. Additional case studies may be able to find a practical application for the other seven remaining high-level principles.

Secondly, in-depth case studies about specific principles may highlight supporting factors that help achieve those principles. For example, case studies that specifically investigate agile adjustments during disruption may highlight that appropriate training and regular emergency exercises foster the potential for agile adjustment during the response.

The academic literature mentioned that a governance structure influences the system’s resilience. Additional research would help determine which governance structure is most suitable for different situations and systems. Therefore, additional research investigating the type of governance structure during day-to-day operations and crises is strongly recommended.

In addition, more outputs from case studies would allow for testing the connections between themes. Additional case studies allow the opportunity to challenge the framework and identify cases where the ICRF may reach its limits. Even though the outputs from the five case studies indicated the usefulness of the ICRF, there might be cases in which the ICRF cannot be applied.

Another limitation of the ICRF may be that the research was based on the UK air transportation industry. Therefore, it could be contended that generalization of the findings to the wider aviation industry or other sectors and domains may not be possible. However, the research investigated several cases with multiple interconnected actors, and similar situations may occur in other domains. Hence, the discovered principles may be generalizable. A first indication was the presentation of the ICRF at the IAPH 2022 World Ports Conference. The positive feedback on the framework suggested that the ICRF may also apply to other sectors and domains. However, further research is required to justify this claim, which may include conducting case studies in other domains and using the findings of those studies to test the applicability and generalization of the ICRF.

6 CONCLUSION AND FINAL REMARKS

The research emphasised the need to approach the topic of resilience holistically. It has gone through significant efforts to contribute to the conceptualisation of resilience. By merging the findings from multiple case studies with the outputs from an extensive SLR, it was possible to develop the ICRF.

Resilience was first defined in the RE literature as a complement to the ordinary view of safety and how safety can be ensured in a complex system (Woods, 2003). Discussions that saw resilience as a synonym for robustness, reliability, or the opposite of brittleness added new elements to the concept. They led to a blurred vision of what resilience is. This research attempted to provide clarity and support the conceptualisation of resilience. The list of contributions of this research contains the following items:

1. The research conducted an SLR of the RE literature. Previous SLR of the RE literature mainly focussed on the need for resilience and the actors that contribute towards resilience in a system (Bergström, van Winsen and Henriqson, 2015), identified research areas (Righi, Saurin and Wachs, 2015), or summarized the current status of the RE literature and linked the areas with future challenges (Patriarca et al., 2018a). This research's SLR is the first known systematic approach to define resilience generating themes and use these themes to analyse and categorise the entire peer-reviewed RE literature published up to the end of 2020. The themes confirmed that different views of resilience exist. However, the categorisation also highlighted that all of these themes are necessary to achieve resilience in the system, and the themes contribute to the system's resilience in different ways.
2. The research conducted case studies to find practical examples of the identified principles. Multiple examples from the UK aviation industry were used to produce empirical evidence of how each theme and subthemes contribute toward generating the potential for a resilient operation. Furthermore, the case studies highlighted connections between the themes and how the theme interrelated and influenced one another. It was

also shown that the UK aviation industry already integrated 19 principles from the identified themes and subthemes.

3. The findings from all case studies were combined with the outputs from the literature review. This combination allowed the development of the ICRF, providing a holistic resilience framework with principles and features of a resilient UK air transportation system. The ICRF helps conceptualise resilience in the RE literature and also provides a guideline for practitioners on how the concept of resilience can be operationalised in a complex socio-technical system.

The work has raised awareness that resilience is more than just a description of how systems respond to disruptions, and helps people think about resilience holistically. The work also supports practitioners better understand how the concept of resilience can be operationalised in a complex socio-technical system to achieve a system with a resilient operation.

Furthermore, using the ICRF to understand the concept of resilience provides opportunities for practitioners to identify ways to maximise the potential for system resilience. The framework breaks down the concept into resilience-generating themes, defining areas that practitioners can work on to improve overall system resilience.

This research has laid the groundwork for additional research that builds on the developed ICRF, tests the research findings, adds further details, and works on the generalization of the ICRF.

REFERENCES

Aburn, G., Gott, M. and Hoare, K. (2016) ‘What is resilience? An Integrative Review of the empirical literature’, *Journal of Advanced Nursing*, 72(5), pp. 980–1000.

ACL (2021) *Airport Coordination Limited: Company Profile*. Staines-Upon-Thames, UK.

Adeyeye, K. and Emmitt, S. (2017) ‘Multi-scale, integrated strategies for urban flood resilience’, *International Journal of Disaster Resilience in the Built Environment*, 8(5), pp. 494–520.

Adger, W.N. (2000) ‘Social and ecological resilience: are they related?’, *Progress in Human Geography*, 24(3), pp. 347–364.

Adriaensen, A., Decre, W. and Pintelon, L. (2019) ‘Can Complexity-Thinking Methods Contribute to Improving Occupational Safety in Industry 4.0? A Review of Safety Analysis Methods and Their Concepts’, *Safety*, 5(65)

Albers, S. and Rundshagen, V. (2020) ‘European airlines′ strategic responses to the COVID-19 pandemic (January-May, 2020)’, *Journal of Air Transport Management*, 87

Alderson, D.L. and Doyle, J.C. (2010) ‘Contrasting views of complexity and their implications for network-centric infrastructures’, *IEEE Transactions on Systems, Man, and Cybernetics Part*, 40(4), pp. 839–852.

Aldianto, L., Anggadwita, G., Permatasari, A., Mirzanti, I.R. and Williamson, I.O. (2021) ‘Toward a Business Resilience Framework for Startups’, *Sustainability*, 13

Alexander, D. (2013a) ‘Volcanic Ash in the Atmosphere and Risks for Civil Aviation: A Study in European Crisis Management’, *International Journal of Disaster Risk Science*, 4(1), pp. 9–19.

Alexander, D.E. (2013b) ‘Resilience and disaster risk reduction: An etymological journey’, *Natural Hazards and Earth System Sciences*, 13, pp. 2707–2716.

Almedom, A.M. and Glandon, D. (2007) ‘Resilience is not the absence of PTSD any more than health is the absence of disease’, *Journal of Loss and Trauma*, 12(2), pp. 127–143.

Amann, B. and Jaussaud, J. (2012) ‘Family and non-family business resilience in an economic downturn’, *Asia Pacific Business Review*, 18(2), pp. 203–223.

Aminoff, H., Johansson, B. and Trnka, J. (2007) ‘Understanding coordination in emergency response’, *Control*

Amodeo, D.C. and Francis, R.A. (2019) ‘The role of protocol layers and macro-cognitive functions in engineered system resilience’, *Reliability Engineering and System Safety*, 190

Anderson, J.E., Ross, A.J., Back, J., Duncan, M., Snell, P., Walsh, K. and Jaye, P. (2016) ‘Implementing resilience engineering for healthcare quality improvement using the CARE model: a feasibility study protocol’, *Pilot and Feasibility Studies*, 2(61)

Anonymous Airport (2020) *Event Report: Repatriation Operation on 11th March 2020*.

Apneseth, K., Wahl, A.M. and Hollnagel, E. (2013) ‘Measuring Resilience in Integrated Planning’, in *Oil and Gas, Technology and Humans*. Farnham, UK: Ashgate, pp. 129–145.

Asadzadeh, S.M., Maleki, H. and Tanhaeean, M. (2020) ‘A resilience engineering-based approach to improving service reliability in maintenance organizations’, *International Journal of System Assurance Engineering and Management*, 11(5), pp. 909–922.

Aspinall, E. (2022) *COVID-19 Timeline*., *British Foreign Policy Group* Available at: https://bfpg.co.uk/2020/04/covid-19-timeline/ (Accessed: 4 February 2022).

Axelsson, L. (2006) ‘Structure for Management of Weak and Diffuse Signals’, in Hollnagel, E., Woods, D. D. and Leveson, N. (eds.) *Resilience Engineering: Concepts and Precepts*. CRC Press, pp. 151–154.

Azadeh, A., Alizadeh Bonab, N., Salehi, V. and Zarrin, M. (2015) ‘A unique algorithm for the assessment and improvement of job satisfaction by resilience engineering: Hazardous labs’, *International Journal of Industrial Ergonomics*, 49, pp. 68–77.

Azadeh, A., Gharibdousti, M.S., Firoozi, M., Baseri, M., Alishahi, M. and Salehi, V. (2016) ‘Selection of optimum maintenance policy using an integrated multi-criteria Taguchi modeling approach by considering resilience engineering’, *The International Journal of Advanced Manufacturing Technology*, 84, pp. 1067–1079.

Azadeh, A., Roudi, E. and Salehi, V. (2017) ‘Optimum design approach based on integrated macro-ergonomics and resilience engineering in a tile and ceramic factory’, *Safety Science*, 96, pp. 62–74.

Azadeh, A. and Salehi, V. (2014) ‘Modeling and optimizing efficiency gap between managers and operators in integrated resilient systems: The case of a petrochemical plant’, *Process Safety and Environmental Protection*, 92, pp. 766–778.

Azadeh, A., Salehi, V., Arvan, M. and Dolatkhah, M. (2014a) ‘Assessment of resilience engineering factors in high-risk environments by fuzzy cognitive maps: A petrochemical plant’, *Safety Science*, 68, pp. 99–107.

Azadeh, A., Salehi, V., Ashjari, B. and Saberi, M. (2014b) ‘Performance evaluation of integrated resilience engineering factors by data envelopment analysis: The case of a petrochemical plant’, *Process Safety and Environmental Protection*, 92, pp. 231–241.

Azadeh, A., Salehi, V. and Kianpour, M. (2018) ‘Performance evaluation of rail transportation systems by considering resilience engineering factors : Tehran railway electrification system’, *Transportation Letters*, 10(1), pp. 12–25.

Azadeh, A., Salehi, V., Salehi, R. and Hassani, S.M. (2018) ‘Performance optimization of an online retailer by a unique online resilience engineering algorithm’, *Enterprise Information Systems*, 12(3), pp. 319–340.

Azadeh, A., Salmanzadeh-Meydani, N. and Motevali-Haghighi, S. (2017) ‘Performance optimization of an aluminum factory in economic crisis by integrated resilience engineering and mathematical programming’, *Safety Science*, 91, pp. 335–350.

Azadeh, A., Yazdanparast, R. and Zadeh, S.A. (2018) ‘An intelligent algorithm for optimizing emergency department job and patient satisfaction’, *International Journal of Health Care Quality Assurance*, 31(5), pp. 374–390.

Barker, K., Ramirez-Marquez, J.E. and Rocco, C.M. (2013) ‘Resilience-based network component importance measures’, *Reliability Engineering and System Safety*, 117, pp. 89–97.

BBC (2018) *Gatwick Airport: Drones ground flights*., *BBC news* Available at: https://www.bbc.com/news/uk-england-sussex-46623754 (Accessed: 15 May 2020).

BBC (2019) *Champions League & Europa League: English clubs make history by taking four final places*. Available at: https://www.bbc.co.uk/sport/football/48222997 (Accessed: 3 January 2021).

Bechky, B.A. and Okhuysen, G.A. (2011) ‘Expecting the unexpected? How SWAT officers and film crews handle surprises’, *Academy of Management Journal*, 54(2), pp. 239–261.

Becker, P., Abrahamsson, M. and Tehler, H. (2011) ‘An emergent means to assurgent ends: Societal resilience for safety and sustainability’, *Proceedings of the fourth Resilience Engineering Symposium*.

van der Beek, D. and Schraagen, J.M. (2015) ‘ADAPTER: Analysing and developing adaptability and performance in teams to enhance resilience’, *Reliability Engineering and System Safety*, 141, pp. 33–44.

Bell, R. (1839) *Eminent literary and scientific men: English poets Vol.2*. London: Longman.

Benn, J., Healey, A.N. and Hollnagel, E. (2008) ‘Improving performance reliability in surgical systems', *Cognition, Technology and Work*, 10, pp. 323–333.

Bergström, J. and Dekker, S.W.A. (2014) 'Bridging the Macro and the Micro by Considering the Meso: Reflections on the Fractal Nature of Resilience', *Ecology and Society*, 19(4)

Bergström, J., van Winsen, R. and Henriqson, E. (2015) 'On the rationale of resilience in the domain of safety: A literature review', *Reliability Engineering and System Safety*, 141, pp. 131–141.

Berkes, F., Colding, J. and Folke, C. (2003) 'Introduction', in Berkes, F., Colding, J. and Folke, C. (eds.) *Navigating Social-Ecological Systems: Building Resilience for Complexity and Change*. Cambridge University Press, pp. 1–30.

Bhamra, R., Dani, S. and Burnard, K. (2011) 'Resilience: The concept, a literature review and future directions', *International Journal of Production Research*, 49(18), pp. 5375–5393.

Bloomberg Markets and Finance (2020) *Airline Industry Has Strength and Resilience, Says AAPA's Herdman*,

Bonanno, G.A. (2004) 'Loss, Trauma, and Human Resilience: Have We Underestimated the Human Capacity to Thrive After Extremely Aversive Events?', *American Psychologist*, 59(1), pp. 20–28.

Borell, J. (2015) 'Manage Everything or Anything? Possible Ways Towards Generic Emergency Management Capabilities', *Journal of Disaster Research*, 10(2), pp. 246–251.

Boring, R.L. (2009) 'Reconciling resilience with reliability: The complementary nature of resilience engineering and human reliability analysis', *Proceedings of the Human Factors and Ergonomics Society*., pp. 1589–1593.

Borys, D., Else, D. and Leggett, S. (2009) 'The fifth age of safety: The adaptive age', *Journal of Health Services Research and Policy*, 1(1), pp. 19–27.

Bouloiz, H. (2020) 'Sustainable performance management using resilience engineering', *International Journal of Engineering Business Management*, 12, pp.

1–12.

Bozza, A., Asprone, D. and Fabbrocino, F. (2017) 'Urban resilience: A Civil Engineering Perspective', *Sustainability (Switzerland)*, 9(1), pp. 103–120.

Bradley, E.H., Curry, L.A. and Devers, K.J. (2007) 'Qualitative Data Analysis for Health Services Research: Developing Taxonomy, Themes, and Theory', *Health Research and Educational Trust*, 42(4), pp. 1758–1772.

Brady, P.W. and Goldenhar, L.M. (2014) 'A qualitative study examining the influences on situation awareness and the identification, mitigation and escalation of recognised patient risk', *BMJ Quality and Safety*, 23(2), pp. 153–161.

Branlat, M. and Woods, D.D. (2010) 'How do systems manage their adaptive capacity to successfully handle disruptions? A resilience engineering perspective', *AAAI Fall Symposium - Technical Report*., pp. 26–34.

Branzei, O. and Abdelnour, S. (2010) 'Another Day, Another Dollar: Enterprise Resilience Under Terrorism in Developing Countries', *Journal of International Business Studies*, 41(5), pp. 804–825.

Braun, V. and Clarke, V. (2006) 'Using thematic analysis in psychology', *Qualitative Research in Psychology*, 3(2), pp. 77–101.

Bridges, K.E., Corballis, P.M. and Hollnagel, E. (2018) '" Failure-to-Identify " Hunting Incidents : A Resilience Engineering Approach', *Human Factors*, 60(2), pp. 141–159.

Brooker, P. (2011) 'Experts, Bayesian Belief Networks, rare events and aviation risk estimates', *Safety Science*, 49, pp. 1142–1155.

Brown, S. (2019) 'Industry Resilience - Putting the passenger and citizen first', *Future Flight Bidding Consortium Workshop at Cranfield University – Aviation Data Transformation*. Cranfield, UK.

Bruneau, M., Chang, S.E., Ronald, T., Lee, G.C., O'Rourke, T.D., Reinhorn, A.M., Shinozuka, M., Tierney, K., Wallace, W.A. and von Winterfeldt, D. (2003) 'A Framework to Quantitatively Assess and Enhance the Seismic Resilience of

Communities', *Earthquake Spectra*, 19(4), pp. 733–752.

Bryant, C. (2022) *Flying Was Already Hellish. Now It's Worse.*, *The Washington Post* Available at: https://www.washingtonpost.com/business/energy/flying-was-already-hellish-now-its-worse/2022/06/03/d6f5c3bc-e2fa-11ec-ae64-6b23e5155b62_story.html (Accessed: 8 June 2022).

Brzeska, K., Borowski, J.R. and Kozuba, J. (2020) 'New law in the air transport during the COVID-19 era', *15th International Scientific Conference: NTinAD 2020 - New Trends in Aviation Development 2020*., pp. 33–36.

Buckley, J. (2022) *Mayhem predicted for travel this summer*., *CNN Travel* Available at: https://www.cnn.com/travel/article/travel-chaos-flight-cancellations-2022/index.html (Accessed: 8 June 2022).

Bukowski, L. (2016) 'System of systems dependability – Theoretical models and applications examples', *Reliability Engineering and System Safety*, 151, pp. 76–92.

Bukowski, L. and Feliks, J. (2012) 'Multi-dimensional concept of supply chain resilience', *Congress Proceedings - CLC 2012: Carpathian Logistics Congress*. Jesenik, Czech Republic, pp. 33–40.

Burbidge, R. (2018) 'Adapting aviation to a changing climate: Key priorities for action', *Journal of Air Transport Management*, 71, pp. 167–174.

Burnard, K. and Bhamra, R. (2011) 'Organisational resilience: Development of a conceptual framework for organisational responses', *International Journal of Production Research*, 49(18), pp. 5581–5599.

BusinessInsider (2019) *London's Gatwick Airport just suffered a complete failure of its air-traffic-control systems*. Available at: https://www.businessinsider.com/london-gatwick-airport-delays-air-traffic-control-systems-failure-2019-7?r=US&IR=T (Accessed: 3 January 2021).

Busvine, D., Rucinski, T. and Freed, J. (2020) *Airline industry crisis deepens as coronavirus kills demand*., *Reuters* Available at:

https://www.reuters.com/article/uk-health-coronavirus-airlines-idUKKBN215433 (Accessed: 20 March 2020).

CAA (2017a) *Report of the Voluntary Industry Resilience Group*. London, UK.

CAA (2017b) *CAP1515: Operating Resilience of the UK's aviation infrastructure and the consumer interest*. West Sussex, UK.

CAA (2015) *CAP 493: Manual of Air Traffic Services - Part 1*. London, UK.

CAA (2020) *CAP 2111: Air Traffic Services Licence for NATS (En Route) PLC*. London, UK.

CAA (2018a) *National Airspace Crisis Management Executive (NACME) protocol*. London, UK.

CAA (2018b) *Airspace Modernisation Strategy - CAP 1711*. London, UK.

CAA (2021) *Airspace change masterplan - future opportunities to express views - CAP 2156c*. London, UK.

Cai, B., Xie, M., Liu, Y., Liu, Y. and Feng, Q. (2018) 'Availability-based engineering resilience metric and its corresponding evaluation methodology', *Reliability Engineering and System Safety*, 172, pp. 216–224.

Cai, Z., Hu, J., Zhang, L. and Ma, X. (2015) 'Hierarchical fault propagation and control modeling for the resilience analysis of process system', *Chemical Engineering Research and Design*, 103, pp. 50–60.

Caldwell, B.S. (2014) 'Cognitive Challenges to Resilience Dynamics in Managing Large-Scale Event Response', *Journal of Cognitive Engineering and Decision Making*, 8(4), pp. 318–329.

Carlson, J.M. and Doyle, J. (2002) 'Complexity and robustness', *Proceedings of the National Academy of Sciences of the United States of America*, 99(1), pp. 2538–2545.

Carpenter, S., Walker, B., Anderies, J.M. and Abel, N. (2001) 'From Metaphor to Measurement: Resilience of What to What?', *Ecosystems*, 4, pp. 765–781.

Carthey, J. (2019) ‘Creating Safety II in the operating theatre: The Durable Dozen!’, *Journal of Perioperative Practice*, 29(7–8), pp. 210–215.

de Carvalho, P.V.R. (2011) ‘The use of Functional Resonance Analysis Method (FRAM) in a mid-air collision to understand some characteristics of the air traffic management system resilience’, *Reliability Engineering and System Safety*, 96, pp. 1482–1498.

de Carvalho, P.V.R., Righi, A.W., Huber, G.J., Lemos, C. de F., Jatobá, A. and Gomes, J.O. (2018) ‘Reflections on work as done (WAD) and work as imagined (WAI) in an emergency response organization: A study on fire fighters training exercises’, *Applied Ergonomics*, 68, pp. 28–41.

Cavanagh, N. (2020) *More than 140 Brits flying home from coronavirus cruise where 21 passengers were infected WON’T be quarantined in UK*., *The Sun* Available at: https://www.thesun.co.uk/news/11143972/brits-coronavirus-cruise-wont-quarantined-uk/ (Accessed: 15 March 2020).

CBC (2018) *Gatwick Airport flights resume amid long lines, delays*., *Canadian Broadcasting Corporation* Available at: https://www.cbc.ca/news/world/gatwick-airport-drone-arrests-flights-resume-1.4957302 (Accessed: 8 June 2022).

Cedergren, A. (2013) ‘Designing resilient infrastructure systems: a case study of decision-making challenges in railway tunnel projects’, *Journal of Risk Research*, 16(5), pp. 563–582.

Chaffin, B.C. and Gunderson, L.H. (2016) ‘Emergence, institutionalization and renewal: Rhythms of adaptive governance in complex social-ecological systems’, *Journal of Environmental Management*, 165, pp. 81–87.

Chan-Yeung, M. and Xu, R.-H. (2003) ‘SARS: epidemiology’, *Respirology*, 8, pp. 9–14.

Checkland, P. (1999) ‘Systems Thinking’, in Currie, W. L. and Galliers, B. (eds.) *Rethinking Management Information System*. Oxford University Press, pp. 45–56.

Chen, F., Nunamaker, J.F., Romano, N. and Briggs, R.O. (2003) ‘A collaborative project management architecture’, *36th Hawaii International Conference on System Sciences*.

Chialastri, A. (2009) ‘Complex systems and safety: An epistemological approach’, *17th Interdisciplinary Information Management Talks Conference, IDIMT 2009*., pp. 265–278.

Cho, H., Leem, L. and Mitra, S. (2012) ‘ERSA: Error Resilient System Architecture for Probabilistic Applications’, *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems*, 31(4), pp. 546–558.

Chuang, S., Ou, J., Hollnagel, E. and Hou, S. (2020) ‘Measurement of resilience potential - development of a resilience assessment grid for emergency departments’, *PLoS ONE*

Cilliers, P. (2002) ‘Why We Cannot Know Complex Things Completely’, *Emergence*, 4, pp. 77–84.

Cimellaro, G.P., Reinhorn, A.M. and Bruneau, M. (2010) ‘Framework for analytical quantification of disaster resilience’, *Engineering Structures*, 32, pp. 3639–3649.

Civil Contingencies Secretariat (2013) *The role of Local Resilience Forums: A reference document*. London, UK.

Cohen, R., Erez, K., Ben-Avraham, D. and Havlin, S. (2000) ‘Resilience of the Internet to random breakdowns’, *Physical Review Letters*, 85(21), pp. 4626–4628.

Collis, L., Schmid, F. and Tobias, A. (2014) ‘Managing incidents in a complex system: A railway case study’, *Cognition, Technology and Work*, 16, pp. 171–185.

Cook, R. (2006) ‘Resilience Dynamics’, *2nd International Symposium on Resilience Engineering*. Juan-les-Pins, France.

Cook, R. and Rasmussen, J. (2005) ‘“Going solid”: A model of system dynamics and consequences for patient safety', *Quality and Safety in Health Care*, 14, pp. 130–134.

Cook, R.I. and Nemeth, C. (2006) 'Taking things in one's stride: Cognitive features of two resilient performances', in Hollnagel, E., Woods, D. D. and Leveson, N. (eds.) *Resilience Engineering: Concepts and Precepts*. CRC Press, pp. 205–222.

Cook, R.I. and Woods, D.D. (2006) 'Distancing through differencing: An obstacle to organizational learning following accidents', in Hollnagel, E., Woods, D. D. and Leveson, N. (eds.) *Resilience Engineering: Concepts and Precepts*. CRC Press, pp. 329–338.

Costella, M.F., Saurin, T.A. and de Macedo Guimarães, L.B. (2009) 'A method for assessing health and safety management systems from the resilience engineering perspective', *Safety Science*, 47, pp. 1056–1067.

Le Coze, J.C. (2019) 'Vive la diversité! High Reliability Organisation (HRO) and Resilience Engineering (RE)', *Safety Science*, 117, pp. 469–478.

Creswell, J.W. (2013) *Qualitative Inquiry & Research Design: Choosing Among Five Approaches*.2nd Editio. London, UK: SAGE Publications.

Cumming, G.S., Barnes, G., Perz, S., Schmink, M., Sieving, K.E., Southworth, J., Binford, M., Holt, R.D., Stickler, C. and Van Holt, T. (2005) 'An exploratory framework for the empirical measurement of resilience', *Ecosystems*, 8, pp. 975–987.

Curt, C. and Tacnet, J.-M. (2018) 'Resilience of Critical Infrastructures: Review and Analysis of Current Approaches', *Risk Analysis*, 38(11), pp. 2441–2458.

Cuvelier, L., Bencheckroun, H. and Morel, G. (2017) 'New vistas on causal-tree methods: from root cause analysis (RCA) to constructive cause analysis (CCA)', *Cognition, Technology and Work*, 19, pp. 13–30.

D'Aspremont, A., Sohier, D., Nilim, A., El Ghaoui, L. and Duong, V. (2006) 'Optimal path planning for air traffic flow management under stochastic weather and capacity constraints', *Proceedings of the 4th IEEE International Conference on Research, Innovation and Vision for the Future, RIVF'06*., pp. 1–6.

D'Souza, D. (2020) *Airline Sector Looking at Long, Expensive Recovery*., *Investopedia* Available at: https://www.investopedia.com/airline-sector-looking-at-long-expensive-recovery-4845631 (Accessed: 22 March 2020).

Datta, P. (2017) 'Supply network resilience: A systematic literature review and future research', *International Journal of Logistics Management*, 28(4), pp. 1387–1424.

Davoudi, S., Brooks, E. and Mehmood, A. (2013) 'Evolutionary Resilience and Strategies for Climate Adaptation', *Planning Practice & Research*, 28(3), pp. 307–322.

Dekker, S. (2006) 'Resilience Engineering: Chronicling the Emergence of Confused Consensus', in Hollnagel, E., Woods, D. D. and Leveson, N. (eds.) *Resilience Engineering: Concepts and Precepts*. CRC Press, pp. 77–92.

Dekker, S., Bergström, J., Amer-Wåhlin, I. and Cilliers, P. (2013) 'Complicated, complex, and compliant: best practice in obstetrics', *Cognition, Technology and Work*, 15, pp. 189–195.

Dekker, S. and Pruchnicki, S. (2014) 'Drifting into failure: theorising the dynamics of disaster incubation', *Theoretical Issues in Ergonomics Science*, 15(6), pp. 534–544.

Deming, W.E. (1986) *Out of the crisis*. Cambridge, Massachusetts: Massachusetts Institute of Technology Center for Advanced Engineering Study xiii.

Demiroz, F. and Haase, T.W. (2019) 'The concept of resilience: a bibliometric analysis of the emergency and disaster management literature', *Local Government Studies*, 45(3), pp. 308–327.

Denyer, D. and Tranfield, D. (2009) 'Producing a Systematic Review', in *Handbook of Organizational Research Methods*. London, UK: SAGE Publications

LtD, pp. 671–689.

Dermot Williams, M. and Smart, A. (2010) ‘Patient safety: a casualty of target success?’, *International Journal of Public Sector Management*, 23(5), pp. 416–430.

DfT (2017) *Upgrading UK Airspace: Strategic Rationale - Moving Britain Ahead*. London, UK.

Dinh, L.T.T., Pasman, H., Gao, X. and Mannan, M.S. (2012) ‘Resilience engineering of industrial processes: Principles and contributing factors’, *Journal of Loss Prevention in the Process Industries*, 25, pp. 233–241.

Dolif, G., Engelbrecht, A., Jatobá, A., da Silva, A.J.D., Gomes, J.O., Borges, M.R.S., Nobre, C.A. and de Carvalho, P.V.R. (2013) ‘Resilience and brittleness in the ALERTA RIO system: a field study about the decision-making of forecasters’, *Natural Hazards*, 65, pp. 1831–1847.

Dollimore, L. (2022) *No end in sight to holiday nightmare: Airlines ‘resign themselves to summer of chaos’ and Heathrow boss warns of 18 MONTHS of misery – as passengers face more mayhem today with huge queues and bag collection in ‘disarray’*., *Daily Mail Online* Available at: https://www.dailymail.co.uk/news/article-10895503/No-end-sight-holiday-nightmare-airlines-resign-summer-chaos.html (Accessed: 8 June 2022).

Doody, O. and Noonan, M. (2013) ‘Preparing and conducting interviews to collect data’, *Nurse Researcher*, 20(5), pp. 28–32.

Duchek, S. (2020) ‘Organizational resilience: a capability-based conceptualization’, *Business Research*, 13, pp. 215–246.

Dunn, P., Allen, L., Cameron, G. and Alderwick, H. (2022) *COVID-19 policy tracker 2020 - 1. Overall policy narrative, and key political events and milestones: 31 December 2019–4 July 2020*., *The Health Foundation* Available at: https://www.health.org.uk/sites/default/files/2022-01/01_Narrative.xlsx (Accessed: 4 February 2022).

Dyer, C. (2020) *US planning flight tomorrow to repatriate Britons stranded on coronavirus plagued ship the Grand Princess, Foreign Office confirms*., *Mail Online* Available at: https://www.dailymail.co.uk/news/breaking_news/article-8092893/US-planning-flight-tomorrow-repatriate-Britons-stranded-coronavirus-ship-Grand-Princess.html (Accessed: 15 March 2020).

EASA (2021) *Drone Incident Management at Aerodromes - Part 1: The challenge of unauthorised drones in the surroundings of aerodromes*. Cologne, Germany.

Elgot, J. and Siddique, H. (2015) *Heathrow airport disrupted as climate activists protest on northern runway*., *The Guardian* Available at: https://www.theguardian.com/uk-news/2015/jul/13/heathrow-disruption-climate-change-activists-claim-chained-runway (Accessed: 10 October 2020).

Engler, E., Göge, D. and Brusch, S. (2018) 'Resilience N – a Multi-Dimensional Challenge for Maritime Infrastructures infrastrukturu', *Nase more*, 65(2), pp. 123–129.

Enjalbert, S. and Vanderhaegen, F. (2017) 'A hybrid reinforced learning system to estimate resilience indicators', *Engineering Applications of Artificial Intelligence*, 64, pp. 295–301.

Erlandson, D.A., Harris, E.L., Skipper, B.L. and Allen, S.D. (1993) *Doing Naturalistic Inquiry: A Guide to Methods*. Newbury Park, USA: SAGE Publications.

Essuman, D., Boso, N. and Annan, J. (2020) 'Operational resilience, disruption, and efficiency: Conceptual and empirical analyses', *International Journal of Production Economics*, 229

EUROCONTROL (2020a) *European Network Operations Plan 2020 Recovery Plan - Edition 1.4*. Brussels, Belgium.

EUROCONTROL (2020b) *European Network Operations Plan 2020 Recovery Plan - Edition 1.0*. Brussels, Belgium.

EUROCONTROL (2016) *What is a slot?*. Available at:

https://www.eurocontrol.int/article/what-is-a-slot (Accessed: 3 March 2022).

FAA (2019) *FAA Statement: Safety is the top priority for the FAA*., *Federal Aviation Authority* Available at: https://www.faa.gov/newsroom/faa-statement-safety-top-priority-faa (Accessed: 8 June 2021).

Fairbanks, R.J., Wears, R.L., Woods, D.D., Hollnagel, E., Plsek, P. and Cook, R.I. (2014) 'Resilience and resilience engineering in health care', *Joint Commission Journal on Quality and Patient Safety*, 40(8), pp. 376–383.

Falegnami, A., Costantino, F., Di Gravio, G. and Patriarca, R. (2019) 'Unveil key functions in socio-technical systems: mapping FRAM into a multilayer network', *Cognition, Technology & Work*, 22(4), pp. 877–899.

FCO (2020a) *British passengers from Grand Princess on US flight to the UK*., *Foreign and Commonwealth Office* Available at: https://www.gov.uk/government/news/british-passengers-from-grand-princess-on-us-flight-to-the-uk--2 (Accessed: 15 March 2020).

FCO (2020b) *Grand Princess cruise ship: Foreign Office statement, 9 March 2020*., *Foreign and Commonwealth Office* Available at: https://www.gov.uk/government/news/foreign-office-statement-on-the-grand-princess-cruise-ship (Accessed: 15 March 2020).

Fereday, J. and Muir-Cochrane, E. (2006) 'Demonstrating Rigor Using Thematic Analysis: A Hybrid Approach of Inductive and Deductive Coding and Theme Development', *International Journal of Qualitative Methods*, 5(1), pp. 745–756.

Fernandes, P.R., Hurtado, A.L.B. and Batiz, E.C. (2015) 'Ergonomics management with a proactive focus', *Procedia Manufacturing*, 3, pp. 4509–4516.

Filippone, E., Gargiulo, F., Errico, A., Di Vito, V. and Pascarella, D. (2016) 'Resilience management problem in ATM systems as a shortest path problem', *Journal of Air Transport Management*, 56, pp. 57–65.

Fischer, K., Hiermaier, S., Riedel, W. and Häring, I. (2018) 'Morphology Dependent Assessment of Resilience for Urban Areas', *Sustainability*, 10(6)

Fletcher, D. and Sarkar, M. (2013) 'Psychological resilience: A review and critique of definitions, concepts, and theory', *European Psychologist*, 18(1), pp. 12–23.

Folke, C. (2006) 'Resilience: The emergence of a perspective for social-ecological systems analyses', *Global Environmental Change*, 16, pp. 253–267.

Francis, R. and Bekera, B. (2014) 'A metric and frameworks for resilience analysis of engineered and infrastructure systems', *Reliability Engineering and System Safety*, 121, pp. 90–103.

Fritz, R.L. and Vandermause, R. (2018) 'Data Collection via In-Depth Email Interviewing: Lessons From the Field', *Qualitative Health Research*, 28(10), pp. 1640–1649.

Fung, I.W.H., Tam, V.W.Y., Chu, J.O.C. and Le, K.N. (2020) 'A Stress-Strain Model for resilience engineering for construction safety and risk management and risk management', *International Journal of Construction Management*

Furniss, D., Back, J., Blandford, A., Hildebrandt, M. and Broberg, H. (2011) 'A resilience markers framework for small teams', *Reliability Engineering and System Safety*, 96(1), pp. 2–10.

Furniss, D., Curzon, P. and Blandford, A. (2016) 'Using FRAM beyond safety: a case study to explore how sociotechnical systems can flourish or stall sociotechnical systems can fl ourish or stall', *Theoretical Issues in Ergonomics Science*, 17(5–6), pp. 507–532.

Gajek, A. (2019) 'Process Safety Education – Learning at the Level of the Establishment and at the Human Level', *Chemical Engineering Transactions*, 77, pp. 841–846.

García-Serna, J., Pérez-Barrigón, L. and Cocero, M.J. (2007) 'New trends for design towards sustainability in chemical engineering: Green engineering', *Chemical Engineering Journal*, 133, pp. 7–30.

Gay, L.F. and Sinha, S.K. (2013) 'Resilience of civil infrastructure systems: Literature review for improved asset management', *International Journal of*

Critical Infrastructures, 9(4), pp. 330–350.

Geraghty, A., Ferguson, L., McIlhenny, C. and Bowie, P. (2020) ‘Incidence of Wrong-Site Surgery List Errors for a 2-Year Period in a Single National Health Service Board’, *Journal of Patient Safety*, 16(1), pp. 79–83.

Gerring, J. (2012) *Social science methodology: A unified framework*.2nd Editio. Cambridge, UK: Cambridge University Press.

Gomes, J.O., Woods, D.D., Carvalho, P.V.R., Huber, G.J. and Borges, M.R.S. (2009) ‘Resilience and brittleness in the offshore helicopter transportation system: The identification of constraints and sacrifice decisions in pilots’ work’, *Reliability Engineering and System Safety*, 94, pp. 311–319.

Grabowski, M. and Roberts, K.H. (2019) ‘Reliability seeking virtual organizations: Challenges for high reliability organizations and resilience engineering’, *Safety Science*, 117, pp. 512–522.

Grecco, C.H.S., Vidal, M.C., Cosenza, C.A., Santos, I.J.A.L. and Carvalho, P.V.R. (2012) ‘New Approach for Safety Management in Radiopharmaceutical Production New Approach for Safety Management in Radiopharmaceutical Production Facilities’, *Latin American Journal of Pharmacy*, 31(8), pp. 1199–1202.

Griffith, D.A. and Myers, M.B. (2005) ‘The performance implications of strategic fit of relational norm governance strategies in global supply chain relationships’, *Journal of International Business Studies*, 36, pp. 254–269.

Grøtan, T.O. and Størseth, F. (2012) ‘Integrated safety management based on organizational resilience’, *Advances in Safety, Reliability and Risk Management*., pp. 1732–1740.

Grote, G. (2012) ‘Safety management in different high-risk domains - All the same?’, *Safety Science*, 50, pp. 1983–1992.

Gunderson, L.H. and Holling, C.S. (2002) *Panarchy: Understanding Transformations in Human and Natural Systems*. Washington D.C., USA: Island

Press.

Haavik, T.K., Antonsen, S., Rosness, R. and Hale, A. (2019) 'HRO and RE: A pragmatic perspective', *Safety Science*, 117, pp. 479–489.

Hale, A., Guldenmund, F. and Goossens, L. (2006) 'Auditing resilience in risk control and safety management systems', in Hollnagel, E., Woods, D. D. and Leveson, N. (eds.) *Resilience Engineering: Concepts and Precepts*. CRC Press, pp. 289–314.

Hale, A. and Heijer, T. (2006a) 'Defining Resilience', in Hollnagel, E., Woods, D. D. and Leveson, N. (eds.) *Resilience Engineering: Concepts and Precepts*. Boca Raton, USA: CRC Press, pp. 35–40.

Hale, A. and Heijer, T. (2006b) 'Is resilience really necessary? The case of railways', in Hollnagel, E., Woods, D. D. and Leveson, N. (eds.) *Resilience Engineering: Concepts and Precepts*. Boca Raton, USA: CRC Press, pp. 125–148.

Hällgren, M., Rouleau, L. and de Rond, M. (2018) 'A Matter of Life or Death: How Extreme Context Research Matters for Management and Organization Studies', *Academy of Management Annals*, 12(1), pp. 111–153.

Harper, L. (2022) *IATA chief hits back at 'idiot politicians' who blame UK airlines for staff shortages.*, *Flight Global* Available at: https://www.flightglobal.com/airlines/iata-chief-hits-back-at-idiot-politicians-who-blame-uk-airlines-for-staff-shortages/148907.article (Accessed: 8 June 2022).

Harrison, H., Birks, M., Franklin, R. and Mills, J. (2017) 'Case study research: Foundations and methodological orientations', *Forum: Qualitative Social Research*, 18(1)

Harvey, E.J., Waterson, P. and Dainty, A.R.J. (2019) 'Applying HRO and resilience engineering to construction: Barriers and opportunities', *Safety Science*, 117, pp. 523–533.

Hasan, R., Chatwin, C. and Sayed, M. (2020) 'Examining alternatives to traditional accident causation models in the offshore oil and gas industry', *Journal of Risk Research*, 23(9), pp. 1242–1257.

Hassall, M.E., Sanderson, P.M. and Cameron, I.T. (2014) 'The Development and Testing of SAfER: A Resilience-Based Human Factors Method', *Journal of Cognitive Engineering and Decision Making*, 8(2), pp. 162–186.

Havinga, J., Dekker, S. and Rae, A. (2018) 'Everyday work investigations for safety', *Theoretical Issues in Ergonomics Science*, 19(2), pp. 213–228.

Hawkins, S.A. and Hastie, R. (1990) 'Hindsight: Biased judgements of past events after the outcomes are known', *Psychological Bulletin*, 107(3), pp. 311–327.

Hegde, S., Hettinger, A.Z., Fairbanks, R.J., Wreathall, J., Krevat, S.A. and Bisantz, A.M. (2020) 'Knowledge Elicitation to Understand Resilience: A Method and Findings From a Health Care Case Study', *Journal of Cognitive Engineering and Decision Making*, 14(1), pp. 75–95.

Hegde, S., Hettinger, A.Z., Fairbanks, R.J., Wreathall, J., Lewis, V., Wears, R. and Bisantz, A.M. (2013) 'A bottom-up approach to understanding the efficacy of event-analysis in healthcare: Paradigm shift from safety to resilience engineering', *Proceedings of the Human Factors and Ergonomics Society*., pp. 673–677.

Hémond, Y. and Robert, B. (2012) 'Preparedness: the state of the art and future prospects', *Disaster Prevention and Management*, 21(4), pp. 404–417.

Henry, D. and Ramirez-Marquez, J.E. (2012) 'Generic metrics and quantitative approaches for system resilience as a function of time', *Reliability Engineering and System Safety*, 99, pp. 114–122.

Herrera, I.A., Hollnagel, E. and Håbrekke, S. (2010) 'Proposing safety performance indicators for helicopter offshore on the Norwegian Continental Shelf', *10th International Conference on Probabilistic Safety Assessment and Management 2010, PSAM 2010*.

Hirose, T. and Sawaragi, T. (2020) ‘Extended FRAM model based on cellular automaton to clarify complexity of socio-technical systems and improve their safety’, *Safety Science*, 123

Hoffman, R.R. and Woods, D.D. (2011) ‘Beyond Simon’s slice: Five fundamental trade-offs that bound the performance of macrocognitive work systems’, *IEEE Intelligent Systems*, , pp. 67–71.

Hohenstein, N.-O., Feisel, E., Hartmann, E. and Giunipero, L. (2015) ‘Research on the phenomenon of supply chain resilience’, *International Journal of Physical Distribution and Logistics Management*, 45, pp. 90–117.

Holling, C.S. (1973) ‘Resilience and stability of ecological systems’, *Annual Review of Ecology and Systematics*, 4, pp. 1–23.

Hollnagel, E. (2011a) ‘Prologue: The Scope of Resilience Engineering’, in Hollnagel, E. (ed.) *Resilience engineering in Practice: A guidebook*. Farnham, UK: Ashgate, p. xxix.

Hollnagel, E. (2009a) ‘The four cornerstones of resilience engineering’, in Nemeth, C. P., Hollnagel, E. and Dekker, S. (eds.) *Resilience Engineering Perspectives Volume 2: Preparation and Restoration*. Ashgate, pp. 117–134.

Hollnagel, E. (2014a) ‘Resilience engineering and the built environment’, *Building Research and Information*, 42(2), pp. 221–228.

Hollnagel, E. (2011b) ‘Epilogue: RAG - The Resilience Analysis Grid’, in Erik Hollnagel, Jean Paries, David Woods, J. W. (ed.) *Resilience engineering in Practice: A guidebook*. Farnham, UK: Ashgate, pp. 275–296.

Hollnagel, E. (2009b) *The ETTO Principle: Efficiency-Thoroughness Trade-Off. Why Things That Go Right Sometimes Go Wrong*. Ashgate.

Hollnagel, E. (2012) *FRAM: The Functional Resonance Analysis Method: Modelling Complex Socio-Technical systems*. Farnham, UK: Ashgate.

Hollnagel, E. (2014b) *Accidents and Barriers*. Linköping, Sweden.

Hollnagel, E. (2006) ‘Resilience – The Challenge of the Unstable’, in Hollnagel, E., Woods, D. D. and Leveson, N. (eds.) *Resilience Engineering: Concepts and Precepts*. Boca Raton, USA: CRC Press, pp. 9–18.

Hollnagel, E. (1999) ‘Accident analysis and barrier functions’, *Institutt for energiteknikk*. Halden, Norway.

Hollnagel, E. and Fujita, Y. (2013) ‘The Fukushima disaster-systemic failures as the lack of resilience’, *Nuclear Engineering and Technology*, 45(1), pp. 13–20.

Hollnagel, E., Nemeth, C.P. and Dekker, S. (2008) *Resilience Engineering Perspective Volume 1: Remaining Sensitive to the Possibility of Failure*. Aldershot, UK: Ashgate.

Hollnagel, E., Pariès, J., Woods, D.D. and Wreathall, J. (2011) *Resilience Engineering in Practice - A Guidebook*. Farnham, UK: Ashgate.

Hollnagel, E. and Sundström, G. (2006) ‘States of Resilience’, in Hollnagel, E., Woods, D. D. and Leveson, N. (eds.) *Resilience Engineering: Concepts and Precepts*. CRC Press, pp. 339–358.

Hollnagel, E. and Woods, D.D. (2006) ‘Epilogue: Resilience Engineering Precepts’, in Hollnagel, E., Woods, D. D. and Leveson, N. (eds.) *Resilience Engineering: Concepts and Precepts*. Boca Raton, USA: CRC Press, pp. 347–358.

Hollnagel, E., Woods, D.D. and Leveson, N. (2006) *Resilience Engineering: Concepts and Precepts*. Boca Raton, USA: CRC Press.

Hopkins, A. (2014) ‘Issues in safety science’, *Safety Science*, 67, pp. 6–14.

Huber, S., van Wijgerden, I., Witt, A. de and Dekker, S.W.A. (2009) ‘Learning From Organizational Incidents: Resilience Engineering for High-Risk Process Environments’, *Process Safety Progress*, 28(1), pp. 90–95.

IATA (2020) *Safety Report 2019*. Montreal, Canada.

IATA (2022) *Worldwide Airport Slot Guidelines - Annex 12.7 - Contact List for Level 2/3 Airports*. Montreal, Canada.

IATA (2019) *Worldwide Slot Guidelines*. Montreal, Canada.

ICAO (2001) *Annex 11 to the Convention on International Civil Aviation: Air Traffic Services*. Montreal, Canada.

IFISA (2021) *Flight Information Services in the United Kingdom*.

Ilbeigi, M. (2019) ‘Statistical process control for analyzing resilience of transportation networks’, *International Journal of Disaster Risk Reduction*, 33, pp. 155–161.

Institute for Government analysis (2021) *Timeline of UK government coronavirus lockdowns and measures , March 2020 to December 2021*. London, UK.

Ip, W.H. and Wang, D. (2011) ‘Resilience and Friability of Transportation Networks: Evaluation, Analysis and Optimization’, *IEEE Systems Journal*, 5(2), pp. 189–198.

IRG (2019) *PLAN 39 - Mass Diversion Protocol – For Internal Briefing*.

IRG (2018a) *Industry Resilience Group Terms of Reference - Jan 2018*.

IRG (2018b) *Temporary Capacity Reduction: Discussion Paper - ODLG - July 2018*.

ITV News (2020) *Britons on coronavirus-hit Grand Princess cruise ship to be flown ho*., *ITV* Available at: https://www.itv.com/news/2020-03-09/britons-on-coronavirus-hit-grand-princess-cruise-ship-set-to-be-repatriated-on-tuesday (Accessed: 15 March 2020).

Jackson, S. and Ferris, T.L.J. (2012) ‘Resilience Principles for Engineered Systems’, *Systems Engineering*, 16(2), pp. 152–164.

Jain, P., Pasman, H.J., Waldram, S., Pistikopoulos, E.N. and Mannan, M.S. (2018) ‘Process Resilience Analysis Framework (PRAF): A systems approach for improved risk and safety management’, *Journal of Loss Prevention in the Process Industries*, 53, pp. 61–73.

Jakšić, Z. and Janić, M. (2020) ‘Modeling resilience of the ATC (Air Traffic

Control) sectors', *Journal of Air Transport Management*, 89

Jersey Evening Post (2020) *Government 'working intensively' to repatriate cruise ship Britons*.

Joannou, D., Kalawsky, R., Saravi, S., Casado, M.R., Fu, G. and Meng, F. (2019) 'A Model-Based Engineering Methodology and Architecture for Resilience in Systems-of-Systems: A Case of Water Supply Resilience to Flooding', *Water*, 11(3)

Johansson, B.J. and Lundberg, J. (2010) 'Engineering Safe Aviation Systems: Balancing Resilience and Stability', in Wise, J. A., Hopkin, V. D. and Garland, D. J. (eds.) *Handbook of Aviation Human Factors*. 2nd Editio. Boca Raton, USA: CRC Press.

Johansson, J. and Hassel, H. (2010) 'An approach for modelling interdependent infrastructures in the context of vulnerability analysis', *Reliability Engineering and System Safety*, 95, pp. 1335–1344.

Johnson, R.B. and Onwuegbuzie, A.J. (2004) 'Mixed Methods Research: A Research Paradigm Whose Time Has Come', *Educational Researcher*, 33(7), pp. 14–26.

Kabashkin, I. (2016) 'Resilient communication network of Air Traffic Management system', *Proceedings - 2016 Advances in Wireless and Optical Communications*., pp. 156–160.

Kallio, H., Pietilä, A.M., Johnson, M. and Kangasniemi, M. (2016) 'Systematic methodological review: developing a framework for a qualitative semi-structured interview guide', *Journal of Advanced Nursing*, 72(12), pp. 2954–2965.

Kawulich, B.B. (2005) 'Participant Observation as a Data Collection Method', *Forum: Qualitative Social Research*, 6(2)

Kaya, G.K., Ovali, H.F. and Ozturk, F. (2019) 'Using the functional resonance analysis method on the drug administration process to assess performance variability', *Safety Science*, 118, pp. 835–840.

Kell, B.S. and Marr, B.K. (2019) ‘Controller workload-based approach to establishing monitor alert parameters for en route sectors’, *AIAA Aviation 2019 Forum*. Dallas, Texas.

Kim, J.T., Park, J., Kim, J. and Seong, P.H. (2018) ‘Development of a quantitative resilience model for nuclear power plants’, *Annals of Nuclear Energy*, 122, pp. 175–184.

Kitamura, M. (2016) ‘Supplementary Remarks on Lessons Learned from the Great East Japan Earthquake’, *International Federation of Automatic Control*, 49(19), pp. 257–260.

Kochan, C.G. and Nowicki, D.R. (2018) ‘Supply chain resilience: a systematic literature review and typological framework’, *International Journal of Physical Distribution and Logistics Management*, 48(8), pp. 842–865.

Kolar, K. (2011) ‘Resilience: Revisiting the Concept and its Utility for Social Research’, *International Journal of Mental Health and Addiction*, 9, pp. 421–433.

Kopardekar, P., Rhodes, J., Schwartz, A., Magyarits, S. and Willems, B. (2008) ‘Relationship of maximum manageable air traffic control complexity and sector capacity’, *26th International Congress of the Aeronautical Sciences*. Anchorage, Alaska.

Kopardekar, P., Schwartz, A., Magyarits, S. and Rhodes, J. (2007) ‘Airspace Complexity Measurement : An Air Traffic Control Simulation Analysis’, *US/Europe 7th Air Traffic Management Seminar*. Barcelona, Spain.

Korber, S. and McNaughton, R.B. (2017) ‘Resilience and entrepreneurship: A systematic literature review’, *International Journal of Entrepreneurial Behaviour & Research*, 24(7), pp. 1129–1154.

Kumar, R. and Singh, A. (2020) ‘Robustness in Multilayer Networks under Strategical and Random Attacks’, *Procedia Computer Science*, 173, pp. 94–103.

Lay, E., Branlat, M. and Woods, Z. (2015) ‘A practitioner’s experiences operationalizing Resilience Engineering’, *Reliability Engineering and System*

Safety, 141, pp. 63–73.

Leveson, N. (2004) 'A new accident model for engineering safer systems', *Safety Science*, 42, pp. 237–270.

Li, W., Sun, Y., Cao, Q., He, M. and Cui, Y. (2019) 'A proactive process risk assessment approach based on job hazard analysis and resilient engineering', *Journal of Loss Prevention in the Process Industries*, 59, pp. 54–62.

Lindblad, M., Flink, M. and Ekstedt, M. (2017) 'Safe medication management in specialized home healthcare - an observational study', *BMC Health Services Research*, 17(1)

Linnenluecke, M.K. (2017) 'Resilience in Business and Management Research: A Review of Influential Publications and a Research Agenda', *International Journal of Management Reviews*, 19, pp. 4–30.

Lundberg, J. and Johansson, B.J. (2015) 'Systemic resilience model', *Reliability Engineering and System Safety*, 141, pp. 22–32.

Lundberg, J. and Rankin, A. (2014) 'Resilience and vulnerability of small flexible crisis response teams: Implications for training and preparation', *Cognition, Technology and Work*, 16, pp. 143–155.

Luthar, S.S., Cicchetti, D. and Becker, B. (2000) 'The Construct of Resilience: A Critical Evaluation and Guidelines for Future Work', *Child Development*, 71(3), pp. 543–562.

Luthar, S.S., Sawyer, J.A. and Brown, P.J. (2006) 'Conceptual issues in studies of resilience: Past, present, and future research', *Annals of the New York Academy of Sciences*, 1094, pp. 105–115.

Ma, Z., Xiao, L. and Yin, J. (2018) 'Toward a dynamic model of organizational resilience', *Nankai Business Review International*, 9(3), pp. 246–263.

MacGregor, S. (2020) *Update: Canada Closes Border To U.S. In Unprecedented New Coronavirus Travel Ban.*, *Forbes* Available at: https://www.forbes.com/sites/sandramacgregor/2020/03/18/update-canadarestricts-travel-to-the-us-in-new-coronavirus-travel-ban/?sh=36463ff2449c (Accessed: 20 March 2020).

Macleod, A. (2015) *An examination of the contemporary meaning and utility of resilience*.

Macrae, C. and Draycott, T. (2019) 'Delivering high reliability in maternity care: In situ simulation as a source of organisational resilience', *Safety Science*, 117, pp. 490–500.

Madni, A. and Jackson, S. (2009) 'Towards a conceptual framework for Resilience Engineering', *IEEE Systems Journal*, 3(2), pp. 181–191.

Manyena, B., Machingura, F. and O'Keefe, P. (2019) 'Disaster Resilience Integrated Framework for Transformation (DRIFT): A new approach to theorising and operationalising resilience', *World Development*, 123

Martins Junior, M., Santos, M.S. e, Vidal, M.C.R. and de Carvalho, P.V.R. (2012) 'Overcoming the blame game to learn from major accidents: A systemic analysis of an Anhydrous Ammonia leakage accident', *Journal of Loss Prevention in the Process Industries*, 25, pp. 33–39.

Masten, A.S. (2001) 'Ordinary Magic: Resilience Processes in Development', *American Psychologist*, 56(3), pp. 227–238.

da Mata, T.F., Gajewski, D.W., Hall, C.K., Lacerda, M.C., Santos, A.G., Gomes, J.O. and Woods, D.D. (2006) 'Application of resilience engineering on safety in offshore helicopter transportation', *Proceedings of the 2006 IEEE Systems and Information Engineering Design Symposium, SIEDS'06*., pp. 228–233.

Matrosov, E.S., Huskova, I., Kasprzyk, J.R., Harou, J.J., Lambert, C. and Reed, P.M. (2015) 'Many-objective optimization and visual analytics reveal key trade-offs for London's water supply', *Journal of Hydrology*, 531, pp. 1040–1053.

McCarney, R., Warner, J., Iliffe, S., van Haselen, R., Griffin, M. and Fisher, P. (2007) 'The Hawthorne Effect : a randomised, controlled trial', *BMC Medical Research*, 7(30)

McDonald, J.D. and Durso, F.T. (2015) ‘A Behavioral Intervention for Reducing Postcompletion Errors in a Safety-Critical System’, *Human Factors*, 57(6), pp. 917–929.

Meerow, S., Newell, J.P. and Stults, M. (2016) ‘Defining urban resilience: A review’, *Landscape and Urban Planning*, 147, pp. 38–49.

Mendonça, D. and Wallace, W.A. (2015) ‘Factors underlying organizational resilience: The case of electric power restoration in New York City after 11 September 2001’, *Reliability Engineering and System Safety*, 141, pp. 83–91.

Mentes, A. and Turan, O. (2019) ‘A new resilient risk management model for Offshore Wind Turbine maintenance’, *Safety Science*, 119, pp. 360–374.

Miller, A. and Xiao, Y. (2007) ‘Multi-level strategies to achieve resilience for an organisation operating at capacity: A case study at a trauma centre’, *Cognition, Technology and Work*, 9, pp. 51–66.

Miller, S.A. (2011) ‘April 2010 UK Airspace closure: Experience and impact on the UK’s air-travelling public and implications for future travel’, *Journal of Air Transport Management*, 17, pp. 296–301.

Morel, G., Amalberti, R. and Chauvin, C. (2009) ‘How good micro/macro ergonomics may improve resilience, but not necessarily safety’, *Safety Science*, 47, pp. 285–294.

Moriarty, L.F., Plucinski, M.M., Marston, B.J., Kurbatova, E. V, Knust, B., Murray, E.L., Pesik, N., Rose, D., Fitter, D., Kobayashi, M., Toda, M., Canty, P.T., Scheuer, T., Halsey, E.S., Cohen, N.J., Stockman, L., Wadford, D.A., Medley, A.M., Green, G., Regan, J.J., Tardivel, K., White, S., Brown, C., Morales, C., Yen, C., Wittry, B., Freeland, A., Naramore, S., Novak, R.T., Daigle, D., Weinberg, M., Acosta, A., Herzig, C., Kapella, B.K., Jacobson, K.R., Lamba, K., Ishizumi, A., Sarisky, J., Svendsen, E., Blocher, T., Wu, C., Charles, J., Wagner, R., Stewart, A., Mead, P.S., Kurylo, E., Campbell, S., Murray, R., Weidle, P., Cetron, M., Friedman, C.R., CDC Cruise Ship Response Team, California Department of Public Health COVID-19 Team and Solano County COVID-19 Team (2020)

Morbidity and Mortality Weekly Report: Public Health Responses to COVID-19 Outbreaks on Cruise Ships — Worldwide , February – March 2020.

Morrison, S. (2020) *Flight home planned for Brits stranded on coronavirus-hit Grand Princess cruise ship in California*., *Evening Standard* Available at: https://www.standard.co.uk/news/world/flight-home-planned-for-brits-stranded-on-coronavirushit-grand-princess-cruise-ship-in-california-a4382976.html (Accessed: 15 March 2020).

Muir, K., Reeve, R., Connolly, C., Marjolin, A., Salignac, F. and Ho, K. (2016) *Financial Resilience in Australia 2015*. Sydney, Australia.

Naderpajouh, N., Yu, D.J., Aldrich, D.P., Linkov, I. and Matinheikki, J. (2018) 'Engineering meets institutions: an interdisciplinary approach to the management of resilience', *Environment Systems and Decisions*, 38, pp. 306–317.

Nagenborg, M. (2019) 'Urban resilience and distributive justice', *Sustainable and Resilient Infrastructure*, 4(3), pp. 103–111.

Nan, C. and Sansavini, G. (2017) 'A quantitative method for assessing resilience of interdependent infrastructures', *Reliability Engineering and System Safety*, 157, pp. 35–53.

Narain, J. (2020) *EXCLUSIVE: Grand Princess cruise British couple tell of 'terrifying flight' home on windowless cargo plane where SIX coronavirus victims were held in a metal box - and cabin crew wore hazmat suits to serve sandwiches*., *Mail Online* Available at: https://www.dailymail.co.uk/news/article-8108315/Grand-Princess-cruise-British-couple-tell-terrifying-flight-home.html (Accessed: 5 May 2022).

NATS (2021a) *History shows why modernising UK airspace is so vital*. Available at: https://www.nats.aero/static/history-shows-why-modernising-uk-airspace-is-so-vital/ (Accessed: 3 January 2022).

NATS (2021b) *Introduction to Airspace*. Available at: https://www.nats.aero/ae-home/introduction-to-airspace/ (Accessed: 10 October 2021).

NATS (2019a) *Planning for a busy summer*. Available at: https://nats.aero/blog/2019/05/planning-for-a-busy-summer/ (Accessed: 3 January 2021).

NATS (2013) *Farnborough LARS Guide*.

NATS (2017) *Annual Report and Accounts 2017*.

NATS (2019b) *Annual Report and Accounts 2019*.

NATS (2019c) *Plan 39 Hot Debrief - Initial Slide Deck* National Air Traffic Services,

Negrello, F., Garabini, M., Grioli, G., Tsagarakis, N., Bicchi, A. and Catalano, M.G. (2019) 'Benchmarking Resilience of Artificial Hands', *IEEE International Conference on Robotics and Automation*. Montreal, Canada, pp. 8374–8380.

Nemeth, C. (2019) 'Resilience Engineering, Safety, and Implications for Pediatric Care', *Current Treatment Options in Pediatrics*, 5, pp. 102–110.

Nemeth, C.P. and Herrera, I. (2015) 'Building change: Resilience Engineering after ten years', *Reliability Engineering and System Safety*, 141, pp. 1–4.

Nemeth, C.P. and Hollnagel, E. (2014) *Resilience Engineering in Practice Volume 2: Becoming Resilient*. Surrey, United Kingdom: Ashgate.

Nemeth, C.P., Hollnagel, E. and Dekker, S.W.A. (2009) *Resilience Engineering Perspectives Volume 2: Preparation and Restoration*. Coca Raton, USA: CRC Press.

Nightingale, A.J. (2020) 'Triangulation', in Kobayashi, A. (ed.) *International Encyclopedia of Human Geography*. , pp. 477–480.

Novak, J., Farr-Wharton, B., Brunetto, Y., Shacklock, K. and Brown, K. (2017) 'Safety outcomes for engineering asset management organizations: Old problem with new solutions ?', *Reliability Engineering and System Safety*, 160, pp. 67–73.

OAG (2022) *Empowering frictionless travel in a data driven world*. Available at: https://www.oag.com/?hsLang=en-gb (Accessed: 20 March 2022).

Øien, K., Massaiu, S., Tinmannsvik, R.K. and Størseth, F. (2010) 'Development of early warning indicators based on incident investigation', *9th International Conference on Probabilistic Safety Assessment and Management 2008, PSAM 2008*. Seattle, USA.

Oliveira, A.T.C. and de Morais, N.A. (2018) 'Community Resilience: An Integrative Literature Review', *Trends in Psychology*, 26(4), pp. 1747–1761.

Ouedraogo, K.A., Enjalbert, S. and Vanderhaegen, F. (2013) 'How to learn from the resilience of Human-Machine Systems?', *Engineering Applications of Artificial Intelligence*, 26, pp. 24–34.

Owen, C., Healey, A.N. and Benn, J. (2013) 'Widening the scope of human factors safety assessment for decommissioning', *Cognition, Technology and Work*, 15, pp. 59–66.

Palazzi, E., Currò, F., Reverberi, A. and Fabiano, B. (2014) 'Resilience Engineering Strategy Applied to an Existing Process Plant', *Chemical Engineering Transactions*, 36, pp. 499–504.

Pardo-Ferreira, M. del C., Rubio-Romero, J.C. and Gibb, A. (2020) 'Using functional resonance analysis method to understand construction activities for concrete structures', *Safety Science*, 128

Paredes, R., Duenas-Osorio, L., Meel, K.S. and Vardi, M.Y. (2019) 'Principled network reliability approximation: A counting-based approach', *Reliability Engineering and System Safety*, 191

Pariès, J., Macchi, L., Valot, C. and Deharvengt, S. (2019) 'Comparing HROs and RE in the light of safety management systems', *Safety Science*, 117, pp. 501–511.

Pasman, H.J., Knegtering, B. and Rogers, W.J. (2013) 'A holistic approach to control process safety risks: Possible ways forward', *Reliability Engineering and System Safety*, 117, pp. 21–29.

Patriarca, R. and Bergström, J. (2017) 'Modelling complexity in everyday operations: functional resonance in maritime mooring at quay', *Cognition, Technology & Work*, 19, pp. 711–729.

Patriarca, R., Bergström, J., Di Gravio, G. and Costantino, F. (2018a) 'Resilience engineering: Current status of the research and future challenges', *Safety Science*, 102, pp. 79–100.

Patriarca, R., Falegnami, A., Costantino, F. and Bilotta, F. (2018b) 'Resilience engineering for socio-technical risk analysis : Application in neuro-surgery', *Reliability Engineering and System Safety*, 180, pp. 321–335.

Patriarca, R., Gravio, G. Di and Costantino, F. (2017) 'A Monte Carlo evolution of the Functional Resonance Analysis Method (FRAM) to assess performance variability in complex systems', *Safety Science*, 91, pp. 49–60.

Patriarca, R., Di Gravio, G., Woltjer, R., Costantino, F., Praetorius, G., Ferreira, P. and Hollnagel, E. (2020) 'Framing the FRAM: A literature review on the functional resonance analysis method', *Safety Science*, 129

Patriotta, G. (2020) 'Writing Impactful Review Articles', *Journal of Management Studies*, 57(6), pp. 1272–1276.

Patterson, E.S., Woods, D.D., Cook, R.I. and Render, M.L. (2007) 'Collaborative cross-checking to enhance resilience', *Cognition, Technology and Work*, 9, pp. 155–162.

Patterson, M. and Deutsch, E.S. (2015) 'Safety-I, Safety-II and Resilience Engineering', *Current Problems in Pediatric and Adolescent Health Care*, 45, pp. 382–389.

Patterson, M.D. and Wears, R.L. (2015) 'Resilience and precarious success', *Reliability Engineering and System Safety*, 141, pp. 45–53.

Penaloza, G.A., Saurin, T.A. and Formoso, C.T. (2020) 'Monitoring complexity and resilience in construction projects: The contribution of safety performance measurement systems', *Applied Ergonomics*, 82

Penaloza, G.A., Saurin, T.A., Formoso, C.T. and Herrera, I.A. (2020) 'A resilience engineering perspective of safety performance measurement systems: A systematic literature review', *Safety Science*, 130

Pereira, R.F., Morgado, C.R. V., Santos, I.J.A.L. and Paulo, V.R. (2015) 'STAMP Analysis of Deepwater Blowout Accident', *Chemical Engineering Research and Design*, 43, pp. 2305–2310.

Pescaroli, G. (2018) 'Perceptions of cascading risk and interconnected failures in emergency planning: Implications for operational resilience and policy making', *International Journal of Disaster Risk Reduction*, 30, pp. 269–280.

Pescaroli, G., Wicks, R.T., Giacomello, G. and Alexander, D.E. (2018) 'Increasing resilience to cascading events: The M.OR.D.OR. scenario', *Safety Science*, 110, pp. 131–140.

Pettersen, K.A. and Schulman, P.R. (2019) 'Drift, adaptation, resilience and reliability: Toward an empirical clarification', *Safety Science*, 117, pp. 460–468.

Pickett, L. and Hirst, D. (2020) *Briefing Paper: Airport Slots*. London, UK.

Pilbeam, C., Alvarez, G. and Wilson, H. (2012) 'The governance of supply networks: a systematic literature review', *Supply Chain Management*, 17(4), pp. 358–376.

Pillay, M. (2016) 'Resilience Engineering, Gaps and Prescription of Safe Work Method Statements Part 1: The View of Organisational Outsiders', in *Advances in Safety Management and Human Factors*. , pp. 261–272.

Pillay, M. and Morel, G. (2020) 'Measuring Resilience Engineering: An Integrative Review and Framework for Bench-Marking Organisational Safety', *Safety*

du Plessis, E.M. and Vandeskog, B. (2020) 'Other stories of resilient safety management in the Norwegian offshore sector: Resilience engineering, bullshit and the de-politicization of danger', *Scandinavian Journal of Management*, 36

Podsakoff, P.M., Mackenzie, S.B. and Podsakoff, N.P. (2016) 'Recommendations for Creating Better Concept Definitions in the Organizational, Behavioral, and Social Sciences', *Organizational Research Methods*, 19(2), pp.

159–203.

Praetorius, G. and Hollnagel, E. (2014) ‘Control and resilience within the maritime traffic management domain’, *Journal of Cognitive Engineering and Decision Making*, 8(4), pp. 303–317.

Praetorius, G., Hollnagel, E. and Dahlman, J. (2015) ‘Modelling Vessel Traffic Service to understand resilience in everyday operations’, *Reliability Engineering and System Safety*, 141, pp. 10–21.

Prasad, T.D. and Park, N.-S. (2004) ‘Multiobjective genetic algorithms for design of water distribution networks’, *Journal of Water Resources Planning and Management*, 130(1), pp. 73–82.

Princess (2021) *Grand Princess Cruise Ship*. Available at: https://www.princess.com/ships-and-experience/ships/ap-grand-princess/ (Accessed: 5 May 2022).

Prosperi, P., Allen, T., Cogill, B., Padilla, M. and Peri, I. (2016) ‘Towards metrics of sustainable food systems: a review of the resilience and vulnerability literature’, *Environment Systems and Decisions*, 36(1), pp. 3–19.

Provan, D.J., Woods, D.D., Dekker, S.W.A. and Rae, A.J. (2020) ‘Safety II professionals: How resilience engineering can transform safety practice’, *Reliability Engineering and System Safety*, 195

Provan, K.G. and Kenis, P. (2008) ‘Modes of Network Governance: Structure, Management, and Effectiveness’, *Journal of Public Administration Research and Theory*, 18(2), pp. 229–252.

Pulley, M.L. and Wakefield, M. (2001) *Building resiliency: how to thrive in times of change*. Center for Creative Leadership.

Qureshi, Z.H., Ashraf, M.A. and Amer, Y. (2007) ‘Modeling industrial safety: A sociotechnical systems perspective’, *IEEM 2007: 2007 IEEE International Conference on Industrial Engineering and Engineering Management*., pp. 1883–1887.

Raben, D.C., Bogh, S.B., Viskum, B., Mikkelsen, K. and Hollnagel, E. (2017) ‘Proposing leading indicators for blood sampling : application of a method based on the principles of resilient healthcare’, *Cognition, Technology & Work*, 19(4), pp. 809–817.

Ranasinghe, U., Jefferies, M., Davis, P. and Pillay, M. (2020) ‘Resilience Engineering Indicators and Safety Management: A Systematic Review’, *Safety and Health at Work*, 11, pp. 127–135.

Rankin, A., Dahlbäck, N. and Lundberg, J. (2013) ‘A case study of factor influencing role improvisation in crisis response teams’, *Cognition, Technology and Work*, 15, pp. 79–93.

Rankin, A., Lundberg, J., Woltjer, R., Rollenhagen, C. and Hollnagel, E. (2014) ‘Resilience in everyday operations: A framework for analyzing adaptations in high-risk work’, *Journal of Cognitive Engineering and Decision Making*, 8(1), pp. 78–97.

Rankine, W. (1867) *A Manual of Applied Mechanics*. London, UK: Charles Griffin and Co.

Rasmussen, J. (1997) ‘Risk Management in dynamic society: A modelling problem’, *Safety Science*, 27(2/3), pp. 183–213.

Ray-Sannerud, B.N., Leyshon, S. and Vallevik, V.B. (2015) ‘Introducing routine measurement of healthcare worker’ s well-being as a leading indicator for proactive safety management systems based on Resilience Engineering’, *Procedia Manufacturing*, 3, pp. 319–326.

Re, A. and Macchi, L. (2010) ‘From cognitive reliability to competence? An evolving approach to human factors and safety’, *Cognition, Technology and Work*, 12, pp. 79–85.

REA (2022) *Welcome to Resilience Engineering Association*. Available at: https://www.resilience-engineering-association.org/ (Accessed: 4 April 2022).

de Regt, A., Siegel, A.W. and Schraagen, J.M. (2016) ‘Toward quantifying metrics for rail-system resilience: identification and analysis of performance weak resilience signals', *Cognition, Technology & Work*, 18, pp. 319–331.

Rehak, D., Senovsky, P. and Slivkova, S. (2018) 'Resilience of Critical Infrastructure Elements and Its Main Factors', *Systems*, 6(21)

Reichardt, U., Ulfarsson, G.F. and Pétursdóttir, G. (2018) 'Volcanic ash and aviation: Recommendations to improve preparedness for extreme events', *Transportation Research Part A*, 113, pp. 101–113.

Reichardt, U., Ulfarsson, G.F. and Pétursdóttir, G. (2019) 'Developing scenarios to explore impacts and weaknesses in aviation response exercises for volcanic ash eruptions in Europe', *Journal of Air Transport Management*, 79

Reniers, G.L.L., Sörensen, K., Khan, F. and Amyotte, P. (2014) 'Resilience of chemical industrial areas through attenuation-based security', *Reliability Engineering and System Safety*, 131, pp. 94–101.

Reuters (2022) *UK says it will work with aviation industry to solve travel chaos*. Available at: https://www.reuters.com/business/aerospace-defense/uk-says-it-will-work-with-aviation-industry-solve-travel-chaos-2022-06-05/ (Accessed: 8 June 2022).

Righi, A.W., Saurin, T.A. and Wachs, P. (2015) 'A systematic literature review of resilience engineering: Research areas and a research agenda proposal', *Reliability Engineering and System Safety*, 141, pp. 142–152.

Rizzo, S. and Nirappil, F. (2022) *Global covid-19 death toll tops 6 million, another grim milestone in the pandemic*., *The Washington Post* Available at: https://www.washingtonpost.com/health/2022/03/07/6-million-covid-deaths/ (Accessed: 4 April 2022).

Robbins, J., Krishnan, K., Allspaw, J. and Limoncelli, T. (2012) 'Resilience engineering: Learning to embrace failure', *Communications of the ACM*, 55(11), pp. 40–47.

Robson, C. (2011) *Real World Research: A Resource for Users of Social*

Research Methods in Applied Settings.3rd Editio. West Sussex, UK: John Wiley & Sons.

Rocha, L.E.C. (2017) ‘Dynamics of air transport networks: A review from a complex systems perspective’, *Chinese Journal of Aeronautics*, 30(2), pp. 469–478.

Rodriguez-Sanchez, A.M. and Vera, M. (2015) ‘The secret of organisation success: A revision on organisational and team resilience’, *International Journal of Emergency Services*, 4(1), pp. 27–36.

Roehrich, J.K., Selviaridis, K., Kalra, J., Van der Valk, W. and Fang, F. (2020) ‘Inter-organizational governance: a review, conceptualisation and extension’, *Production Planning & Control*, 31(6), pp. 453–469.

Rosa, L. V, França, J.E.M., Haddad, A.N. and Carvalho, P.V.R. (2017) ‘A Resilience Engineering Approach for Sustainable Safety in Green Construction’, *Journal of Sustainable Development of Energy, Water and Environment Systems*, 5(4), pp. 480–495.

Rose, A. (2007) ‘Economic resilience to natural and man-made disasters: Multidisciplinary origins and contextual dimensions’, *Environmental Hazards*, 7(4), pp. 383–398.

Ross, A.J., Anderson, J.E., Kodate, N., Thompson, K., Cox, A. and Malik, R. (2014) ‘Inpatient diabetes care: Complexity, resilience and quality of care’, *Cognition, Technology and Work*, 16, pp. 91–102.

Rousseau, D.M., Sitkin, S.B., Burt, R.S. and Camerer, C. (1998) ‘Not So Different After All: A Cross-Discipline View of Trust’, *Academy of Management Review*, 23(3), pp. 393–404.

Rubio-Romero, J.C., Pardo-Ferreira, M. del C., Varga-Salto, J.D. la and Galindo-Reyes, F. (2018) ‘Composite leading indicator to assess the resilience engineering in occupational health & safety in municipal solid waste management companies’, *Safety Science*, 108, pp. 161–172.

Ryan, F., Coughlan, M. and Cronin, P. (2009) ‘Interviewing in qualitative research: The one-to-one interview’, *International Journal of Therapy and Rehabilitation*, 16(6), pp. 309–314.

Said, S., Bouloiz, H. and Gallab, M. (2019) ‘A new structure of sociotechnical system processes using resilience engineering’, *International Journal of Engineering Business Management*, 11, pp. 1–10.

Salehi, V. and Veitch, B. (2020) ‘Performance optimization of integrated job-driven and resilience factors by means of a quantitative approach’, *International Journal of Industrial Ergonomics*, 78

Salehi, V., Veitch, B. and Musharraf, M. (2020) ‘Measuring and improving adaptive capacity in resilient systems by means of an integrated DEA-Machine learning approach’, *Applied Ergonomics*, 82

Salzano, E., Di Nardo, M., Gallo, M., Oropallo, E. and Santillo, L.C. (2014) ‘The application of System Dynamics to industrial plants in the perspective of Process Resilience Engineering’, *Chemical Engineering Transactions*, 36, pp. 457–462.

Saurin, T.A. and Carim Junior, G.C. (2012) ‘A framework for identifying and analyzing sources of resilience and brittleness: A case study of two air taxi carriers’, *International Journal of Industrial Ergonomics*, 42, pp. 312–324.

Saurin, T.A. and Carim Júnior, G.C. (2011) ‘Evaluation and improvement of a method for assessing HSMS from the resilience engineering perspective: A case study of an electricity distributor’, *Safety Science*, 49, pp. 355–368.

Saurin, T.A., Wachs, P., Righi, A.W. and Henriqson, É. (2014) ‘The design of scenario-based training from the resilience engineering perspective: A study with grid electricians’, *Accident Analysis and Prevention*, 68, pp. 30–41.

Schack, C.M. and van den Essen, I. (2014) ‘Building organisational resilience - A fit for purpose approach’, *Society of Petroleum Engineers - SPE International Conference on Health, Safety and Environment 2014: The Journey Continues*, 1, pp. 48–57.

Scheffer, M., Carpenter, S., Foley, J.A., Folke, C. and Walker, B. (2001) ‘Catastrophic shifts in ecosystems’, *Nature*, 413

Scheytt, T., Soin, K., Sahlin-Andersson, K. and Power, M.K. (2006) ‘Special Research Symposium: Organizations and the Management of Risk - Introduction: Organizations, Risk and Regulation’, *Journal of Management Studies*, 43(6), pp. 1331–1337.

Schipper, D. (2017) ‘Challenges to multiteam system leadership : an analysis of leadership during the management of railway disruptions’, *Cognition, Technology & Work*, 19(2), pp. 445–459.

Scully, E., Dyer, C., Pleasance, C. and Mulraney, F. (2020) *More than 100 Brits are flown home after being evacuated from corona... https://www.dailymail.co.uk/news/article-8099369/More-100-Brits-fl...*, *Daily Mail Online* Available at: https://www.dailymail.co.uk/news/article-8099369/More-100-Brits-flown-home-evacuated-coronavirus-hit-Grand-Princess.html (Accessed: 15 March 2020).

Shiraki, W., Takahashi, K., Inomo, H. and Isouchi, C. (2017) ‘A Proposed Restoration Strategy for Road Networks After an Earthquake Disaster Using Resilience Engineering’, *Journal of Disaster Research*, 12(4), pp. 722–732.

Shirali, G.A., Mohammadfam, I. and Ebrahimipour, V. (2013) ‘A new method for quantitative assessment of resilience engineering by PCA and NT approach: A case study in a process industry’, *Reliability Engineering and System Safety*, 119, pp. 88–94.

Shirali, G.A., Motamedzade, M., Mohammadfam, I., Ebrahimipour, V. and Moghimbeigi, A. (2016) ‘Assessment of resilience engineering factors based on system properties in a process industry’, *Cognition, Technology and Work*, 18, pp. 19–31.

Shirali, G.A. and Nematpour, L. (2019) ‘Evaluation of resilience engineering using super decisions software’, *Health Promotion Perspectives*, 9(3), pp. 191–197.

Shirali, G.A., Shekari, M. and Angali, K.A. (2016) ‘Quantitative assessment of resilience safety culture using principal components analysis and numerical taxonomy: A case study in a petrochemical plant', *Journal of Loss Prevention in the Process Industries*, 40, pp. 277–284.

Shirali, G.H.A., Mohammadfam, I., Motamedzade, M., Ebrahimipour, V. and Moghimbeigi, A. (2012a) 'Assessing Resilience Engineering Based on Safety Culture and Managerial Factors', *Process Safety Progress*, 31(1), pp. 17–18.

Shirali, G.H.A., Motamedzade, M., Mohammadfam, I., Ebrahimipour, V. and Moghimbeigi, A. (2012b) 'Challenges in building resilience engineering (RE) and adaptive capacity: A field study in a chemical plant', *Process Safety and Environmental Protection*, 90, pp. 83–90.

Sillers, P. (2020) *Ghost flights: Why our skies are full of empty planes*., *CNN Travel* Available at: https://edition.cnn.com/travel/article/airport-slots-ghost-flights/index.html (Accessed: 14 March 2020).

Sisto, A., Vicinanza, F., Campanozzi, L.L., Ricci, G., Tartaglini, D. and Tambone, V. (2019) 'Towards a Transversal Definition of Psychological Resilience: A Literature Review', *Medicina (Lithuania)*, 55(11), pp. 745–767.

Sky News (2020) *Coronavirus: 135 Britons from quarantined Grand Princess ship flying back to UK*. Available at: https://news.sky.com/story/coronavirus-135-britons-from-quarantined-ship-flying-back-to-uk-11955033 (Accessed: 15 March 2020).

Snook, S. (2000) *Friendly Fire*. Princeton, New Jersey: Princeton University Press.

Son, C., Bernat, M. and Sasangohar, F. (2013) *Towards More Resilient Performance of Emergency Departments*

Son, C., Sasangohar, F., Neville, T., Peres, S.C. and Moon, J. (2020) 'Investigating resilience in emergency management: An integrative review of literature', *Applied Ergonomics*, 87

Sperstad, I.B., Kjølle, G.H. and Gjerde, O. (2020) 'A comprehensive framework for vulnerability analysis of extraordinary events in power systems', *Reliability Engineering and System Safety*, 196

Sridhar, B., Chatterji, G.B., Grabbe, S. and Sheth, K. (2002) 'Integration of traffic flow management decisions', *AIAA Guidance, Navigation, and Control Conference and Exhibit*. Monterey, California.

Steen, R. and Aven, T. (2011) 'A risk perspective suitable for resilience engineering', *Safety Science*, 49, pp. 292–297.

Sujan, M., Spurgeon, P. and Cooke, M. (2015) 'The role of dynamic trade-offs in creating safety - A qualitative study of handover across care boundaries in emergency care', *Reliability Engineering and System Safety*, 141, pp. 54–62.

Sun, X., Wandelt, S. and Zhang, A. (2020) 'How did COVID-19 impact air transportation? A first peek through the lens of complex networks', *Journal of Air Transport Management*, 89

Sundström, G. and Hollnagel, E. (2006) 'Learning how to create resilience in business systems', in Hollnagel, E., Woods, D. D. and Leveson, N. (eds.) *Resilience Engineering: Concepts and Precepts*. Boca Raton, USA: CRC Press, pp. 235–252.

Sutcliff, K.M. and Christianson, M.K. (2013) *Managing for the Unexpected*.

Ta, C., Goodchild, A. V. and Pitera, K. (2009) 'Structuring a Definition of Resilience for the Freight Transportation System', *Transportation Research Record*, 2097, pp. 19–25.

Taghi-Molla, A., Rabbani, M., Gavareshki, M.H.K. and Dehghani, E. (2020) 'Safety improvement in a gas refinery based on resilience engineering and macro-ergonomics indicators: a Bayesian network – artificial neural network approach', *International Journal of System Assurance Engineering and Management*, 11(3), pp. 641–654.

Taleb-Berrouane, M. and Khan, F. (2019) 'Dynamic Resilience Modelling of Process Systems', *Chemical Engineering Transactions*, 77, pp. 313–318.

Tang, J. and Heinimann, H.R. (2018) ‘A resilience-oriented approach for quantitatively assessing recurrent spatial-temporal congestion on urban roads’, *PLoS ONE*, 13(1)

Teodorović, D. and Janić, M. (2022) ‘Transportation Systems’, in *Transportation Engineering*. Second Edi. Oxford, UK: Butterworth-Heinemann, pp. 5–62.

The Free Dictionary (2022) *air transportation system*., *Farlex* Available at: https://www.thefreedictionary.com/air+transportation+system (Accessed: 8 June 2022).

Thieme, C.A. and Utne, I.B. (2017) ‘Safety performance monitoring of autonomous marine systems’, *Reliability Engineering and System Safety*, 159, pp. 264–275.

Thomas, J. and Harden, A. (2008) ‘Methods for the thematic synthesis of qualitative research in systematic reviews’, *BMC Medical Research Methodology*, 8

Thomas, J.E., Eisenberg, D.A., Seager, T.P. and Fisher, E. (2019) ‘A resilience engineering approach to integrating human and socio-technical system capacities and processes for national infrastructure resilience’, *Journal of Homeland Security and Emergency Management*

Tian, J., Lin, Z. and Wang, F. (2020) ‘Ant Colony Optimization Algorithm for understanding of trade-offs between safety and benefit: a case of Beijing taxi service system’, *Cognition, Technology & Work*, 22, pp. 489–499.

Tjorhom, B. and Aase, K. (2011) ‘The Art of Balance: Using Upward Resilience Traits to Deal with Conflicting Goals’, in Erik Hollnagel, Jean Paries, David Woods, J. W. (ed.) *Resilience engineering in Practice: A guidebook*. Ashgate, pp. 157–170.

Tofukuji, N. (1993) ‘An Enroute ATC Simulation Experiment for Sector Capacity Estimation’, *Transactions on Control Systems Technology*, 1(3), pp. 138–143.

Tokadli, G., Marzuoli, A. and Boidot, E. (2016) ‘Resilience of the national airspace system: A case study of the fire at the Chicago ARTCC', *AIAA/IEEE Digital Avionics Systems Conference - Proceedings*. Sacramento, USA.

Tomes, R. (1857) *The Americans in Japan: an abridgement of the Government narrative of the U.S. expedition to Japan, under Commodore Perry*. London, UK: British Library.

Topham, G. (2022) *Why have flights been cancelled and will problem be fixed by summer?*., *The Guardian* Available at: https://www.theguardian.com/business/2022/jun/06/why-have-flights-been-cancelled-and-will-problem-be-fixed-by-summer (Accessed: 8 June 2022).

Tran, H.T., Domercant, J.C. and Mavris, D.N. (2019) 'Parametric Design of Resilient Complex Networked Systems', *IEEE Systems Journal*, 13(2), pp. 1496–1504.

Tranfield, D., Denyer, D. and Smart, P. (2003) 'Towards a Methodology for Developing Evidence-Informed Management Knowledge by Means of Systematic Review', *British Journal of Management*, 14, pp. 207–222.

Tredgold, T. (1818) 'On the transverse strength of timber', *Philosophical Magazin: A Journal of Theoretical, Experimental and Applied Science*

Tukamuhabwa, B.R., Stevenson, M., Busby, J. and Zorzini, M. (2015) 'Supply chain resilience: Definition, review and theoretical foundations for further study', *International Journal of Production Research*, 53(18), pp. 5592–5623.

Turner, B. (1978) *Man-made Disasters*. London, UK: Wykeham Publications.

Tveiten, C.K., Albrechtsen, E., Wærø, I. and Wahl, A.M. (2012) 'Building resilience into emergency management', *Safety Science*, 50, pp. 1960–1966.

Vandaele, D., Rangarajan, D., Gemmel, P. and Lievens, A. (2007) 'How to govern business services exchanges: Contractual and relational issues', *International Journal of Management Reviews*, 9(3), pp. 237–258.

Vegas, M.R. and Del Yerro, J.L.M. (2013) 'Stiffness, Compliance, Resilience, and Creep Deformation: Understanding Implant-Soft Tissue Dynamics in the

Augmented Breast: Fundamentals Based on Materials Science', *Aesthetic Plastic Surgery*, 37(5), pp. 922–930.

Vogus, T.J. and Sutcliffe, K.M. (2007) 'Organizational Resilience: Towards a Theory and Research Agenda', *IEEE International Conference on Systems, Man and Cybernetics*., pp. 3418–3422.

de Vries, L. (2017) 'Work as Done? Understanding the Practice of Sociotechnical Work in the Maritime Domain', *Journal of Cognitive Engineering and Decision Making*, 11(3), pp. 270–295.

Wachs, P., Saurin, T.A., Righi, A.W. and Wears, R.L. (2016) 'Resilience skills as emergent phenomena: A study of emergency departments in Brazil and the United States', *Applied Ergonomics*, 56, pp. 227–237.

Wahl, A., Kongsvik, T. and Antonsen, S. (2020) 'Balancing Safety I and Safety II: Learning to manage performance variability at sea using simulator-based training', *Reliability Engineering and System Safety*, 195

Walker, B., Holling, C.S., Carpenter, S.R. and Kinzig, A. (2004) 'Resilience, adaptability and transformability in social-ecological systems', *Ecology and Society*, 9(2)

Wan, C., Yang, Z., Zhang, D., Yan, X. and Fan, S. (2018) 'Resilience in transportation systems: a systematic review and future directions', *Transport Reviews*, 38(4), pp. 479–498.

Wang, D. and Ip, W.H. (2009) 'Evaluation and Analysis of Logistic Network Resilience With Application to Aircraft Servicing', *IEEE Systems Journal*, 3(2), pp. 166–173.

Wang, J.W., Wang, H.F., Zhou, Y.M., Wang, Y. and Zhang, W.J. (2019) 'On an integrated approach to resilient transportation systems in emergency situations', *Natural Computing*, 18, pp. 815–823.

Watt, A., Jun, G.T. and Waterson, P. (2019) 'Resilience in the blood transfusion process : Everyday and long-term adaptations to " normal " work', *Safety Science*, 120, pp. 498–506.

Weaver, M. and Grierson, J. (2016) *Black Lives Matter protest stops flights at London City airport*., *The Guardian* Available at: https://www.theguardian.com/uk-news/2015/jul/13/heathrow-disruption-climate-change-activists-claim-chained-runway (Accessed: 10 October 2020).

Weber, D.E., Macgregor, S.C., Provan, D.J. and Rae, A. (2018) '"We can stop work, but then nothing gets done." Factors that support and hinder a workforce to discontinue work for safety', *Safety Science*, 108, pp. 149–160.

Westrum, R. (2006) 'A Typology of Resilience Situations', in Hollnagel, E., Woods, D. D. and Leveson, N. (eds.) *Resilience Engineering: Concepts and Precepts*. Boca Raton, USA: CRC Press, pp. 55–65.

Wheaton, M.J. and Madni, A.M. (2019) 'Model-based approach for resilience-affordability tradeoff analysis', *AIAA Scitech 2019 Forum*. San Diego, USA.

Whitson, J.C. and Ramirez-Marquez, J.E. (2009) 'Resiliency as a component importance measure in network reliability', *Reliability Engineering and System Safety*, 94, pp. 1685–1693.

WHO (2020) *Statement on the second meeting of the International Health Regulations (2005) Emergency Committee regarding the outbreak of novel coronavirus (2019-nCoV)*., *World Health Organization* Available at: https://www.who.int/news/item/30-01-2020-statement-on-the-second-meeting-of-the-international-health-regulations-(2005)-emergency-committee-regarding-the-outbreak-of-novel-coronavirus-(2019-ncov) (Accessed: 31 January 2020).

Williams, M.D. and Smart, A. (2010) 'Patient safety: a casualty of target success?', *International Journal of Public Sector Management*, 23, pp. 416–430.

Woltjer, R. (2019) 'Exploring Resilience at Interconnected System Levels in Air Traffic Management', in Wiig, S. and Fahlbruch, B. (eds.) *Exploring Resilience*. Springer International Publishing, pp. 105–112.

Woltjer, R., Pinska-Chauvin, E., Laursen, T. and Josefsson, B. (2013) 'Resilience

Engineering in Air Traffic Management', *Proceedings of 3rd SESAR Innovation Days*. Stockholm, Sweden.

Woltjer, R., Pinska-Chauvin, E., Laursen, T. and Josefsson, B. (2015) 'Towards understanding work-as-done in air traffic management safety assessment and design', *Reliability Engineering and System Safety*, 141, pp. 115–130.

Woods, D. (2006a) 'Engineering organizational resilience to enhance safety: A progress report on the emerging field of resilience engineering', *Proceedings of the Human Factors and Ergonomics Society*., pp. 2237–2241.

Woods, D.D. (2003) *Creating foresight: How resilience engineering can transform NASA's approach to risky decision making*.

Woods, D.D. (2015) 'Four concepts for resilience and the implications for the future of resilience engineering', *Reliability Engineering and System Safety*, 141, pp. 5–9.

Woods, D.D. (2006b) 'Essential Characteristics of Resilience', in Hollnagel, E., Woods, D. D. and Leveson, N. (eds.) *Resilience Engineering: Concepts and Precepts*. CRC Press, pp. 21–34.

Woods, D.D. (2011) 'Resilience and the Ability to Anticipate', in Erik Hollnagel, Jean Paries, David Woods, J. W. (ed.) *Resilience engineering in Practice: A guidebook*. Ashgate, pp. 121–126.

Woods, D.D. (2006c) 'Resilience engineering: Redefining the culture of safety and risk management', *Human Factors and Ergonomics Society Bulletin*, 49

Woods, D.D. (2018) 'The theory of graceful extensibility: basic rules that govern adaptive systems', *Environment Systems and Decisions*, 38, pp. 433–457.

Woods, D.D. and Cook, R.I. (2006) 'Incidents – markers of resilience or brittleness?', in Hollnagel, E., Woods, D. D. and Leveson, N. (eds.) *Resilience Engineering: Concepts and Precepts*. Boca Raton, USA, pp. 69–76.

Woods, D.D. and Hollnagel, E. (2006) 'Prologue: Resilience Engineering Concepts', in Hollnagel, E., Woods, D. D. and Leveson, N. (eds.) *Resilience*

Engineering: Concepts and Precepts. Boca Raton, USA: CRC Press, pp. 1–6.

Woods, D.D., Johannesen, L.J., Cook, R.I. and Sarter, N.B. (1994) *Behind human error: Cognitive systems, computers and hindsight*.

Woods, D.D. and Wreathall, J. (2008) 'Stress-strain plots as a basis for assessign system resilience', in Hollnagel, E., Nemeth, C. P. and Dekker, S. (eds.) *Resilience Engineering Perspectives Volume 1: Remaining Sensitive to the Possibility of Failure*. Farnham, UK: Ashgate, pp. 143–158.

Wreathall, J. (2006) 'Properties of Resilient Organizations: An Initial View', in Hollnagel, E., Woods, D. D. and Leveson, N. (eds.) *Resilience Engineering: Concepts and Precepts*. Boca Raton, USA: CRC Press, pp. 275–285.

Xu, G., Wang, J., Huang, G.Q. and Chen, C.-H. (2018) 'Data-Driven Resilient Fleet Management for Cloud Asset-enabled Urban Flood Control', *IEEE Transactions on Intelligent Transportation Systems*, 19(6), pp. 1827–1838.

Xu, L. and Kajikawa, Y. (2018) 'An integrated framework for resilience research: a systematic review based on citation network analysis', *Sustainability Science*, 13(1), pp. 235–254.

Yazdi, M., Adesina, K.A., Korhan, O. and Nikfar, F. (2019) 'Learning from Fire Accident at Bouali Sina Petrochemical Complex Plant', *Journal of Failure Analysis and Prevention*, 19, pp. 1517–1536.

Yeginsu, C. (2022) *Hold Onto Your Hats (and Bags). Travelers to Europe Face Chaos* ., *The New York Times* Available at: https://www.nytimes.com/2022/06/14/travel/travel-europe-tips-summer.html (Accessed: 8 June 2022).

Yin, R.K. (2018) *Case study research design and methods*.6th Editio. Thousand Oaks, USA: SAGE Publications LtD.

Yin, R.K. (1984) *Case Study Research Design and Methods*. Newbury Park, USA: SAGE Publications.

Yodo, N. and Wang, P. (2016) 'Resilience Allocation for Early Stage Design of

Complex Engineered Systems', *Journal of Mechanical Design*, 138

Yu, D.J., Schoon, M.L., Hawes, J.K., Lee, S., Park, J., Rao, P.S.C., Siebeneck, L.K. and Ukkusuri, S. V. (2020) 'Toward General Principles for Resilience Engineering', *Risk Analysis*, 40(8), pp. 1509–1537.

Yvon, P. and Carré, F. (2009) 'Structural materials challenges for advanced reactor systems', *Journal of Nuclear Materials*, 385, pp. 217–222.

Zaborek, P. (2009) 'Application of multiple case study method in doctoral dissertation', in Strzyżewska, M. (ed.) *Selected Methodological Issues for Doctoral Students*. 1st Editio. Warsaw, Poland: Warsaw School of Economics Publishing, pp. 83–98.

Zarrin, M. and Azadeh, A. (2019) 'Mapping the influences of resilience engineering on health, safety, and environment and ergonomics management system by using Z-number cognitive map', *Human Factors Management*, 29, pp. 141–153.

Zemba, V., Wells, E.M., Wood, M.D., Trump, B.D., Boyle, B., Blue, S., Cato, C. and Linkov, I. (2019) 'Defining, measuring, and enhancing resilience for small groups', *Safety Science*, 120, pp. 603–616.

Zhang, W.J. (2007) 'Is resilience a destiny of safety management paradigm?', *Seminar at the East China University of Science and Technology*.

Zhang, W.J. and Lin, Y. (2010) 'On the principle of design of resilient systems - application to enterprise information systems', *Enterprise Information Systems*, 4(2), pp. 99–110.

APPENDICES

Appendix A: Sources considered for SLR Stage 1

Aburn, G., Gott, M. and Hoare, K. (2016) 'What is resilience? An Integrative Review of the empirical literature', *Journal of Advanced Nursing*, 72(5), pp. 980–1000.

Ali, A., Mahfouz, A. and Arisha, A. (2017) 'Analysing supply chain resilience: integrating the constructs in a concept mapping framework via a systematic', *Supply Chain Management*, 22(1), pp. 16–39.

Bergström, J., van Winsen, R. and Henriqson, E. (2015) 'On the rationale of resilience in the domain of safety: A literature review', *Reliability Engineering and System Safety*, 141, pp. 131–141.

Bhamra, R., Dani, S. and Burnard, K. (2011) 'Resilience: The concept, a literature review and future directions', *International Journal of Production Research*, 49(18), pp. 5375–5393.

Bozza, A., Asprone, D. and Fabbrocino, F. (2017) 'Urban resilience: A Civil Engineering Perspective', *Sustainability (Switzerland)*, 9(1), pp. 103–120.

Curt, C. and Tacnet, J.-M. (2018) 'Resilience of Critical Infrastructures: Review and Analysis of Current Approaches', *Risk Analysis*, 38(11), pp. 2441–2458.

Datta, P. (2017) 'Supply network resilience: A systematic literature review and future research', *International Journal of Logistics Management*, 28(4), pp. 1387–1424.

Demiroz, F. and Haase, T.W. (2019) 'The concept of resilience: a bibliometric analysis of the emergency and disaster management literature', *Local Government Studies*, 45(3), pp. 308–327.

Gay, L.F. and Sinha, S.K. (2013) 'Resilience of civil infrastructure systems: Literature review for improved asset management', *International Journal of Critical Infrastructures*, 9(4), pp. 330–350.

Hohenstein, N.-O., Feisel, E., Hartmann, E. and Giunipero, L. (2015) 'Research on the phenomenon of supply chain resilience', *International Journal of Physical Distribution and Logistics Management*, 45, pp. 90–117.

Kamalahmadi, M. and Parast, M.M. (2016) ‘A review of the literature on the principles of enterprise and supply chain resilience: Major findings and directions for future research’, *International Journal of Production Economics*, 171 Elsevier, pp. 116–133.

Kochan, C.G. and Nowicki, D.R. (2018) ‘Supply chain resilience: a systematic literature review and typological framework’, *International Journal of Physical Distribution and Logistics Management*, 48(8), pp. 842–865.

Korber, S. and McNaughton, R.B. (2017) ‘Resilience and entrepreneurship: A systematic literature review’, *International Journal of Entrepreneurial Behaviour & Research*, 24(7), pp. 1129–1154.

Ma, Z., Xiao, L. and Yin, J. (2018) ‘Toward a dynamic model of organizational resilience’, *Nankai Business Review International*, 9(3), pp. 246–263.

Manyena, B., Machingura, F. and O’Keefe, P. (2019) ‘Disaster Resilience Integrated Framework for Transformation (DRIFT): A new approach to theorising and operationalising resilience’, *World Development*, 123

Meerow, S., Newell, J.P. and Stults, M. (2016) ‘Defining urban resilience: A review’, *Landscape and Urban Planning*, 147, pp. 38–49.

Oliveira, A.T.C. and de Morais, N.A. (2018) ‘Community Resilience: An Integrative Literature Review’, *Trends in Psychology*, 26(4), pp. 1747–1761.

Patriarca, R., Bergström, J., Di Gravio, G. and Costantino, F. (2018) ‘Resilience engineering: Current status of the research and future challenges’, *Safety Science*, 102, pp. 79–100.

Righi, A.W., Saurin, T.A. and Wachs, P. (2015) ‘A systematic literature review of resilience engineering: Research areas and a research agenda proposal’, *Reliability Engineering and System Safety*, 141, pp. 142–152.

Rodriguez-Sanchez, A.M. and Vera, M. (2015) ‘The secret of organisation success: A revision on organisational and team resilience’, *International Journal of Emergency Services*, 4(1), pp. 27–36.

Sisto, A., Vicinanza, F., Campanozzi, L.L., Ricci, G., Tartaglini, D. and Tambone, V. (2019) ‘Towards a Transversal Definition of Psychological Resilience: A Literature Review’, *Medicina (Lithuania)*, 55(11), pp. 745–767.

Ta, C., Goodchild, A. V. and Pitera, K. (2009) ‘Structuring a Definition of Resilience for the Freight Transportation System’, *Transportation Research Record*, , pp. 19–25.

Tukamuhabwa, B.R., Stevenson, M., Busby, J. and Zorzini, M. (2015) 'Supply chain resilience: Definition, review and theoretical foundations for further study', *International Journal of Production Research*, 53(18), pp. 5592–5623.

Wan, C., Yang, Z., Zhang, D., Yan, X. and Fan, S. (2018) 'Resilience in transportation systems: a systematic review and future directions', *Transport Reviews*, 38(4), pp. 479–498.

Xu, L. and Kajikawa, Y. (2018) 'An integrated framework for resilience research: a systematic review based on citation network analysis', *Sustainability Science*, 13(1), pp. 235–254.

Zhang, L., Lu, J., Fu, B. and Li, S. (2018) 'A Review and Prospect for the Complexity and Resilience of Urban Public Transit Network Based on Complex Network Theory', *Complexity*

Appendix B: List of presentations and developed lectures

List of presentations:

Air Transport Resilience, *Presentation at the Pilot Expo 2020*, Berlin, Germany, 21st – 22nd February 2020

Avoiding failure by implementing resilience proactively, *Presentation at the 24th Air Transport Research Society World Conference*, Virtual, 25th – 29th August 2021

UK aviation response to COVID-19, Presentation at the Complex and Interactive Processes Expert Meeting, Antwerp, Belgium, 26th – 27th November 2021

Learning from other industries – Aviation Resilience, *Presentation at the International Association of Harbor and Ports World Ports Conference*, Vancouver, Canada, 16th – 19th May 2022

When good planning is not good enough – the case of a repatriation flight during COVID-19, *Presentation at the 25th Air Transport Research Society World Conference*, Antwerp, Belgium, 24th – 27th August 2022

List of developed lectures:

Introduction to Resilience & Complex Systems, *MSc in Safety and Human Factors in Aviation*, Cranfield University, United Kingdom, 22nd October 2020 & 28th October 2021

Air Transport Resilience Management, *MSc in Air Transport Management*, Cranfield University, United Kingdom, 12th January 2021 & 11th January 2022

Strategies for Air Transport Resilience, *Executive Management in Air Transport Management*, Cranfield University, United Kingdom, 3rd March 2021 & 1st March 2022

System Resilience, *Executive MBA*, Sun Yat-sen University – Lingnan (University) College, China, 30th May 2021 & 12th June 2022

COVID-19, Resilience and the Future Prospects for Air Transport, *MSc in Air Transport Management*, Cranfield University, 25th October 2021

From Scratch to splash: Turning ideas into methodology, *MSc in Air Transport Management & MSc in Airport Planning and Management*, Cranfield University, United Kingdom, 03rd February 2022

Introduction to Organisational Resilience, *Executive MBA*, Antwerp Management School, Belgium, 15th February 2022

Resilience Management, *MSc Global Supply Chain Management*, Antwerp Management School, Belgium, 17th February 2022

Appendix C: Sample of Informed Consent Form

Informed consent form

Title of the project:	UK Aviation Response to COVID-19
Name of the researcher:	Fabian Steinmann
Researcher's contact details:	
Participant number:	
Date:	

Part 1: General information

1. I confirm that I have been informed about this research project and I agree to take part.
2. I understand that all personal information I provide will be treated with confidence and my name will not be used in any report, publication or presentation, unless explicit consent is given in Part 2.
3. I have been provided with a participant number as shown above. The researcher will record data against my participant number instead of recording my name. The file linking my name to my participant number will be accessible only to the main researchers and will be securely destroyed after twelve months.
4. I understand that I can withdraw from this project at any stage by informing a member of the research team, for whom contact details have been provided. I also understand that I can withdraw my data for a period of up to twelve months from today, as after this time it will not be possible to identify my individual data from the aggregated results as explained in point 3.
5. I understand that the data I provide will be used by Cranfield University for the purpose of research. The data will be stored on the University's network that can only be accessed by authorised users, in line with UK Data Protection Act 2018.
6. Interviews will be recorded and securely stored on the Cranfield University network as audio files. These audio files will be securely deleted as soon as they are no longer required. The recordings will be transcribed and saved as text files. These files (and any backups) will also be securely deleted as soon as they are no longer required.

Part 2: Consent

I hereby give my consent that my name can be used in any report, publication or presentation.	Yes No	☐ ☐
I hereby give my consent that my position within the organization can be used in any report, publication or presentation.	Yes No	☐ ☐
I hereby give my consent that the name of my organization can be used in any report, publication or presentation.	Yes No	☐ ☐

Should the participant wish not to be linked with the interview, anonymised transcripts will be created, by removing or replacing identifiers such as name, age, and location. These anonymised transcripts may be quoted from or published in full, in support of findings (e.g. in journal articles, conference papers).

I am happy for my transcript to be published	Yes No	☐ ☐
I am happy for my anonymised transcript to be published	Yes No	☐ ☐

Analytical software will be used to aggregate the results of the research and every reasonable step will be taken to anonymise the data.

I understand that the aggregated data will be published in support of the research findings.	Yes	☐

I confirm that I have read and understand the information provided on this form and give my consent to taking part in this research.

Participant's signature:		Date:	
Participant's name:			
Researcher's signature:		Date:	

Appendix D: Semi-structured interview questions for case study 5

Main questions for semi-structured interviews with IRG members

1- **What were the main challenges for your organization related to COVID-19?**
   a. Lack of information
   b. Lack of clarity
   c. Lack of guidance
2- **When did you realize the severity of the disruption?**
   a. Leading indication
3- **What actions did you take and when to cope with crisis?**
   a. Reorganization
   b. COVID-19 Intel Group
4- **What went well?**
5- **How did you see the role of the IRG/ODLG and what was your expectation?**
   a. Facilitator for discussion
   b. Distribution of information
   c. Access point for DfT into industry
   d. Coordinator
6- **What did the IRG/ODLG do to support the industry during crisis?**
   a. Provide information
   b. Clarify process
   c. Provide guidance
   d. Enabled cross-industry learning
7- **What additional support could the IRG have provided?**
   a. Expectations which were not met
   b. What was the reason you joined IRG?
8- **Are there any other issues which you think need to be addressed for a more successful cross-industry collaboration?**
   a. Well established escalation process
   b. Governance during major crises