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Published in:
Safety Science

DOI:
10.1016/j.ssci.2024.106498

2024

Document Version:
Publisher's PDF, also known as Version of record

Safety Science 175 (2024) 106498

Contents lists available at ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/safety

Dark knights: Exploring resilience and hidden workarounds in commercial aviation through mixed methods

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ARTICLE INFO

Keywords:
Adaptive capacity
Aviation safety
Human factors
Resilience
Responsibilization
Workload

ABSTRACT

In this study, the duality of adaptive capacity in aviation safety is examined, where the need for resilience of frontline workers conflicts with the expectations and assumptions of upstream entities, leading to system brittleness. We explore three critical categories: responsibilization, the application of practical wisdom in navigating challenging situations, and the unrecognized sacrifices that accompany adaptation. A qualitative research design is used, using three focus groups consisting of pilots in a European airline, the airline's safety department, and the respective civil aviation authority. The study's findings reveal *i.* significant organizational constraint and pressure on pilots, resulting in workarounds, personal playbooks, and exhaustion, *ii.* a culture of apathy, cynicism, and secrecy, contributing to a disconnect between the idealized and practical aspects of work (work-as-imagined versus work-as-done), *iii.* an oversimplification of complex issues and attributing problems to individual factors rather than systemic factors, *iv.* normalizing the risk of saturation by pushing the boundaries of safe performance, and *v.* the current prescriptive training approach may increase risk by not accounting for adaptations that are necessary in the frontline work environment. Recognizing both the technical and social complexities of aviation, the study calls for a reimagined framework away from a prescriptive training approach, as it may increase risk by not accounting for adaptations that are necessary in the frontline work environment. In summary, the study presents a nuanced view of aviation as a complex system, where the push for adaptivity is challenged by ethical dilemmas and trade-offs. Left unresolved, this conflict may hinder aviation safety.

1. Introduction

In aviation, instances of resilience have been displayed in many high-profile incidents and accidents. Examples include United 232, Qantas 32, and US Airways 1549 'Miracle on the Hudson' (Martin, 2019). During these events, flight crews faced with conditions for which training did not exist and had to rely on human ingenuity to create novel heuristics under intense time compression. Pilots often encounter situations not foreseen by operational manuals, requiring them to navigate challenges for which training has not been provided (Stanton et al., 2019). These have been termed *black swan* events (Wickens et al., 2009). Recovery from these near disasters captures public attention, often bestowing heroic status to the captain (McCall, 2017). In 2023, a spate of ground-based close calls revealed instances of resilient performance between air traffic control (ATC) and flight crews (NTSB, 2023). Disaster was averted either through technology or human intervention. In 2024, a detachment of an Alaska Airlines door during flight displayed remarkable resilience in aircraft design; despite a hole in the fuselage, the aircraft returned for a safe landing (Glanz et al., 2024).

What is less understood in aviation is progenitor organizational factors that exist upstream that may either promote or hinder resilient behavior on the front line. Paradoxically, these factors are embedded as standard operating procedures; however, they are routinely deviated from in a highly complex and dynamic environment such as aviation (Giles, 2013; Malakis and Kontogiannis, 2023). As flight crews operate in a tightly coupled, decentralized system (Perrow, 1999), crew autonomy and judgement eclipse procedural compliance in an effort to get the job done. This chasm may then have an amplifying effect, where 'dark'

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https://doi.org/10.1016/j.ssci.2024.106498
Received 24 November 2023; Received in revised form 11 February 2024; Accepted 12 March 2024

procedures become commonplace and the reliance on resilience becomes normalized. Furthermore, the heroic captain can be seen as the 'knight', requiring a balance between strict adherence to formalized duty against a high level of flexibility, adaptability and resilience when time calls.

As aviation has advanced with understanding of technological, organizational, and human factors, corollary challenges have resulted, including skill degradation (automation), perfunctory check-the-box audits (safety management systems), and cognitive overload (electronic flight bags) (Miller and Holley, 2019; Volz et al., 2016). The resilience construct thus far has been understood to be a beneficial attribute in aviation (see, e.g., Carroll and Malmquist, 2022; Woltjer, 2019); however, like the advancements mentioned, it may lead to unintended consequences. Recent scholarship has begun to address these challenges with resilience, including the normative trap and the necessity of system preservation (Dekker, 2019). This study seeks, in part, to continue the line of inquiry advocated by Dekker.

Despite the adoption of safety management systems (SMS) and its holistic approach, the aviation industry has often attributed operational failures to 'human error', emphasizing the deficiencies of individual operators (Reason, 1997). Remedial measures, such as additional simulator training, downgrading, or even termination of employment, have been conventional responses to these perceived shortcomings (Dekker et al., 2008; Johnson, 2006; Rasmussen, 1997). Consequently, studies have raised questions about the alignment between training effectiveness and the reality of the frontline working environment (Bergström, 2019; Dekker, 2011). These studies challenge existing assumptions of aviation as a simplistic system where frontline personnel's behavior modification through training alone is sufficient to prevent incidents and accidents. Safety science has introduced a 'second story' that highlights an inherent lack of safety in the system (Dekker, 2011, p. 3; Woods and Cook, 2002), suggesting that prescriptive training may not be adequate to meet the demands of the complex socio-technical nature of aviation (Adriaensen et al., 2019; Grøtan and van der Vorm, 2015; Patriarca, 2018). In this regard, the pursuit of resilience in aviation has become increasingly critical in enhancing system robustness and managing the complex interplay of factors that impact safety and operational efficiency.

Seeking resilience involves modifying training programs based on feedback and data from incidents and audits, which helps in shaping desired behavior and competency levels (Alderson et al., 2022; Carroll and Malmquist, 2022). Thus, training plays a vital role in ensuring system safety and preparing frontline personnel for their functions within the socio-technical system (Steen and Pollock, 2022). However, this approach assumes the need for well-designed work structures and functions in a safety–critical industry, which may not fully capture the complexity of the system (Heylighen et al., 2006).

As a result of the demands of novel situations without available heuristic grounding, pilots can develop personal strategies to meet airline demands and meet operational goals. This study raises concerns about the efficacy of current prescriptive-based training, given the complex socio-technical system aviation exists in, leaving frontline personnel to figure things out independently. It also examines the underlying mechanisms that influence work and the potential outcomes that may arise, especially in the context of resilient performance. Therefore, our singular research question (RQ) focuses on the resilience aspect: How does reliance on resilient performance in aviation impact system brittleness and overall performance and safety?

To address this RQ, the study concentrates on examining specific values and interests within power dynamics at different levels of analysis, exploring the interplay between rationality, power, and the spectrum of meanings across micro-, meso-, and macro- levels. By exploring these dynamics, the research aimed to illuminate the complex interactions and influences that shape decision-making processes. The choice of a focus group was justified by its potential to facilitate in-depth discussions and capture diverse perspectives, using a purposeful sampling strategy (Suri, 2011). By integrating micro-level stories with meso- and macro-level perspectives, we achieved a comprehensive understanding of the complex dynamics within the system.

Three focus group interviews using a sequential modified Delphi approach, encompassing the micro-level (pilots), *meso*-level (safety department), and macro-level (Civil Aviation Authority). This approach provided a comprehensive perspective to grasp the intricate system dynamics within aviation (Bugalia et al., 2021). From these interviews, three key themes emerged: i) responsibilization; ii) using experience to solve double binds, and iii) hidden and unintended sacrifices of adaptations.

The construct of responsibilization coincides with a shift toward neoliberalism by the end of the twentieth century, where centralized societal structures were gradually eroded by privatization, deregulation, and a host of other initiatives (Brown, 2006; Dekker, 2020). Responsibilization, as originally conceived by Shamir (2008) and Gray (2009), addresses the polarity change from the duty of care for worker safety to that of the worker themselves. It relies on the intrinsic moral capacity of frontline social actors as a root motivation for action, lessening the role of governance and formal oversight (Selznick, 2002). While touted as an equal partnership, responsibilization in fact places more responsibility on workers, because they are conspicuously exposed to unsafe conditions (Gray, 2009).

The study findings reveal the significant influence of organizational constraints and pressures on pilots, resulting in increased stress levels, exhaustion, and associated risks. Additionally, they uncover a culture of secrecy within the aviation industry, contributing to a disconnect between the idealized and practical aspects of work, which, in turn, raises concerns about safety and well-being. Moreover, the research emphasizes the vital role of experience-based adaptation in ensuring operational effectiveness, highlighting the need for a broader perspective in training and work design. Furthermore, it raises critical questions about the alignment of regulatory constraints with the practical realities of aviation operations.

This paper also examines the practices and strategies of adaptive capacities employed by frontline personnel, particularly pilots, to understand how and why these adaptive strategies are adopted within the aviation system. Additionally, consideration is given to the perspectives of the safety department at the same airline (*meso*-level) and the national Civil Aviation Authority (macro-level) to gain a broader understanding of how adaptive capacities propagate in emergent features at different system levels.

The paper is structured as follows. Section two provides a background of resilience in aviation and contextualizes this study in the literature. Section three describes the research methodology, which is grounded in the work of Rasmussen (1997) and builds on a three-tier approach as elucidated by Bergström and Dekker (2014). Section four provides an overview of the study findings, revealing hidden and unintended adaptation sacrifices. Finally, section five provides a discussion, places the study in the literature, identifies limitations, and suggests lines of inquiry for future research.

2. Background: resilience in the aviation context

The concept of resilience engineering (RE) was introduced at the turn of the millennium, acknowledging the need to adopt a more holistic perspective in safety management. As safety critical organization operations become complex and opaque systems to the point of incomprehensibility, a subdiscipline emerged to study human operators as adaptive contributors, balancing safety and productivity in a not only imperfect but fundamentally intractable system (Dekker, 2012; Holbrook et al., 2019). RE emphasizes the crucial role of humans in aviation safety, enhancing adaptive capacity (Dekker, 2006; Hollnagel, 2014), and challenges the notion that training focused solely on following procedures, or that rote procedural compliance can fully equip for work in a dynamic sociotechnichal system (Bergström et al., 2011; Dekker, 2011).

While the notion of resilience is used for analytical purposes in fields such as engineering, health sciences, and socio-ecology; the adoption of the term rather finds its theoretical heritage in 'Rasmussian cybernetics' and complexity theory (Bergström and Dekker, 2019). Rooted in Ashby's cybernetics (Ashby, 1957), Rasmussen dedicated much of his safety science discourse to how people adapt to rapidly changing conditions in naturalistic high-risk environments (Le Coze, 2015a, 2015b; Rasmussen, 1997; Rasmussen and Lind, 1981; Rasmussen et al., 1990; Waterson et al., 2017). Although Rasmussen did not use the term *resilience*, resilience engineering becomes a rather logical continuation of cognitive systems engineering (Bergström and Dekker, 2019). This is supported by both Woods and Hollnagel's later scholarship relating to RE, and their theoretical grounding in Rasmussen's earlier work (Dekker et al., 2008; Woods and Hollnagel, 1987). Advancements in aviation safety management have also mapped to the evolution of these discourses, from early crew resource management (CRM) and prescriptive-based simulator training to advanced threat and error management (TEM) and flexible scenario-based training (SBT).

The RE community generally focuses on resilience as a normatively positive capability (Cantelmi et al., 2022; Steen et al., 2022). Indeed, in aviation, the connotations of resilience are aligned with positive attributes (see, e.g., Carroll and Malmquist, 2022; Muecklich et al., 2023). However, there is a gap in the literature on alternative perspectives of resilience as a neutral or possibly negative influence. Aligned with the socio-ecological view on resilience, our study suggests that resilient behavior at one system level might unintentionally conceal or even create new pathways for system brittleness at other levels (Bergström and Dekker, 2019; Bergström et al., 2015; Perry and Wears, 2012). This problem is typically referred to in terms of a system being 'locally adaptive but globally maladaptive' (Woods and Branlat, 2011). An additional aspect of not seeing resilience as normatively good is that it allows us to analyze adaptive capacities in terms of what values different actors are trying to protect with their adaptive strategies, and at what temporal scales their adaptive strategies are intended to function (Lama et al., 2017). In other words, adaptive strategies can manifest trade-offs between protecting certain values concurrently or aiming at more long-term goals and values.

RE has grown to become the leading theoretical framework in aviation safety science research (Muecklich et al., 2023), in part due to its flexibility for multiple viewpoints (system, organizational, human factors) and its allowance for analysis of normal work. This is important because aviation has become the safest mode of transportation (Oster et al., 2013). Consequently, accidents rarely offer systemic learning opportunities. Aviation benefits from robust data acquisition (Norman, 2022a), and searching for lower-severity events and leading indicators has become the new paradigm of safety management in this industry (Carroll and Malmquist, 2022; Norman, 2022b; Walker, 2017). Furthermore, RE's emphasis on focusing on why things went well, in addition to why things fail, aligns closely with the just culture construct, which has been widely adopted in the aviation domain (Buttigieg et al., 2024; Smith, 2015).

3. Research methodology

3.1. Research approach

Using the Rasmussen socio-technical system model (Rasmussen, 1997a), we analyzed the interactions between regulators, management, and staff (pilots) to understand their impact on overall system performance. The objectives of this research were to understand resilient performance, identify emergent properties resulting from adaptive capacities, critically evaluate system features that influence resilient performance from micro-, meso-, and macro- perspectives, and assess the emergence of unintended consequences from resilient performance and their impact on system behavior.

Inspired by critical realism (Pettersen et al., 2010) and phronetic research (Flyvbjerg, 2012; Hadjimichael and Tsoukas, 2023; Petersén and Olsson, 2015), we seek to understand contextual factors (e.g., values and powers) that shape practical decision-making skills. In the aviation sector, the interaction between phronesis (practical wisdom), techne (technical skills), and episteme (theoretical knowledge) forms a crucial framework essential for handling the intricate challenges present in daily operations. Although aviation traditionally focuses on the techne and episteme, evident in technical skills training and deep theoretical knowledge, the role of phronesis becomes critical in dealing with unpredictable real-world scenarios (Knudsen, 2009; Shotter and Tsoukas, 2014). This leads to phronesis being a logical framework for investigating resilient behavior, as constant changes in the environment, aircraft state, airspace, and other factors encourage aviation actors to rely on phronetic wisdom (Malakis and Kontogiannis, 2023).

By integrating micro-level stories with meso- and macro-level perspectives, we achieved a comprehensive understanding of the complex dynamics within the system. We focused on examining specific values and interests within power dynamics at different levels of analysis, exploring the interplay between rationality, power, and the range of meanings across micro-, meso-, and macro- levels. Through exploration of these dynamics, the research sought to shed light on the complex interactions and influences that shape decision-making processes. A qualitative research methodology was used to explore the research topic. The choice of a focus group was rationalized by its potential to facilitate in-depth discussions and capture diverse perspectives, and its use in the literature for the study of socio-technical systems such as aviation (Salehi et al., 2021). To this end, a purposeful sampling strategy was used (Suri, 2011).

3.2. Data collection

3.2.1. Study sample

This study began by interviewing pilots employed by a European aircraft, crew, maintenance and insurance (ACMI) carrier. Also known as 'wet lease' programs, these carriers can provide leasing capacity to other carriers to meet seasonal demand, fill a maintenance gap in existing fleets, or conduct charters, among other possibilities (Vasigh and Azadian, 2022). Due to the varied nature of ACMI flying, crews may encounter various constraints such as unfamiliar destinations, demanding geographical operations, adaptation to different carriers' procedures, and increased on-time performance scrutiny. These constraints introduce significant challenges in the working environment, constantly demanding coordination from the pilots, who may not have access to the same tools as the parent airline for which they are flying. The scope of the study then expanded to the ACMI safety department, and finally the Civil Aviation Authority (CAA) of the respective carrier.

3.2.2. Data gathering: focus group interviews

The study employed focus group interviews (Nyumba et al., 2018), using a sequential modified Delphi approach (Hecht, 1979). This approach allowed us to refine the specific purpose of each question and create a sequence of questions that would assist in deriving themes for further analysis. To frame the collection of the initial scope for the focus group data, the researchers adopted cognitive task analysis (CTA) (Crandall and Hoffman, 2013). Three separate sequential interviews were conducted (see Table 1), each of which expanded in scope. The first interview aimed to capture pilots' real-life experiences (micro-level) and understand the extent to which adaptive strategies promote resilient performance and graceful extensibility (Woods, 2018). This practical insight was crucial to uncovering any unintended consequences resulting from sustained adaptability, shedding light on the underlying mechanisms that influence behavior and power dynamics across levels.

Building upon insights from the first group, the safety department (*meso*-level) became the next focus group, where pilots' feedback was iteratively used without disclosing details from the initial session. This

Table 1
Respondents, level, and position.

Focus group	Level	Number of participants	Position	Identification	Experience (hours/years)
1	Micro-	45	Flight commanderFirst officer	P1-P4P5-P9	9000–18000 hrs. 1500–8900 hrs.
2	Meso-	3	Head of safety/ Flight commander	S1-S3	5500–8500 hrs.
3	Macro-	6	Chief inspector	C1-C6	0–13 yrs., 200–14000 hrs.

interview explored system features and their role in explaining micro-level dynamics. It also sought to gauge the meso- group's understanding of sustaining daily operations, including assumptions about safety, work-as-done (Hollnagel, 2014), and implicit power relations. Finally, a macro- group was established, involving a European Civil Aviation Authority (CAA) at the highest level. Here, the specific airline's identity remained undisclosed, allowing for a broader perspective on industry trends and patterns. Through the CAA inspectors' lens of rules, regulations, and audits, the aim was to uncover challenges faced by frontline personnel (micro-level) and gain insights into emerging issues.

3.2.3. Selection of respondents

To match our participants in the focus group interview with the objectives of this study, a purposive sampling approach was applied, which involved participants who have adequate expertise in the domain of interest (Campbell et al., 2020). The respondents were selected from the ACMI airline that agreed to participate, with pilots attending a recurrent CRM course, as well as a separate meeting a few weeks later with the safety department. However, the airline emphasized that the participants would remain anonymous for the purpose of this investigation. Participants at the CAA level were obtained from an existing professional relationship between one of the researchers and the Authority. The following table describes the participants.

The three focus group interviews were conducted using a semi-structured approach. Drawing from the Critical Decision Method (Klein et al., 1986), a four-question interview protocol was formulated which aimed to delve into the narratives of the interviewees and access their extensive experience and expertise. This method facilitated the uncovering of valuable insights and allowed observations of group dynamics within the room. Attention was paid to both explicit and implicit interactions, with a meticulous notation of unspoken cues and subtle signals exchanged among participants during the discussions. Table 2 outlines the protocol used during the interviews.

The groups received an initial 25 min to discuss each question before the facilitation process began (Table 2). Throughout the facilitation, additional open-ended sub questions were posed, considering the flow of the conversation and the collaborative interaction between the interviewer (us) and the interviewees. By prompting participants to share challenging or difficult situations they encountered in their daily operations, researchers were able to delve deeper into their tacit knowledge narratives. To ensure accurate data collection, permission was obtained from interviewees and a digital recorder was utilized to capture the discussions.

Before the three focus group interviews, the participants received an informed consent form, which they read and acknowledged. Each group interview lasted approximately two hours. To protect the confidentiality of the participants, the researcher deidentified any personal information shared during the transcription process. This involved removing names, locations, organizational slang, or any other details that could potentially be linked to an individual. The interviewees signed an informed consent form that included various details, such as the plan and purpose of the research, the methods that would be used, the possible consequences and risks associated with the research, and the voluntary nature of participation. In addition, it was made clear that participants had the right to terminate their participation at any time.

Table 2
Interview protocol.

Question	Purpose	Theoretical grounding
Discuss one or two situations that you find challenging to deal with in the daily operation.	Enable interviewees to reflect on their experiences, particularly in relation to adversity (brittleness) and resilience	Explore how resilience manifests itself in daily operations.
What resources do you consider essential for coping and adapting in such situations?	Gain insights into the interviewees' perspective on the components of resilience and what attributes individuals believe are necessary to exercise resilience.	Identify the aspects associated with resilience. Additionally, we sought to examine whether there exists both a positive and potentially negative (dark) side to exercising resilience.
What impact do these adaptations have on daily operations?	Understand how resilience enhances the ability to handle daily disruptions and changes and to identify challenges that may arise.	Connected to operational continuity, our objective was to investigate how resilience contributes to their maintenance and to identify potential consequences that may arise as a result.
Do you believe there are instances where the crew absorbs and adopts an excessive or disproportionate amount?	To find out if they find that there is a 'dark' side to resilience.	Examine whether resilience could contribute to system brittleness.

Additionally, one of the coauthors conducted the interviews and personally transcribed all the recordings to ensure the highest level of confidentiality and accuracy, particularly regarding vocabulary specific to the aviation lexicon. Other coauthors received a copy of the transcribed document for data analysis purposes. During the group work, field notes were recorded, noting pertinent terminology from the groups, as it was challenging to clarify certain points from the recorded conversations alone. To accommodate the number of interviewees, the pilots were divided into two groups, called the red team and the blue team. During the facilitation, red and blue whiteboard markers were used to distinguish between groups, simplifying our data organization. The flip charts and initial brainstorming that were documented served as a mind map after the workshop and were included as artifacts of our data collection process.

3.3. Data analysis

From a theoretical standpoint, the study's investigators emphasized the crucial role of frontline personnel in modifying structures within a socio-technical system to ensure smooth functioning. By integrating the perspectives of the safety department (meso-) and the CAA (macro), our goal was to comprehensively understand these relationships and their impact on the performance of frontline operators (micro). Our inductive approach recognized diverse interpretations and meanings while acknowledging potential power dynamics and multiple voices.

Understanding cognition within its context involved considering cognitive processes alongside relevant cues, factors, and goals. Concept maps were used in all groups (micro-, meso-, and macro-) to facilitate knowledge elicitation and identify key themes for further analysis. Thus, our framework adhered to the fundamental principles of CTA.

The analytical process began with the transcription of the focus group interviews, during which areas of interest were marked on the transcripts, with data initially captured in the Danish language. The transcripts were translated from Danish into English by a researcher fluent in both languages and an expert in the subject matter of aviation. This proficiency ensured that phrases and euphemisms unique to airline operations were accurately reflected in the translation. A thorough review of the data ensued, which involved reviewing the recorded tapes and multiple examinations of the transcripts to ensure fidelity to the original discussions. By including cross-links (Novak and Cañas, 2008), statements from participants were collated and displayed on large posters for analytical reflection, and concept maps were constructed to facilitate knowledge elicitation between all groups.

In the next phase of our analysis, a detailed coding procedure was conducted. This thorough approach involved carefully identifying key phrases and recurring topics from the transcripts and assigning them initial codes that succinctly captured their essence. A wide array of concepts emerged, such as mental health limits, workload, human error, practical wisdom, heuristics and intuition, and compliance. These initial codes were iteratively refined, leading to the creation of 44 distinct codes that encapsulated the nuanced insights from the focus group discussions.

The analytical journey did not end with coding. The 44 codes were then thoughtfully synthesized into eight coherent themes. These themes represented crucial aspects of the data, shedding light on the complexity and diversity of experiences and perspectives within the aviation sector. These eight themes provided a structured overview of the findings, illustrating the interconnected nature of the coded data. To further refine the complexity of these insights, the themes were organized into three aggregate levels, shown in Fig. 1. Together, these levels show how various dimensions of the aviation system unite to form a responsive and adaptive whole, capable of adjusting to both expected and unforeseen challenges. These levels take into account all three levels of abstraction as described in Section 3.1 (phronetic, epistemic, and techne).

Hierarchical categorization (Fig. 1) facilitated a structured interpretation of the data, with each level offering a more abstract perspective on the identified themes. This scientific approach improves understanding of safety and efficiency in aviation operations and ensures that the findings are aligned with the wider discourse in aviation research. Section 4 thoroughly explores the emerging themes and associated codes, a crucial process to reveal the diverse aspects of adaptation and their impact on aviation safety and efficiency.

4. Findings

4.1. Responsibilization

The following figure (Fig. 2) illustrates key themes identified from data analysis, which collectively contribute to the concept of 'responsibilization' in the aviation industry. It maps out the operational and cultural influences, ranging from ACMI operations to professional conduct, that shape and challenge industry standards for accountability and efficiency.

Pilots, representing the micro-level in our analysis, face challenges in their daily activities due to frequent procedure changes and adaptation to different operations. In one specific ACMI operation, time pressure was a major concern for the pilots, as they had to handle numerous last-minute changes that required recalculating the load sheet. This task often proved time-consuming and could lead to delays. The following table includes comments from participants highlighting issues associated with 'responsibilization'.

4.2. Using experience to solve double binds

There is a nuanced interplay between experience and expertise in resolving inherent contradictions. As illustrated in the following figure, pilots navigate complex scenarios by drawing on deep domain knowledge and practical wisdom. This expertise allows them to bridge the gap between rigid training protocols and the dynamic realities of flying. By adapting to the unpredictable and often messy details that extend beyond the scope of manuals, they craft adaptive strategies. These include the creation of homemade standard operating procedures (SOPs) and the establishment of personal minimums guided by heuristics and intuition. Collectively, these codes reveal a landscape where adherence to rules conflicts with the need for flexible, context-sensitive action, essential for maintaining safety and efficiency in the face of aviation's complex challenges.

The following table presents selected examples of comments from participants, offering concrete examples of the themes and codes identified in Fig. 3. It captures a subset of the insights provided, illustrating how pilots and aviation professionals apply their expertise and adaptive strategies in real-world contexts. Not all comments are included, but those chosen reflect the critical aspects of navigating the complexities within the aviation field.

4.3. Hidden and unintended sacrifices of adaptation

The study's findings reveal that adaptations within aviation, intended to enhance operations, often come with hidden and unintended costs. The following figure maps out these complexities, highlighting how routine adjustments can subtly shift risk perceptions and lead to an overreliance on quick fixes. These adaptations, influenced by internal power structures and a culture that may encourage secrecy, can obscure the real impact of such changes. Moreover, the figure points out the human aspect of these adaptations, emphasizing how stress and its consequent impact on well-being often become apparent only with hindsight.

Table 5 complements Fig. 4 by presenting concrete instances of comments from participants, revealing hidden and unintended sacrifices of adaptation.

5. Discussion of results

This section elucidates the data findings using three themes: responsibilization, solving double binds through experience, and hidden

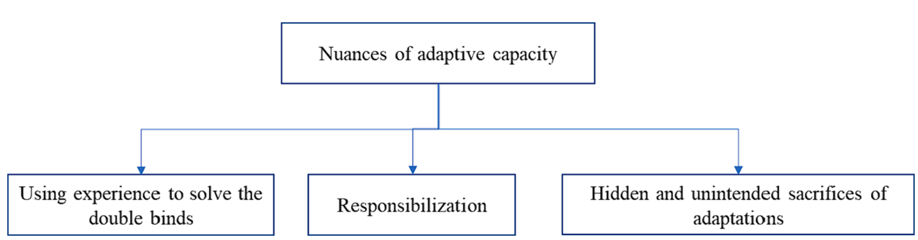

Fig. 1. Nuances of adaptive capacity.

Fig. 2. Responsibilization themes.

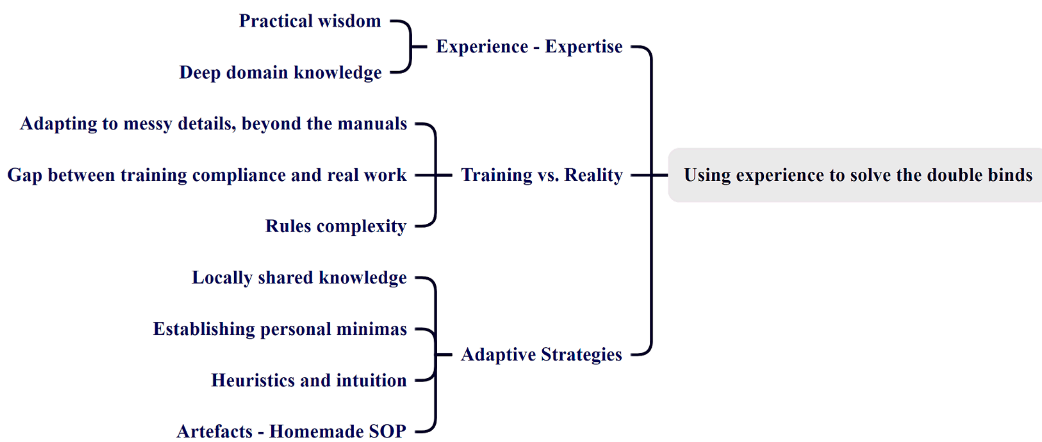

Fig. 3. Using experience to solve double-bind themes.

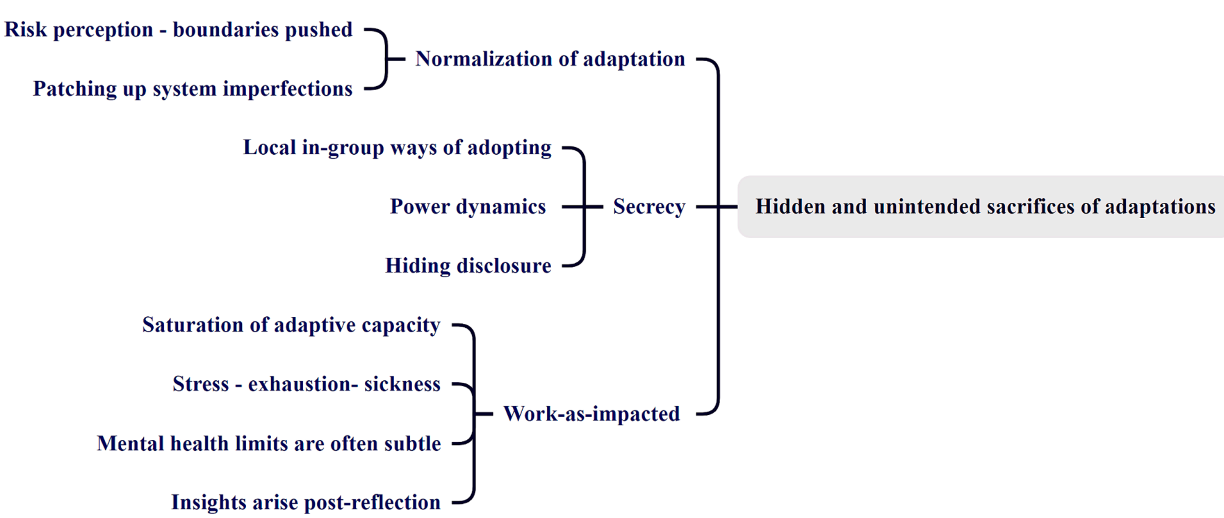

Fig. 4. Hidden and unintended sacrifices of adaptation themes.

sacrifices of adaptation. The goal is to understand the manifestation of relations and interactions within the system, relating them to the study's research question and the existing literature.

5.1. *Responsibilization*

In a dynamic work environment where operations vary significantly, rules and compliance alone are insufficient. Pilots must navigate complexities, exercise judgment, and adapt to meet on-time performance demands (Cherng et al., 2022). They develop strategies, sometimes resorting to shortcuts. However, this perspective might be misinterpreted by those not directly involved in daily operations. At the meso- level within the airline's safety department, the focus shifts toward ensuring procedure compliance, emphasizing the prevention of shortcuts. This approach aims to address a cultural issue, where cutting corners, even with good intentions, can backfire (S3). An epistemological stance favoring strict procedure adherence contrasts with pilots' experiences, revealing an alternative rationality. At the macro- level within the CAA group, the focus was on empowering pilots to say 'no' before reaching their limits (C4, Table 3).

According to a CAA respondent, there seems to be a prevailing perspective within aviation that justifying reasons for saying 'no' might be challenging. This implies that organizations prioritize adherence to rules over considering human factors in their work. These interactions indicate a form of responsibilization. What appears to be a necessary adaptation to operational and procedural constraints at the micro- level is seen as deliberate acts (Reason, 1997) of cutting corners at the meso- level, which can potentially result in negative outcomes. At the macro- level, it was observed that while rules allow pilots to say 'no', the social context and culture can create difficulties in doing so. Despite representing different rationalities, they share a common focus on placing responsibility in the hands of pilots.

To understand how pilots navigate these constraints, facilitators delved into the interplay between social context and individual actions (Snook, 2000). In ACMI operations, an influential factor emerged in the form of the organization's strong emphasis of on-time performance, which had a profound impact on the prevailing culture. As stated by one respondent (P9), pilots feel compelled to adapt to time constraints, as there is no longer an inclination to allocate the necessary time. Indicating a significant cultural influence on pilot behavior, the company's strong drive to complete tasks promptly over safety becomes evident.

The value of taking necessary time is not recognized by management, and time constraints and on-time performance were not discussed at the meso- level. Implicit expectations of being a good pilot, driven by cost pressures, were indirectly expressed by some employees, emphasizing the alignment of tasks and a shared awareness of financial pressures at different organizational levels. Aviation is strongly metric-driven, with on-time performance being a conspicuous measure that is seemingly influenced by pilots, when in fact myriad factors come into play (Kwon et al., 2021).

Participants in the three focus groups frequently used aviation terminology like 'professionalism' and 'airmanship,' indicating a collective understanding of narratives and concepts promoting standardized behavior. In the micro-level focus group, airmanship was characterized as proactive problem solving, emphasizing collaboration and adaptability within the crew. Essentially, in our finding, good airmanship was synonymous with resourcefulness and teamwork (P6). Pilot stories reveal different layers of meaning regarding airmanship and professionalism (Shorrock, 2016). Real work stories provided intricate insights and rich details about challenges, notably those arising from time constraints and limited resources. Within the safety department, the primary focus was on strict adherence to legal boundaries. Expressions such as 'going to the edge' (S3), 'crossing the line' and 'the envelope' emerged repeatedly, reflecting the perspectives of experienced individuals intimately familiar with operational nuances (Pettersen et al., 2010).

In exploring pilots' understanding of the 'line' or 'edge' in decision making, a drawing provided by a respondent depicted aviation operating close to the lines due to commercial pressures, with two crosses, one in the middle of the box and one near the edge. The 'line' is perceived as an abstract concept, not a rigid boundary. Pilots, like participant S1, play a crucial role in recognizing when deviation from procedures is necessary, but interpretations of this boundary vary. The discourse around the 'line' reflects rationality influenced by underlying motives (Cromie and Bott, 2016). It provides some freedom of choice for pilots but can be retrospectively used as a clear boundary for violations. The concept of 'legality' gains prominence in aviation discourse particularly at meso- and macro- levels, focusing on legality over social acceptance (Woodlock, 2023). This shift stems from the influence of lawyers and heightened airline accountability (Bignami, 2011), as noted by informant C6, highlighting how 'many things have changed because

Table 3
Responsibilization thematic analysis.

Feedback	Codes	Themes
[…] We subcontract to many different suppliers, and they all have different ways of doing it. So, when you are under time pressure, then the procedures start to slide… the procedures cover one scenario, it does not take into account these outer factors. (P2)	Airline lobbyism	Variability
[…] We have seen several examples of people cutting corners out of good intentions because they thought they were doing the company a favor. And they did, right then and there, but not in the long run, because suddenly we may end up in a corner where things go wrong. (S3)	Pilot culture of cutting corners	Discourse
[…] that you are supported and able to say 'listen, I cannot fly anymore, I am totally crushed,' and that it is accepted in the company. […] (C4)	Getting the job done – efficiency	Financial Awareness
[…] it's like the company makes an agreement, where we just have to adapt to time constraints, and that contributes to a change in the culture… company-wise… as there no longer is a wish for us to take the time necessary… (P9)	Changing work environments	Variability
[…] we have some employees that we are proud of and who feel a responsibility in getting everything to match up, to get the big puzzle to fit and not just seeing their work from their cockpit. (S1)	Professionalism & airmanship	Discourse
[…] because you have the opportunity to choose and say 'we will not be able to fly all the way home or we could… you could just make it happen.' (C2)	Getting the job done – efficiency	Financial Awareness
[…] working proactively. That you do not just say this is not my problem, or I do not know how to do this, accepting that all in the crew are part of the process that eventually succeed in the best possible way. Knowing that we all make mistakes and it's about catching those mistakes. (P6)	Professionalism & airmanship	Discourse
[…] being capable of working as a unit and arriving at the possible result with the things available; and if things are not available, then good airmanship is getting those things available. That's good airmanship! (P6)	Pilot culture of cutting corners	Discourse
[…] If you ask me, the bottom line is that you do not cut any corners, but you can go to the edge because it is actually legal to go to the edge. (S3)	Legal awareness & accountability	Discourse
[…] You are hired as a captain to be able to distinguish and make decisions about when it is necessary to deviate from the procedures. (S1)	Manuals has become complex	Discourse
[many things] have changed because lawyers have entered the picture, and now you are held accountable in an airline […]. (C6)	Legal awareness & accountability	Discourse
[…] You know in advance that no one knows anything, so…. I have made my own little black notebook, where I write everything down, it becomes sort of a homemade SOP. (P6)	Inconsistent procedures and tools	Variability
[the aviation regulatory system] foundation was based on scientific studies, but then you have lawyers from 28 EU countries that have to write it all up, combined with lobbyism from 25 airlines and 10 pilot	Airline lobbyism	Variability

(continued on next page)

Table 3 (*continued*)

Feedback	Codes	Themes
unions, and what eventually comes out of this is just… mud! So, they say 'this is the result', and then we say 'What?' Where the hell did that come from? It makes no sense! (C2)		

lawyers have entered the picture, and airlines are now held accountable.'

Legal boundaries at the macro- and meso- levels may overshadow the nuanced reality of organizational situations (Vaughan, 1996). In the aviation context, EU rules often fail to capture the complexities of day-to-day operations, yet organizations must demonstrate compliance while navigating these intricacies. The pilots emphasized the importance of knowledge sharing in ACMI operations, and during the focus group, it became clear that each respondent had devised their own methods, such as personal note-taking systems, to manage various aspects of operations and SOPs. These strategies emerged from the need to quickly adapt to new contracts and unfamiliar situations.

Additionally, pilots' use of personal notebooks, referred to as 'Boy Scout books', is a practical strategy for navigating challenges in ACMI operations (Perry and Wears, 2012). These notebooks contain detailed notes supporting efficient adaptation and workflow, reflecting their commitment to operational effectiveness. The common understanding of terms such as 'not crossing the line' and 'adherence to the rules' diverges based on different levels (micro-, meso-, macro-) defining them.

Our findings suggest that the social context receives considerably less attention from the organizational and regulatory system. Consequently, the actions of frontline workers may be seen as deviant at the meso- and macro- level, but essential for getting the job done at the micro- level. Large and bureaucratic organizations may lack the language and power to address the intricate details that contribute to the system's performance, which is often an emergent property (Dekker et al., 2011). Power shapes knowledge according to its convenience (Flyvbjerg, 2012), as seen in the formulation and interpretation of rules by airlines and their manifestation in training. This places the primary responsibility on frontline operators rather than the organization itself, which is encompassed by the construct of responsibilization.

5.2. Using experience to solve double binds

Actors in aviation are routinely presented with mutually exclusive choices. A pilot either adheres to an air traffic control (ATC) clearance or, due to adverse weather, deviates from it. Airline technology may need to be upgraded, but shareholders may not see the immediate financial benefit. A regulator delegates oversight to the very airline or manufacturer they are tasked with evaluating, risking capture. These scenarios underscore a diversity of rationalities and perspectives that can exist in aviation, often with ethical implications.

Despite these challenges, adaptive strategies are normalized in daily work, providing solutions to complex challenges. Phronesis, which involves practical wisdom and judgment, emerged in pilot conversations (Flyvbjerg, 2012). By the phrase 'what I need tomorrow' (Table 4, P3), the respondent anticipates the unpredictable operational challenges of the next day. This statement further highlights the integration of phronesis (ethics, values, intuition) and techne (craft, know-how, techniques) in the pilot's decision-making process, drawing on practical knowledge (Flyvbjerg, 2012). It emphasizes the importance of deep domain knowledge, pre-planning, intuition, and experience in adapting to the complexities of daily operations. Experience becomes a valuable resource for navigating the intricacies of work and maintaining daily operations. In the meso- focus group (safety department), the discussion centered around the significance of experience as an essential element of adaptation elicitation for pilots, acknowledging the challenges of

Table 4
Expertise and adaptive strategies thematic analysis.

Feedback	Codes	Themes
[…] you cannot incorporate all. But as a rule of thumb, or 'fingerspitzgefühl', for example, if you cannot fly the entire distance without a fuel stop, where do we refuel? You can contact crew control and provide them with a worst-case scenario… say: this is what I need tomorrow. (P3)	Heuristics & intuition	Adaptive Strategies
[…] When people have learned to adapt to many different situations, you arrive at a better result. (S3)	Deep domain knowledge	Experience – Expertise
[…] It only takes ten years to get ten years of experience, right? You may think of all sorts of decision-making scenarios, and what have you… but it just takes ten years because you never get into the situation you practiced in the decision-making scenario. It never happens, but you will experience hundreds of other scenarios. (P5)	Deep domain knowledge	Experience – Expertise
[…] In the initial stages, you can feel isolated in the left seat, as you may fly with highly skilled individuals who you trust immediately, or inexperienced ones whose capabilities are unknown. Suddenly, there is a shift, placing you in a different situation where you become more skeptical about trusting advice from the other side (e.g., the first officer). It can be quite lonely if you lack experience. (S1)	Locally shared knowledge	Adaptive Strategies
[…] It is not unthinkable that it has happened that you have found some legal way of adapting, on some sort of minimum equipment list (MEL). But if you had not had the EU261 concerns, you would have said: 'hold the horses, let us stay here and get someone to look at the aircraft'… You may not think that it is an optimal solution, but I am going to do it. (S2)	Rules complexity	Training vs. reality
I'm not saying that [homemade artifacts] has that effect, but it could have that effect, that the crew gets used to solving all these challenges themselves, by being a bit too creative all the time because then we would end up in a situation where the result would have a negative effect on the daily operations. That is why if you suddenly have an SOP and then also some sort of'shadow' SOP. (S1)	Heuristics and intuition	Adaptive Strategies
If 50 captains out there have their own SOP, then it would extensively so have a negative impact, not at least on the first officers, who would feel very confused about what is actually applicable, and that would cause sloppiness among the pilots. (S1)	Establishing personal minimas	Adaptive strategies
[…] if you by adaptations mean that the pilots are given so much freedom that they control their own game, that would end up in anarchy… our safety index would go out the window, and no doubt risk in our operation would increase, and worst-case scenario we would end up in an incident… it would be a negative spiral as we would influence each other. (S1)	Adapting to messy details	Training vs. reality
[adapting to fatigue] requires simplified rules, improved overviews,	Establishing personal minimas	Adaptive strategies

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Table 4 (*continued*)

Feedback	Codes	Themes
and tools to better understanding applicable regulations. (C6)		
The 24-hour shifts with sporadic flights make it tough. Even as a pilot, looking at the Flight Time Limitations, especially with time zone crossings and adapting to them, it is confusing and easy to lose track; I just don't get it, even with experience. (C1)	Deep domain knowledge	Experience-Expertise
[...] We attempt to cover all scenarios within a complex set of rules.	Rules complexity	Training vs. reality
One aspect is the writing style for the average [experienced] pilot. Simply put, when you are interpreting the rules in the 12th hour of flying, exhausted, whether you are on a short or long haul, the complexity can become quite apparent. (SR)	Practical wisdom	Experience-Expertise
[...] there are nighttime and daytime, and sectors and everything that comes into play.	Adapting to messy details	Training vs. reality
[...] is just the thing... It is a logbook, it is a car manual, it is an operating manual, it is not a basic regulation, and it should not be written in a complicated manner. (C1)	Rules complexity	Training vs. reality
Being rigorous and quick, we consistently apply OM-B* during OPC** simulations, which continually introduce new procedures, from engine shutdowns to FMC or FMA services. Consequently, we are perpetually a year or two behind in fully mastering these updates. (B1)	Gap between training compliance & real world	Training vs. reality

*OM-B: Operational manual with rules and procedures.
**OPC: Operational proficiency check, conducted every 6 months in the simulator.

training them for their role. This recognition indicates that the safety department is partly aware of the intricate details that pilots face in their daily work. Although one respondent suggested that simulator training would help pilots cope with the realities of their job, another respondent (S2) disagreed, stating that ground training the 'craft' alone would not encompass the necessary skills (Table 4, P5).

The conflict between training design and experiential requirements is evident in our findings. Setting personal minimums for new captains becomes crucial to navigate the realities of their work. Respondent S1 emphasized the importance of creating a protective shield and strictly following procedures during the initial six months to gain experience and understand operational boundaries. This dilemma highlights the challenge of training pilots to fulfill their role when training alone cannot replicate years of experience. Reliance on personal traits and adaptations, such as setting personal minima, becomes necessary to compensate for incomplete training. This interaction reveals the constant negotiation between agency and structure in the system.

The safety department also acknowledged the value of homemade artifacts in daily operations. When asked about the potential excess of adaptations, respondent S1 expressed concern about the potential negative consequences of excessive pilot adaptations and individualized standard operating procedures (SOP). They emphasized that if each captain has their own SOP, it will lead to confusion and sloppiness among the pilots. This could result in a loss of safety and increased operational risk, potentially leading to incidents. A respondent warned against allowing pilots too much freedom and emphasized the importance of maintaining a standardized approach to avoid a negative spiral and ensure safety.

The pilots engineered resilience by adapting to work demands and ensuring safety, while the safety department emphasized following procedures. This resonates with Hollangel's (2008) theory W (or 'traditional perspective'), which focuses on seemingly well-designed systems. Variability is seen as a threat and measures like barriers, rules, and procedures are used to constrain performance. Theory Z (or the 'systems perspective'), on the contrary, acknowledges normal performance variability (Grøtan et al., 2014; Zimmermann et al., 2011). For the latter, the solution is to identify situations where actions may lead to unwanted effects, monitor the system to intervene, and control performance variability when necessary. This dialectic creates a tension between authority and responsibility. Pilots can then develop their own 'shadow' SOPs to balance objectives and operational efficiency. The relationship between the safety department and pilots is complex and objectives interpreted differently. Homemade SOPs help pilots adapt and maintain efficiency, navigating the tension between authority and experience. This arises from the interconnectedness of safety objectives and pilots' interpretations, allowing them to meet objectives while ensuring timely operations.

Experienced pilots discussed the need for first officers to have additional artifacts to adapt to their specific ways of doing the job. First officers acknowledged the variation in practices and adjusted accordingly. This highlights the challenge of navigating diverse operations and constraints, including adapting to different pilots' approaches. As noted by Orasanu (2017), pilots not only have to handle demanding operations and operational constraints, but also adjust their performance to match the person they are flying with. Participant S1 (Table 4) highlighted the potential loneliness and skepticism experienced in the left seat when flying with inexperienced first officers during the initial stages of their career.

These statements highlight the unintended consequences of work design, particularly in the early stages of becoming a captain. This dialectic raises questions about whether the current work design only captures certain aspects of working in a socio-technical system. It also leads to the need for custom procedures and puts organizations in a position to rely on pilots to navigate these challenges. The language of being 'professional' and 'staying within the envelope' further influences this dynamic until pilots gain enough experience.

The influence of organizational and regulatory constraints was not extensively discussed at the meso- level. However, a respondent hinted at the social dynamics at play when dealing with concerns such as flight delays under EU261 regulations (EC, 2004). This respondent's remark indicates the intricate relationship between regulatory constraints, organizational goals, and pilot decision-making. It sheds light on how European Union (EU) law and European Union Aviation Safety Agency (EASA) regulations impact pilots' behavior, leading to the emergence of alternative adaptation methods to avoid financial penalties while maintaining the operation.

The process of making sense of the rules extends beyond the micro-level. In the CAA group, the complexity of the rules was discussed. Some participants acknowledged the need to comply with the EASA rules, but expressed the desire for them to be more practical and useful as tools. The shift from JAR rules to EASA implementation in 2012, influenced by EU law, introduced changes in language and formulations of the rules. The effect of this complexity was described by another respondent who expressed frustration with the process. They highlighted the involvement of lawyers from multiple EU countries, airline lobbyism, and pilot unions, resulting in a convoluted outcome.

Furthermore, the disconnect between the realities faced by those on the frontline, national oversight bodies, and EASA's safety standards raises questions about the effectiveness of work design. The current design is based on ideals that may not align with the practicalities of work and the competitive nature of the industry. Experience becomes a crucial ingredient for navigating this complex landscape, as it requires practical wisdom and deep domain knowledge to address the competing pressures of work. Safety is ultimately the contribution made by pilots through their lived experience, adaptive strategies, and shared knowledge. However, the unintended consequence of their current work design is the potential loss of tacit knowledge on how work is actually done, because this wisdom is not acknowledged nor codified.

Our findings reveal an expectation for people to develop practical wisdom and skills, indicating a ‘rational fallacy’ (Flyvbjerg and Bester, 2021) in work design that relies solely on analytical rationality. Meeting the requirements for proficient performance, as mandated by EASA, requires a broader perspective that considers the complexity of human activity. This requires training and work design that incorporate elements such as context, judgment, practice, experience, intuition, and bodily sensation. Experience plays a crucial role in filling the double-bind gap between regulatory requirements and the real-world work environment, where context-dependent practical wisdom is essential for operational sustainability and competitiveness.

5.3. Hidden and unintended sacrifices of adaptation

The interaction between competitive environments, organizational characteristics, and regulatory systems influences individuals’ actions and their interpretation of information, shaping their worldview (Vaughan, 1996, p. 408). Within the socio-technical system, a hidden social reality exists (Pettersen et al., 2010, p. 190) that has not been adequately addressed in the literature. During the pilots’ session (micro-level), deeper reflection through their stories uncovered previously overlooked areas of vulnerability in aviation, highlighting the need for further exploration. It became apparent that while adaptations became normalized elements of work, unintended consequences emerged when dealing with the numerous organizational constraints (see Table 5).

Human adaptability is crucial for system functioning (Adjekum and Tous, 2020; Wears and Hettinger, 2014), but it has its limits and potential unforeseen risks (Cook and Rasmussen, 2005; Woods, 2018). The dilemma of compensating for organizational deficiencies while feeling a responsibility to support business priorities reveals an underlying relationship. When asked about similar experiences of job exhaustion, silence in the room uncovered a rarely discussed area of vulnerability among pilots, often concealed in their own world of secrecy. In response to this issue, one respondent (P3) stated that experiencing exhaustion in daily operations is a common occurrence, and that everyone has been through it to some degree. Another respondent (P2) acknowledged that the experience occurs more frequently than it should. These comments highlight not just individual stories of exhaustion, but support a recurring pattern within the airline industry (Bendak and Rashid, 2020). The unintentional consequence of this pattern is the potential exhaustion of the system’s adaptive capacity itself.

In the safety department session, similar statements highlighted the pilots’ awareness of the uncertainties they face in daily operations, which goes beyond mere adherence to rules and procedures. They described the process of constantly redrawing lines as new events unfold, sometimes forgetting the bigger picture. A pilot respondent emphasized the intensity and immersion in the complexities of work, leading to a potential saturation of adaptive capacity. This state may not be immediately recognizable but becomes apparent in post-flight. It is important to recognize that humans within a socio-technical system rarely work in isolation, as they are part of a group or organization, even if their actions are separated in time and space (Rasmussen, 1997; Steen and Pollock, 2022).

Embedded within sustained adaptations are hidden risks, often unnoticed by pilots immersed in their work. They may overlook small indicators in complex situations, becoming aware of their actions later through flight data monitoring (FDM) notifications (P2). Pilot narratives revealed constraints imposed by the organization, impacting adaptive capacity and forcing compliance despite potential exhaustion (P8). This suggests the need for further exploration of these hidden risks (Woods, 2018; Barton et al., 2020).

The concept of secrecy (Under and Gerede, 2021; Vaughan, 1996) emerged as a valuable analytical tool, observed through nonverbal cues,

Table 5
Hidden and unintended sacrifices of adaptation thematic analysis.

Feedback	Codes	Themes
I was under such pressure, where I just absorbed all the shit that just did not work… I just took it in…, and you get so far out… where you get so tired and are just so fed up, and you start to snap at people… and then you are far out… by personally taking in all the deficiencies of the organization. […] so, instead of just absorbing and carrying the commercial pressure on our shoulders, we have to say… ‘forget it!’ (P3).	Stress – exhaustion – sickness	Work-as-impacted
[…] We are humans, we want to solve this task, we want to go from A to B, almost at any price. (P8)	Risk perception – boundaries pushed	Normalization of adaptation
[…] We simply accomplish the task… we do it with the sincere intention of assisting… But it can also lead to the procedures not being adopted, and those responsible for addressing or taking action are unaware because we resolved the issue, we handled it, we completed the job.’ (P2)	Patching up system imperfections	Normalization of adaptation
The process begins at check-in with normal operations as our baseline. When an event occurs, we adjust to a new position and may overlook the factors that led us there. Subsequent events prompt further adjustments, creating multiple changes in our operational approach. However, there is a tendency to base decisions only on the most recent change, not the cumulative context. We sometimes neglect to consider the entire evolving situation. (S2)	Saturation of adaptive capacity	Work-as-impacted
When you wake up feeling too fatigued to fly and know that there is no one on standby, you face a dilemma: call in sick and face potential consequences or adapt inappropriately to handle the situation, despite knowing it is not the right action to take. (P7)	Stress – exhaustion – sickness	Work-as-impacted
You are aware that if you don’t complete the task, someone else must step in. This isn’t like an office job where unfinished work waits until Monday. Here, the work must be completed, regardless of the circumstances. (P8)	Risk perception – boundaries pushed	Normalization of adaptation
You may be a burden, but you are reluctant to inconvenience your colleagues due to increased pressure. (P8)	Local in-group ways of adopting	Secrecy
It’s like the boundaries are pushed. Your level of fatigue can seem overwhelming the first couple of times, but subsequently, it becomes more and more a normal condition, a very recognizable condition in which you operate, and in reality, it is a sliding condition, where you sort of get pushed out and where it can be hard to be ‘in control’… and I think that is dangerous… it becomes the new norm, right? (C6)	Stress – exhaustion – sickness	Work-as-impacted
We then complete the job, with the intention to help, but this may prevent procedures from being updated. Those responsible for addressing issues remain unaware, because we have already resolved	Patching up system imperfections	Normalization of adaptation

(continued on next page)

Table 5 (*continued*)

Feedback	Codes	Themes
the problem and fulfilled the task. (P2)		
Manual data entry under time pressure increases the risk of errors. This haste can affect subsequent procedures, as there may not be enough time to confirm the accuracy of the inputs. (R2)	Patching up system imperfections	Normalization of adaptation
In my opinion, technology should reduce our workload. Yet, from the outset, we have found that it actually heightens it, which surely isn't correct, considering the risks associated with increased workload from technology implementation. (B1)	Mental health limits are often subtle	Work-as-impacted
Experience helps to resolve double binds by fulfilling regulatory demands through rules, procedures, and context-independent simulations, while also addressing real-world needs with context-dependent practical wisdom, crucial for operational sustainability and competitive survival.	Insights arise post-reflection	Work-as-impacted

silence, and power dynamics during interviews. In this space of secrecy, pilots feel that the range of adaptation has exceeded its limits (Woods, 2018), compensating for a poorly designed and dysfunctional system, which could result in severe unintended consequences. The secrecy observed in this study reflects prosocial silence within the pilot group regarding the impact of work on individuals, highlighting a gap between work-as-imagined and work-as-done (Hollnagel, 2014). We suggest a hidden 'work-as-impacted', representing the emergent result of balancing these two worlds and containing uncomfortable realities judged by moral standards (Flyvbjerg, 2012). Pilot exhaustion, driven by the pursuit of efficiency and productivity, is influenced by the fear of potential sanctions, leading to self-protective secrecy and prioritizing efficiency over safety and well-being (Shorrock, 2016).

In the CAA group, little attention was given to the intricate details of work and the emergent properties associated with the adaptation required by frontline personnel in daily operations. However, their acknowledgment of fatigue as a major challenge on the frontline suggests a recognition of underlying social processes within the system, indicating a deeper systemic problem. Flight inspectors, speaking from their pilot experience, expressed concerns about rules that benefit airlines at the expense of human well-being. They described fatigue as a sliding condition that becomes the new norm, making it difficult to maintain control and is considered dangerous (C6).

These statements highlight a system with low graceful extensibility, where adaptive capacity becomes saturated and goes unnoticed during operations (Woods, 2018). The interconnectedness between pilots' adaptive capacity and organizational constraints places the responsibility on pilots to recognize and address issues (Perrow, 1984). Delays in human capacity availability can reveal unintended consequences of the system. Adaptations may be 'hidden in plain sight' to management, giving a false impression of system performance (Wears and Hettinger, 2014).

During a discussion on complying with minimum fuel procedures, the pilots disclosed that they often deviate from procedures when not observed or checked, adapting to prioritize on-time performance (P7). While being checked, respondent P2 reported complying with procedures, but afterwords mentioned 'but then we adapt again!' This highlights the gap between actual work practices (work-as-done) and official disclosures (work-as-disclosed). The pilots adapt their behavior when under observation, revealing awareness of power dynamics and cultural understanding (Vaughan, 1999, p. 280). This demonstrates the influence of organizational culture on individuals' perceptions of their behavior as conforming, even when it may be objectively considered deviant. Normalization of adaptations in the system conceals the need to address underlying work design issues, as these adaptive skills mask imperfections and create the illusion of better performance (Wears and Hettinger, 2014). The saturation of adaptive capacity (Woods, 2018) remains unrecognized and unofficial, as adaptations become an accepted part of the pilots' routine.

6. Implication of results: emerging patterns of resilience and brittleness

Building on initial findings, as analyzed in the previous section, this section conducts a second-order analysis, exploring the emergent pattern of resilience and brittleness.

From the pilots' perspective, the researchers heard stories of how they adapt to an imperfect system with poorly designed work structures, as their working environment constantly changes (Cook and Rasmussen, 2005). Lacking the necessary tools and equipment, pilots engineer resilience by developing strategies such as adjusting load sheets, managing fuel requirements, prepping in advance, and creating their own systems to meet disparate demands (Perry and Wears, 2012). Resilience in this context arises from experience, domain knowledge, practical wisdom, intuition, and anticipation, supported by strategies and artifacts. These findings reveal pilot compensation for incomplete work design. Conversations with pilots highlight a strong commitment to meeting management and peer expectations, forming a pilot subculture characterized by secrecy and a shared understanding of achieving their goals (Dekker, 2011). Despite inadequate equipment and consideration in work design, pilots compensate by sharing, supporting, and adapting knowledge, enhancing the adaptive capacity and resilience of the system. However, sustaining daily operations is highly dependent on this adaptive capacity. Stories of frequent exhaustion of the pilots reveal a darker side of their resilient performance. Pilots' adaptive capacity is finite, occasionally reaching the limits of acceptable workload (Rasmussen, 1997). However, the extent and reasons for exhaustion remain concealed at the micro-level, with the tensions and affinities associated with their work remaining invisible (Vaughan, 1990, p. 272). Unintended consequences of adaptations manifest themselves as sacrifices to pilot health and well-being, exhaustively depleting the system's adaptive capacity and increasing its fragility.

Pilots in this study faced pressure to prioritize on-time performance, reflecting a production-oriented culture. There was an expectation to push legal boundaries as pilots gained experience. Complex rules at the macro- level benefit airlines, but compromise human well-being. This gap between rules and the realities of work created challenges. The pilots were responsible for navigating legal boundaries and power relations. CRM training influenced pilots with terms like 'professionalism' and 'airmanship', which required adaptive skills aligned with organizational goals. The pilots developed their own strategies to address the imperfections in the work. These adaptations were often hidden within the pilot community due to potential sanctions. Consequently, the range of adaptive capacity available to manage saturation risk remained concealed beyond the micro-level, limiting organizational and regulator learning.

The aviation industry consistently pushes the boundaries of safe performance, normalizing the risk of saturation (Dismukes et al., 2017). EU rules shape workers' behavior, oversimplifying complex issues and attributing problems to individual factors like fatigue (Pettersen and Bjørnskau, 2015). Scrutiny then focuses on the human element rather than acknowledging the system's contribution. The exhaustion of the system's adaptive capacity remains hidden, potentially normalizing deviance. Competing purposes is another source of brittleness, with different safety rationalities among different stakeholders. Frontline workers develop necessary homemade standard operating procedures (SOPs) for safety; however, these are viewed as rare or inconsequential by the safety department. This disconnect obscures resilience and brittleness.

Conflicts arise between the safety department's value rationality and the training of new captains. Training focuses on establishing personal limits and protecting oneself due to incomplete work design, which leads to new captains feeling isolated in their role. Experience helps navigate these challenges. Due to efficiency and productivity pressures in the airline industry, adaptive strategies like advanced preparation and extra coordination are required for on-time performance. Homemade 'shadow' SOPs contribute to smoother operations, but may obfuscate systemic problems.

In summary, this analysis reveals resilience patterns that lead to brittleness due to poor system design, organizational constraints, and regulatory demands. Simplistic training practices and an analytical rationality perspective from oversight authorities limit system safety by neglecting the socio-technical nature of work. Legal rules from the EU perpetuate outdated behaviors. The study brings forth the hidden role of social reality and the ability to manage the saturation of adaptive capacity, making the system more brittle. Individual values and practical realities of work design are, instead, shaped by an analytical rationality. As a consequence, tacit knowledge and values across levels are overshadowed and discounted, hindering our ability to understand resilience in a socio-technical system.

7. Conclusion and final remarks

This study addressed how regulatory and organizational forces strongly shape human actions and are based on discourse, expectations, and legal boundaries. For example, experienced pilots reported fatigue that has the potential to saturate adaptive capacity in the system, exacerbated by organizational and regulatory influences. The study suggests that instead of adding more programs and procedures, existing structures should be reevaluated and updated. Specifically, the current prescriptive training approach may increase risk by not accounting for or training for adaptations that are necessary in the frontline work environment. Implementing practical measures that promote systems thinking could be beneficial. For example, sharing stories of resilience instances between work groups would encourage workers to create an institutional memory. When training, these stories can be codified for others to learn from. This dynamic knowledge, in turn, enhances the relevance of training.

The research emphasizes the importance of experience, expertise, and practical wisdom in resilient performance and adaptive capacity. Work design is shaped by legal rules, often overlooking ethical considerations. Attempts to address ethical concerns are often superficial and do not foster system learning and improvement. This narrow perspective hinders the recognition of aviation as a complex system with technical and social dimensions.

Building on the insights gleaned from this study, it becomes evident that the challenges faced in the aviation industry, particularly with respect to safety and well-being, are not isolated, but rather systemic issues that require a comprehensive and inclusive approach. The study's focus on the saturation of adaptive capacity among pilots underlines the pressing need for a paradigm shift in how safety and well-being are conceptualized and managed in high-risk industries. This shift necessitates a move away from traditional, compliance-focused safety models towards a more adaptive, human-centered approach. The findings also highlight the critical role of mental health and well-being in ensuring safety. Brittleness arising from overextended adaptive capacities can have profound implications not just for individual workers but for the overall safety and efficiency of the aviation system. This underscores the need for organizations and regulatory bodies to adopt a more holistic view of safety that includes mental health and well-being as integral components.

Additionally, the study suggests that it is crucial to incorporate ethical considerations into safety management. This involves acknowledging the impact of work design and operational pressures on the health and well-being of employees. Ethical considerations should guide the development of policies and practices that prioritize the well-being of workers without compromising safety.

The need for further research is apparent, especially to explore how these concepts can be practically implemented in the aviation industry. Such research should aim to develop strategies that not only enhance safety but also promote the well-being of frontline workers. Furthermore, the findings of the study, while based on an ACMI airline and a European regulator, resonate with global challenges in aviation. Therefore, the insights could be valuable to a broader audience, including international regulatory bodies such as the ICAO.

This study contains limitations. The three focus groups were drawn from a single airline and national regulator, limiting generalizability. The operator conducts varied types of flying and unscheduled operations on a regular basis, potentially creating an inherent need for pilots to display resilient behavior compared to scheduled airline operations in a consistent environment. The single-method design of the study utilizing focus groups allowed factors such as group dynamics, social desirability bias, and investigator influence to be introduced. The researchers attempted to control for these factors by observing nonverbal cues and encouraging all participants to contribute to the conversation.

In conclusion, this study contributes to a growing body of research that advocates a more nuanced understanding of safety in aviation. It calls for a holistic approach that balances safety compliance with adaptive capacities and well-being, paving the way for a more resilient and ethically grounded aviation industry. Future research could benefit from employing quantitative techniques applied to identify sources of resilience and brittleness, utilizing natural language processing and machine learning on large textual datasets, such as safety reports.

CRediT authorship contribution statement

Riana Steen: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis. **James E. Norman:** Writing – review & editing, Writing – original draft, Software, Methodology, Formal analysis. **Johan Bergström:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis, Conceptualization. **Gitte F. Damm:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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