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RESEARCH ARTICLE

Exploring unstable approaches in aviation: utilising functional resonance analysis method

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Abstract
Unstable approaches are one of the main safety concerns that contribute to approach and landing accidents. The International Air Transport Association reports that, between 2012 and 2016, 61% of accidents occurred during the approach and landing phase, of which 16% involved unstable approaches. This study addresses this issue by applying the Functional Resonance Analysis Method to examine the dynamics of stable approaches. A total of 195 aviation safety reports, which referred to near-miss data from a single airline, were used in the analysis to identify both actual and aggregated variability. The findings revealed that variability mainly occurred in the following functions: control speed, configure aircraft for landing, communicate with air traffic control and manage flight paths. Effective communication, coordination and collaboration, as well as monitoring, briefings and checklists, were key factors in managing the variability of a stable approach. The study reveals how adopting a perspective of 'how things go right' provides insightful findings regarding approach stability, complementing traditional approaches focused on 'what went wrong'. This study also highlights the value of utilising the Functional Resonance Analysis Method to analyse near-miss data and uncover systemic patterns in everyday flight operations.

Nomenclature

ATC	air traffic control
Cn	Case n
ECAM	electronic centralised aircraft monitor
EFB	electronic flight bag
EGPWS	enhanced ground proximity warning system
fpm	feet per minute
FRAMF	unctional Resonance Analysis Method
ft	feet
IATA	International Air Transport Association
min	minute
nm	nautical mile pf pilot flying
PM	pilot monitoring
Rn	recommendation n
RA	radar altimeter
SOP	standard operating procedure
Vapp	approach speed
VLS	lowest selectable speed

WAD	work-as-done
WAI	work-as-imagined

1.0 Introduction

The aviation industry is held up as the model of a safety-critical sector that prioritises safety. However, despite its high safety performance, the aviation industry continues to experience catastrophic accidents, most of which occur during the approach and landing phases of the flight [12, 27, 64]. An unstable approach is one of the primary safety concerns, as it increases the risk of accidents during the approach and landing phases [6, 27, 43]. Although not all unstable approaches lead to adverse outcomes, they can be considered the symptoms of accidents [69]. An unstable approach occurs when the aircraft does not follow a stable and predictable flight path along prescribed parameters. In a stable approach, the aircraft is correctly configured for landing, descends at a consistent rate, is on the correct glide path, and maintains the proper airspeed and power control; all briefings and checklists are completed [3, 43].

Significant efforts have been made to manage the unstable approach problem in the aviation industry. Various parts of the aviation industry, including regulators and international organisations, have launched numerous campaigns and action plans. For instance, the Flight Safety Foundation gathered a task force to explore the unstable approach. The outputs of the task force precipitated two decades of corrective actions across parts of the aviation industry that have an interest in and impact on instances of unstable approach [15]. However, despite the success of these activities and reduced unstable approach rates, IATA reports that 61% of the accidents between 2012 and 2016 occurred during the approach and landing phase, of which 16% were unstable approaches [26]. More recent assessments have shown that the issue remains a prevalent risk in the aviation industry [28]. Albeit at exceptionally low rates, an unstable approach remains a safety concern [27]. The question then arises as to why, despite significant overall reductions in accidents, unstable approaches continue to occur.

In the literature, a few studies have explored the 'unstable approach' problem, although the issue has been well-recognised in many studies. Moriarty and Jarvis [43] interviewed pilots to understand unstable approaches and how pilots adjust their performance to ensure flight stability. Duchevet et al. [11] developed a digital assistant to support pilot decision-making. Carroll [4] examined unstable approaches using flight data monitoring, with a focus on energy management. Some studies used flight monitoring data to predict unstable approaches [40, 67]. Lai et al. [35] developed an agent-based model to analyse the impact of mental model disconnects between pilots and air traffic controllers in unstable approach scenarios.

So far, efforts to reduce unstable approaches in aviation have focused on analysing 'what went wrong', which aligns with the Safety I approach. The Safety I approach focuses on component-level failures by considering the reliability of each component and aims to create systems that work as imagined (WAI) [21]. This approach has limitations in understanding complex systems and the interactions of system elements. Hollnagel [21] introduced the Safety II approach as a complement to the Safety-I approach, shifting the focus from analysing failures to understanding how everyday operations succeed under varying conditions [46, 58]. Safety II focuses on system-level success by ensuring system resilience and understanding work-as-done (WAD). With Safety II, WAI systems can differ from WAD to sustain success in a changing work context, whereas Safety I assumes they should be the same, and any deviation from the WAI is considered a failure [21].

In cases involving 'how things go right' and revealing system component interactions, the Functional Resonance Analysis Method (FRAM) has proved to be a fruitful method for analysing systems in various industries, including aviation [7, 51, 57], healthcare [32, 59], industrial operations [23] and oil and gas [71], despite the criticisms of Safety II [36] or Safety I, II and III concepts [2]. FRAM has been used for various purposes [47, 53], including revealing the interrelationship of system elements [24], identifying gaps between WAD and WAI [42], supporting risk assessment [30], assessing resilience [50], analysing

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incidents [45], addressing industrial problems [38]), analysing near misses and integrating Safety I and Safety II approaches [8].

FRAM is built on four principles: (1) equivalence of failures and success, (2) approximate adjustments, (3) emergence and (4) resonance. The first principle emphasises that failures and successes have the same origin and are thus equivalent. In other words, things could go wrong and right for the same reasons. The second principle explains that human performance in everyday work is variable due to various factors, including physiological, psychological and organisational factors. FRAM views performance variability as a strength rather than a liability, arguing that it is a key factor in the success of socio-technical systems. People adjust their performance to match working conditions [20]. The third principle recognises that safety is an emergent property in socio-technical systems [22, 70]. In complex systems, it might not be possible to explain how things happen by focusing on system components. In those cases, the outcome is emergent rather than resultant [20]. The final principle emphasises that the functions of a system interact with each other and work together to achieve the overall system's goal [16]. The variability of two or more functions can interact and resonate, resulting in amplifying or dampening effects within the system [19].

FRAM identifies system functions, examines variability in each function, explores how they may resonate and proposes ways to manage performance variability [16, 20]. This study applies FRAM to investigate the unstable approach problem in commercial aviation, utilising aviation safety report data from a single airline. The study has two contributions: (1) revisiting the unstable approach problem in aviation by using near-miss data and (2) exploring functional variabilities in a stable approach.

2.0 Methods

2.1 Data collection

This study applies FRAM to explore the unstable approach problem, using reports, standard operating procedure (SOP) and interview data.

This study collected aviation safety reports from a single airline operator for unstable approach occurrences between 2012 and 2023. In total, we received 6461 aviation safety reports from various event locations. To minimise the variability of external factors, we selected a single event location and runway by choosing the most frequently used one. We first selected reports involving London Gatwick Airport ($n = 447$), then filtered for those related to runway 26L ($n = 196$), and finally included only arrival flights ($n = 195$). Among these, 106 involved the A319 aircraft, and 89 involved the A320 aircraft.

The aviation safety report dataset contained 40 parameters, with the event description being the key parameter for understanding the aircraft's landing configuration (at the 1000ft radio altitude gate), speed, power and sink rate (vertical profile at 1000ft) for approach stability. The rest of the parameters included event date and reference, event location, route, departure/arrival flights, aircraft registration, flight phase, event summary, descriptor type, descriptor name, speed, altitude, visibility, light conditions (e.g., daylight and night), weather conditions (e.g., temperature, turbulent, wind, cloud, ice, rain and fog) and runway state (e.g., wet and dry). The dataset represented the WAD practice and was used in the FRAM application to identify functional variabilities and determine aggregated variabilities.

In addition to aviation safety reports, we reviewed Flight Safety Foundation reports on the unstable approach [3, 14, 15] and the airline's SOP to understand the WAI practice and to identify functions.

Furthermore, we conducted semi-structured interviews with seven subject matter experts via face-to-face and online meetings to undertake the FRAM analysis and review findings. Participants were purposively selected based on their experience in flying and safety management (see Table 1). Interviews took between 45 minutes and 120 minutes. The interviews provided insights into the WAD practice, informing the FRAM analysis steps.

The research elements of this study were conducted in accordance with the ethical procedures of Cranfield University (approval reference 18126/2023). In this study, no personal data was explicitly requested or collected. All data gathered was securely stored.

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Table 1. *Participants characteristics*

Participant ID	Job title	Years of experience	Involvement in FRAM application steps
P1	Captain	20+	Step 1 (face-to-face)
P2	Senior safety captain	20+	Step 1 (online)
P3	Senior first officer and sim instructor	25+	Step 1 (face-to-face)
P4	Senior first officer	10+	Steps 1 (face-to-face) and 4 (online)
P5	Pilot, safety manager and accident investigator	35+	Steps 1 and 4 (face-to-face)
P6	Human factors expert	30+	Step 4 (face-to-face)
P7	Senior airline training pilot	35+	Step 4 (face-to-face)

2.2 FRAM application

In this study, FRAM was applied in four steps: (1) identify and describe functions, (2) identify variability, (3) aggregate variability and (4) analyse consequences.

Step 1: *Identify and describe functions*

In FRAM, functions are identified as 'a set of activities', and characterised by six aspects: inputs, outputs, precision, control, resources and time [20]. In this study, we identified functions for a stable approach. Initially, we reviewed the airline's SOP and Flight Safety Foundation reports to understand the WAI practice. Then, we interviewed subject matter experts and watched three recorded videos, including two complete cockpit recordings of flights into airports and one recreation of a near-miss resulting from an unstable approach, to understand WAD practice. Having built on these, we identified background and foreground functions for a stable approach. Foreground functions were described considering five aspects: inputs, outputs, preconditions, resources and control. The 'time' aspect was intentionally left blank, not because it was irrelevant, but because it was too dynamic to meaningfully assign fixed temporal constraints to individual functions. Background functions were identified to represent activities that produce outputs used by the foreground functions.

After identifying all functions, they were refined through an iterative process based on inputs from subject matter experts. We used the FRAM model visualiser to describe the functions and to build a FRAM model, representing the everyday successful performance of a stable approach (Fig. 1).

Step 2: *Identify variability*

We used aviation safety reports to identify actual variability within the function, primarily using the event description parameter, which pilots enter following the events. We created an Excel sheet (see Table 2) to list all functions.

We considered functional variability in terms of time (i.e., too early, on time, too late and not at all) and precision (i.e., precise, acceptable and imprecise). The output of a function can be too early, on time, too late or not at all. Here, 'not at all' means an extreme version of too late. A precise output of a function refers to satisfying the needs of the downstream function, thereby not increasing the variability of the downstream function. An acceptable variability requires adjustments and will likely increase a downstream function's variability. An imprecise output indicates that it is inaccurate, incomplete, or misleading [20]. For instance, one of the event descriptions says, 'I decided to use flap 3, given the potential for wind shear. . .'. The variability type for the 'configure aircraft for landing' function was selected as 'precise' to maintain a stable approach. For the same function, we categorised the variability as 'too late' when reviewing the event description, saying '. . .late configuration full selection, believing that they did by the 1000 ft gate.'. In some event descriptions, we identified multiple variability types, whereas on other occasions, no variabilities were identified (see Table 2).

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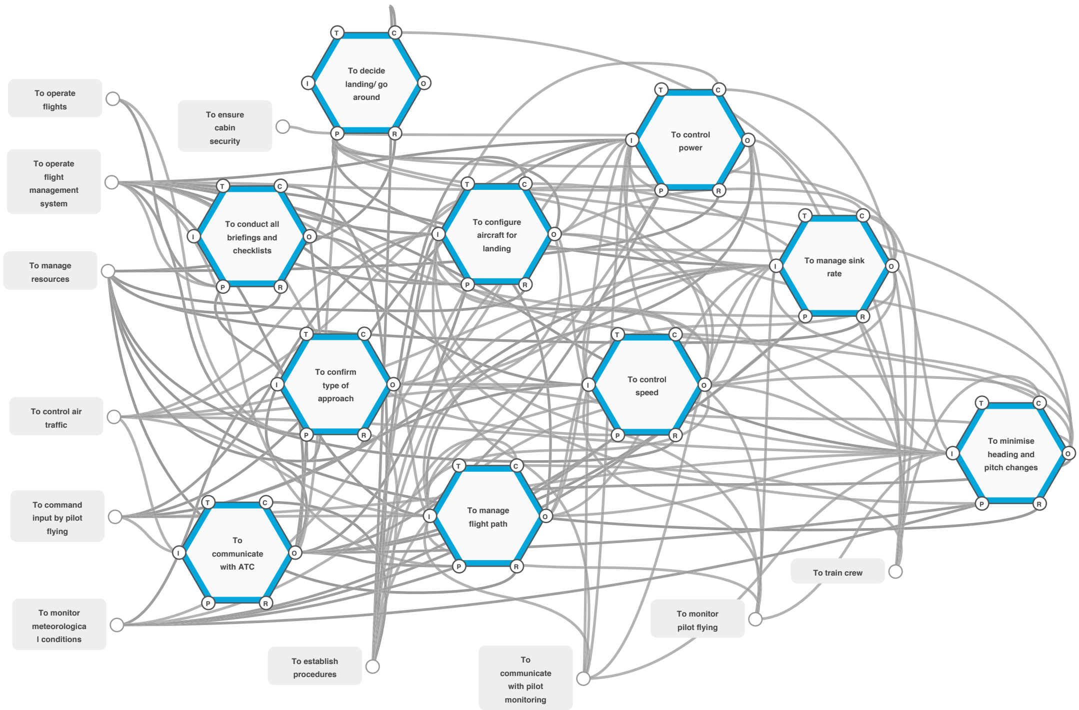

Figure 1. *FRAM model for a stable approach.*

Step 3: ***Aggregate variability***

This step analyses how variability in one function may propagate, combine or resonate with variability in other functions [48]. Variability has three sources: internal (resulting from the function itself), external (such as weather conditions), and variability from an upstream function [20]. This study used aviation safety reports to identify couplings between upstream and downstream functions. For instance, in one case, the decision to use flap 3 dampened the variability of downstream functions by aiding speed control. In contrast, delayed configuration was found to either amplify variability, creating time pressure on subsequent tasks or have minimal downstream impact, depending on the context. There might also be cases where an upstream function has an amplified effect, and another has a dampening effect on the same function. All these variabilities reveal how the variability of a function influences others.

Step 4: ***Analyse consequences***

Variability can lead to both desirable and undesirable outcomes. This step proposes ways to manage variability by sustaining desirable variability and preventing undesirable variability [20]. In this step, we interviewed four subject-matter experts to review aggregated variability findings and propose ways to manage variability. In addition to expert inputs, the authors generated suggestions considering variability aggregation for each event.

3.0 Results

In this study, we used FRAM to explore the unstable approach. The stable approach was modelled with 10 foreground functions (shown as hexagons in Fig. 1) and 11 background functions (shown as grey-background rectangles in Fig. 1). Table 3 provides an example of the function description.

The FRAM model was developed after all functions had been identified and described. Figure 1 shows all functions of a stable approach, revealing their interactions. The FRAM model visualiser is used to

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Table 2. *The template used to identify functional variability*

Aviation safety reports-event description	Variability of foreground function 1	Variability of foreground function *n*	Variability of background function 1	Variability of background function *n*
Event 1	Time: too early Time: on time		Precision: acceptable Time: too late	
. . .				
Event 195	Precision: acceptable			Time: too early, Precision: acceptable

Table 3. *Description of control speed function*

Function aspect	Description
Input	Adjust thrust, adjust pitch, set desired speed, configuration change, flight path change, heading and pitch change, sink rate change, power change, type of approach change, PM calls out any significant deviation from speed or heading
Output	Controlled speed, aircraft within the speed limits of the configuration, the speed change
Precondition	PF calls out the desired speed change to be acknowledged by PM, monitored flight and engine instruments, considered wind speed and direction, information on the meteorological conditions, and communication with the air traffic controller
Resources	Crew, crew's readiness, aircraft, flight management system, cockpit iPad
Control	Crew training, standard operating procedures

examine the interactions between functions and to explore how variability might aggregate across the system.

In the second step, performance variability was identified by analysing the aviation safety reports. The findings revealed that variability mainly occurred in the following functions: control speed, configure aircraft for landing, communicate with air traffic controllers and manage flight path. Considering the source of variability, weather conditions, such as wind, turbulence and gusts, were the primary sources of external variability, especially regarding the control power function. For instance, an air traffic controller reporting to pilots about 'wind, gusts and previous aircraft going around' is labelled as 'precise', and this supports crew decision-making on whether to continue the landing or effect a go-around. Similarly, pilots changing the role of pilot flying when necessary was another example of variability, which is labelled as 'acceptable', contributing to safe operations and sustaining a stable approach. Figure 2 presents the actual variability in all background (B1–B11) and foreground (F1–F10) functions. Variability is categorised by both time (too early, on time, too late and not at all) and precision (precise, acceptable and imprecise), with colour coding as shown in the legend. Notably, certain functions (e.g., F6: To configure aircraft for landing and F5: To control speed) exhibit high levels of temporal and precision variability, highlighting critical operational points. In contrast, others (e.g., B7: To establish procedures) show minimal variability. This could be due to various factors, including B7 being an organisation-related function, where variability tends to be less than human-related functions or simply the lack of data capturing the variability of the function.

In the third step, the authors explored aggregated variability. For example, an air traffic controller gave an unusually expeditious approach to approximately 11nm final in one of the cases analysed. The

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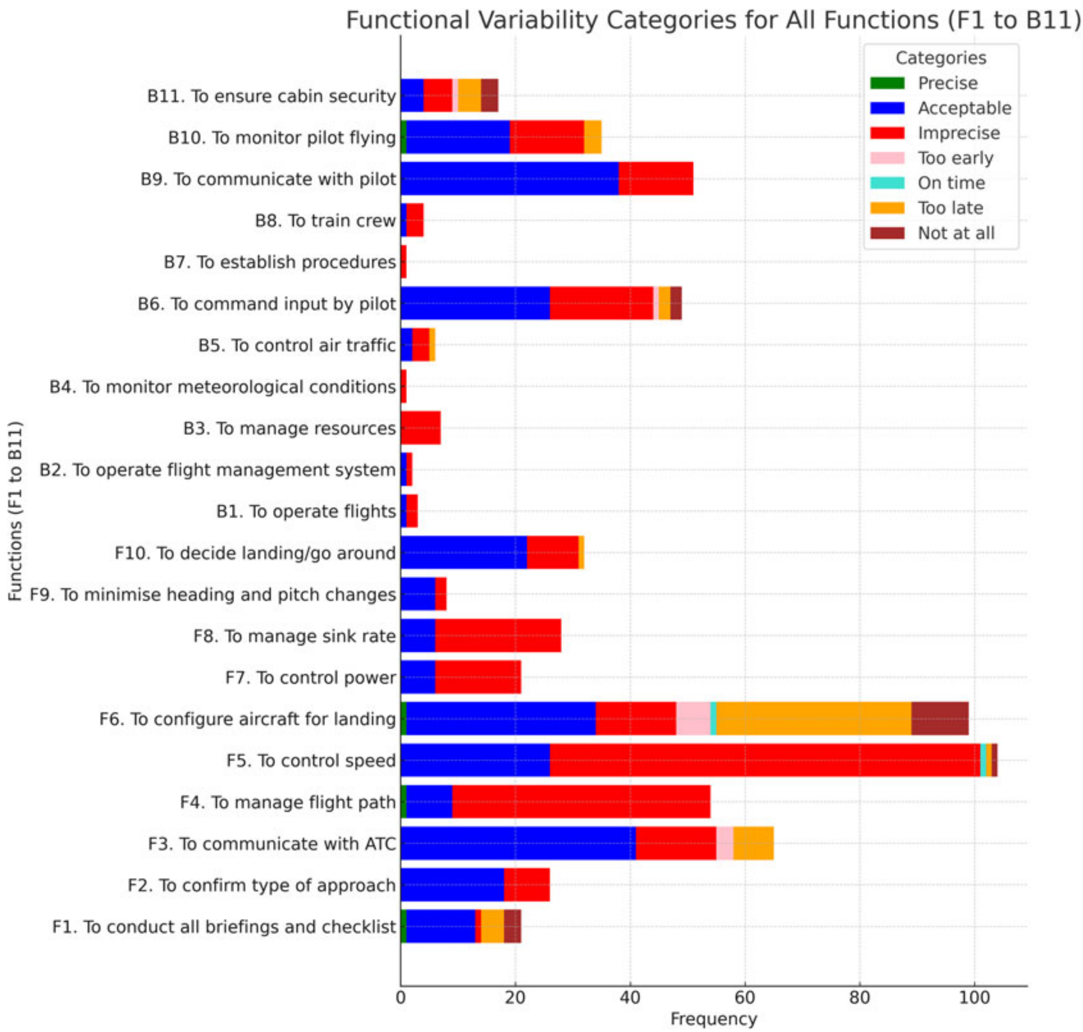

Figure 2. *The variability of the functions in terms of time and precision. The y-axis lists all background and foreground functions, and the x-axis illustrates the frequency of actual variabilities in these functions, with colour coding shown in the legend.*

variability of the outputs from the functions ‘To communicate with air traffic controller’ and ‘To control air traffic’ amplified the variabilities of the functions ‘To configure aircraft for landing’, ‘To command input by pilot’ and ‘To control speed’ by using speed brake to keep the variability of ‘To manage flight path’ function at an acceptable level. While the variability on the ‘To manage flight path’ function was dampened, the amplified effects on the ‘control speed’ function triggered the ‘To decide landing/going around’ function, in which case the pilot decided to go around. Figure 3 illustrates the aggregated variability effects for this instance. The highlighted connections show the link between the ‘To communicate with ATC’ function and other functions, and the waveforms in certain hexagons (e.g., To communicate with ATC) indicate points where variability was observed in this instance. As shown in Fig. 3, the variability of the selected function does not always lead to amplified variability in connected functions, showing that variability does not always propagate linearly or predictably.

In this study, several instances occurred where performance variability in the stable approach led to go-around decisions (C1 to C6 in Fig. 4). While these actions may appear inconsistent with standard

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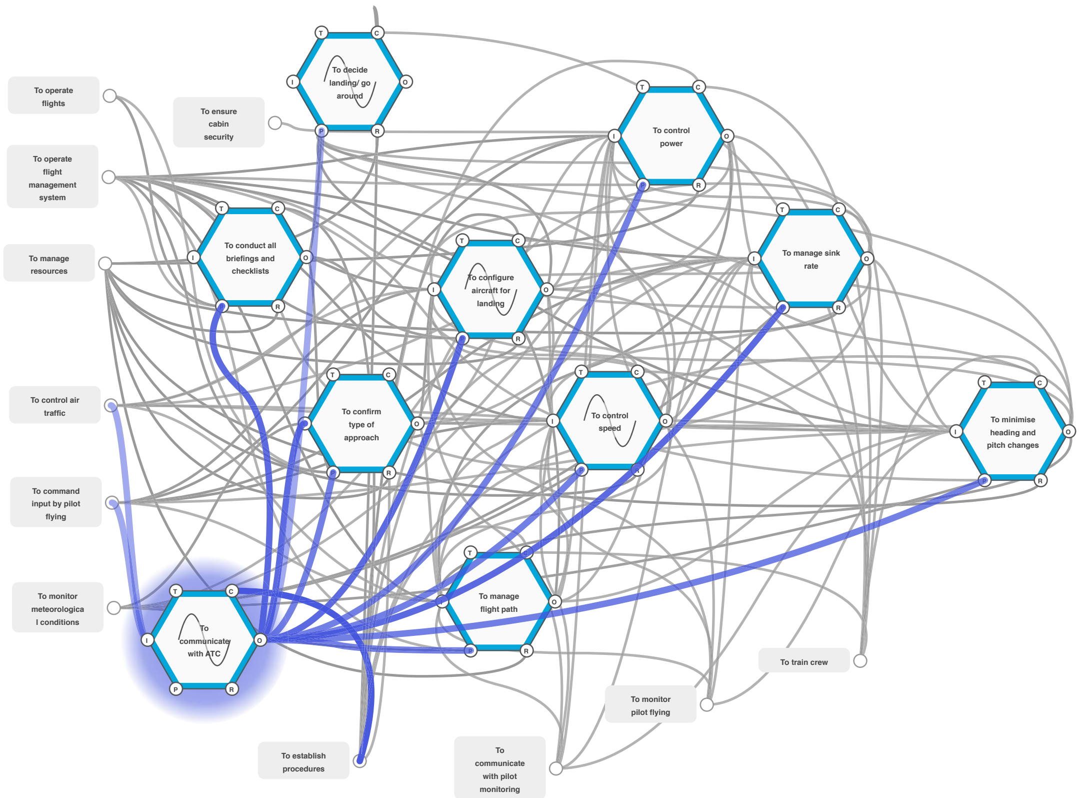

Figure 3. *Aggregated variability effects from the 'communicate with ATC' function.*

procedures or WAI practice, they reflect the adaptive strategies pilots employ in real-world conditions, aligning more closely with WAD practice. We further analysed these events by considering the decision gates identified in the airline's SOP, representing the WAI practice. In the SOP, two gate points were identified at 1000ft and 500ft radio altitude, associated with the following prescribed speeds: speed at 1000ft should be Vapp (approx. 140kts) + 30 and at 500ft between Vapp− 5 and Vapp+ 10 for Airbus A320 and A319 aircraft types. An approach is considered stable when the aircraft meets the gate criteria; if the gate criteria are not met, the approach should be deemed unstable, and the pilot should initiate a go-around. Figure 4 illustrates the categorisation of events in the analysed aviation safety reports. Events were categorised depending on whether they met or failed to meet the 1000ft and 500ft gates, and whether this resulted in a go-around or a landing. For instance, C3 represents 24 events in the dataset, where a go-around was initiated between 1000ft and 500ft, and pilots did not meet the 1000ft gate criteria. C9 represents 37 events where the flight did not meet the 1000ft gate criteria (N) but continued landing and met the 500ft gate criteria (Y).

From the crew's compliance with SOP perspective, the cases could be interpreted as follows: (1) C1, C2 and C4 (in a total of 43 events) being compliant and cautious – pre-emptive initiation of a go-around, (2) C3, C5 and C7 (in a total of 100 events) being compliant – crew initiation of go-around in accordance with SOP, or continued approach to land within SOP, and (3) C6, C8, C9 and C10 (in a total of 52 events) being non-compliant – crew continued approach to land or delayed the initiation of go-around in contravention of SOP. From the WAD aspect, all these cases were reported as having landed/gone around successfully, with only two of the flights stating that the landing was slightly firmer than usual.

Table 4 summarises the FRAM analysis findings by listing all functions, providing variability examples (linking them with the cases demonstrated in Fig. 4), explaining the variability context and its

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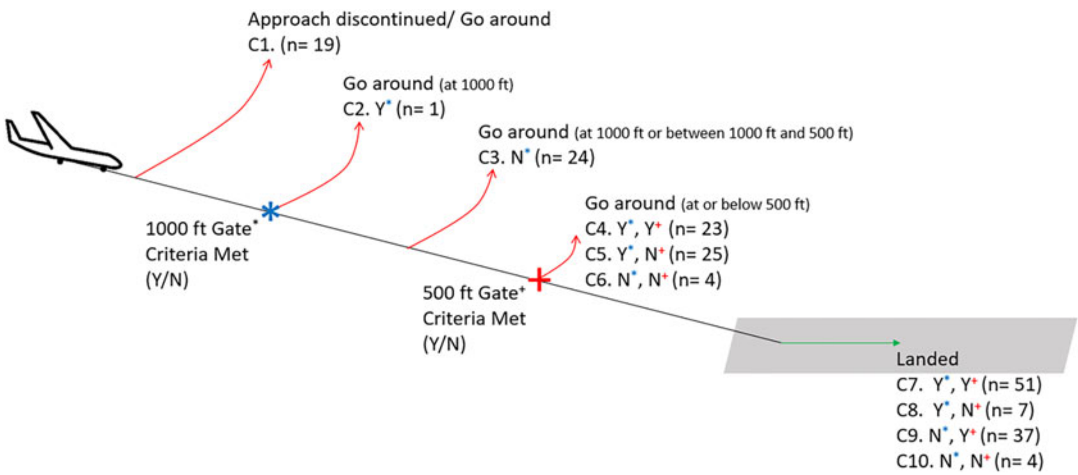

Figure 4. *Categorisation of events in the analysed aviation safety reports.*

aggregated impacts, and proposing measures for managing variability. In Table 4, the authors aimed to provide examples of variability with both dampening and amplifying effects; however, Table 4 predominantly lists examples of undesired variability. This was due to the nature of the aviation safety reports, which represented near misses. Near misses are events that could have led to accidents. Near-miss data provided more information on 'how things went wrong' than 'how things went right' or 'how they recovered from the situation'.

In most cases where variability had an amplified effect, it led to delays in the operation by initiating a go-around and repeating all activities for the subsequent approach and landing. In cases where variability had a dampening effect, this was often linked to having effective communication, whether between pilots, pilots and ATC, or pilots and cabin crew. These interactions increased the situational awareness and preparedness of pilots to make landing/ going-around decisions. Results showed various cases (e.g., C1, C2 and C4 in Fig. 4) where a trade-off between efficiency and safety was made by prioritising safety.

With inputs from subject-matter experts, Table 4 presents measures to manage performance variabilities. The recommendations encompass various aspects, including checklist use, situational awareness, pilot training, communication and coordination, fatigue risk management, crew rostering, pilot callouts, monitoring, equipment maintenance, energy and speed management and the use of automation.

4.0 Discussion

The stability of an approach is identified by meeting a set of criteria; however, various factors impact approach stability, including pilot experience, automation, energy management and environmental factors [4]. Not all unstable approaches lead to unsuccessful landings [69].

In this study, the authors analysed 195 aviation safety reports from a single airline to explore unstable approaches. Of these, the authors identified 43 events as being compliant and cautious, 100 as compliant, and 52 non-compliant with the SOP (see Fig. 4). Despite the variability in performance, all events resulted in successful landings, with only two being considered as hard landings. The analysis revealed specific cases in which pilots mitigated earlier imprecisions or timing deviations, such as late checklists or incorrect configurations, through timely communication, role reassignment or energy management. These actions often resulted in dampening variability in other functions, allowing the approach to stabilise. This aligns well with a previous study in which Wischmeyer [69] suggested that pilot skills and aircraft performance enable recovery from an unstable approach.

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Table 4. *FRAM findings summary*

Function	Variability in terms of time and precision (linked to the event case)	Context	Effects on downstream function(s)	Measures for managing variability (Recommendation (R))
F1. To conduct all briefings and check-lists	Not at all – Landing checklist not completed at 500ft (C6)(C5).	Gear was taken down early due to a tailwind, a shortcut given by the ATC, and pilots communicated with cabin crew to secure the cabin earlier. All these distracted pilots to complete the landing checklist.	Triggered the function <to decide landing/go around>, and a G/around decision was made, which resulted in an amplified impact on all functions. All functions were repeated for the second approach.	R1. Ensure that a missing or late checklist should initiate pilot preparation for a possible go-around. Nothing else apart from landing should be done below 500ft. R2. Enhance pilot preparedness at the point (e.g., cued with altitude) to initiate and complete the landing checklist. R3. Enhance pilot knowledge and skills to consider all the impacts of the shortcut or tailwind in terms of compressing the time or distance available to complete the approach. R4. Enhance pilot preparedness to decline ATC requests if it jeopardises approach stability. R5. Ensure that pilots have anticipatory awareness and shared situational awareness. R6. Provide training in flight simulators, including this scenario.

Table 4. *Continued.*

Function	Variability in terms of time and precision (linked to the event case)	Context	Effects on downstream function(s)	Measures for managing variability (Recommendation (R))
	On time – Landing briefed on time (C9).	There was good communication between pilots.	Resulted in dampening variability in the function <to configure aircraft>, and pilots picked and corrected errors. However, that correction action resulted in an amplifying impact on the function due to the change of the approach type requiring repeating the function <to conduct all briefings and checklists>.	R7. Enhance communication between pilots. R8. Create organisational culture that supports effective communication and coordination.
	Imprecise – Briefed for configuration 3 but requested flaps full (C10).	Crew fatigue after an early (03:35) reporting time and two-hour delays departing London Gatwick contributed to forgetting the briefed approach. Noticed during the landing checklist.	Results in amplified impact on <to configure aircraft>, <to control speed> and <to command input by pilot>. Flap 3 was selected off and continued with flaps full in order not to destabilise the approach.	R9. Enhance crew awareness and management of fatigue risk and its impact on crew performance, especially during critical phases of flight. R10. Develop plans to reduce the potential impact of operational delays in their crew rostering. R11. Emphasise that the landing checklist is the last opportunity for pilots to ensure that the aircraft's landing configuration is as briefed.

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Table 4. *Continued.*

Function	Variability in terms of time and precision (linked to the event case)	Context	Effects on downstream function(s)	Measures for managing variability (Recommendation (R))
	Too late – Landing checklist completed by 800ft (C9).	Pilots were slightly distracted by understanding why the previous aircraft had gone around, and the sudden workload.	Resulted in an amplified impact on the function <to decide landing/go around>, and pilots decided to land as the flight was stable.	R6, R7 R12. Ensure that the landing checklist is completed before reaching the stabilised approach altitude. R13. Enhance pilot awareness of other aircraft operations. R14. Enhance pilot preparedness and anticipation for a possible go-around. R15. Encourage pilot monitoring (PM) pass altitude calls and call-out deviations.
F2. To confirm the type of approach	Too late – The final type of approach confirmed too late (C9).	Variabilities in the function <to conduct all briefings and checklist> as the type of approach changed.	Amplified variability on the function <to configure aircraft>.	R14
	Imprecise – Briefed configuration 3, confirmed and applied full, but then realised and returned to flap 3 (C9)	Poor communication between PM and PF, and confused responsibilities between them: PM calling for flaps full and PF confirming.	Amplified variability on the function <to configure aircraft>.	R6, R7, R8. R16. Develop more opportunities for crew resource management training. R17. Consider individual pilots' communication skills and team familiarity for crew pairing. R18. Ensure effective monitoring and cross-checking. R19. Enhance coordination and clear responsibility setting.

Table 4. *Continued.*

Function	Variability in terms of time and precision (linked to the event case)	Context	Effects on downstream function(s)	Measures for managing variability (Recommendation (R))
	Acceptable – The approach was planned with configuration 3 but changed to flap full to reduce speed (C9) or due to ATC's request for minimum runway time (C7).	Due to amplified variabilities on the function <to control speed> as rapid speed increases or busy air traffic and aircraft being on hold on air.	Amplified variability on the functions <to configure aircraft> and <to conduct all briefings and checklist>.	R4, R5, R8. R20. Enhance pilot preparedness for the change of configuration when minimum runway time is requested by ATC or to manage speed. R21. Enhance pilot knowledge and skills on the considerations of the ATC request's safety impacts to complete the approach.
F3. To communicate with ATC	Too early – An unusually early ATC clearance to land (C3)	Low air traffic at the time.	Pilots forgot to manage speed and configure the aircraft in combination with the PF's electronic flight bag (EFB) failure. So, amplified variability on the functions <to configure aircraft>, <to cintrol speed>, and <to decide landing/go around>.	R22. Examine the reliability of the EFBs. R23. Enhance ATC preparedness in abnormal cases. R24. Develop pilot training in EFB failure. P25. Develop pilot training to improve prospective memory.

Table 4. *Continued.*

Function	Variability in terms of time and precision (linked to the event case)	Context	Effects on downstream function(s)	Measures for managing variability (Recommendation (R))
	Too late – The director handed the pilots over to the tower at 1600 ft (C1).	Busy airport traffic.	Amplified variability effects on the functions <to configure aircraft>, <to control power> and <to decide landing/go around>. Resulted in a go-around.	R23 R26. Plan ATC rostering by considering busy times and having a backup ATC in place. R27. Enhance ATC knowledge on pilot needs. R28. Create an organisation culture to encourage ATC to be responsive to pilot requests. R29. Foster coordination between sectors (terminal, arrival and tower).
	Imprecise – Due to busy air traffic, the director forgot to hand pilots over to the tower (C7).	The director was distracted by another aircraft lining up very slowly. Busy airport traffic.	Amplified variability on the functions <to configure aircraft> and <to conduct all briefings and checklist>.	R23, R26 R30. Support effective management of traffic flow.
	Precise – ATC reported other traffic reports of negative shear up to 40kts (C5).	The ATC was very informative.	Dampening variability impacts <to control speed>, <to configure aircraft>, <to manage flight path>, <to control power> and <to decide landing/go around>.	R23 R31. Support communication between ATC and pilots. R32. Ensure that ATC provides the necessary information, including traffic, weather and wind shear warnings. R33. Support having a shared situational awareness between ATC and pilots.

Table 4. *Continued.*

Function	Variability in terms of time and precision (linked to the event case)	Context	Effects on downstream function(s)	Measures for managing variability (Recommendation (R))
F4. To manage the flight path	Imprecise – Aircraft ended up above the profile (C1).	The final APP did not engage, and the late selection of the APP at OLEVI.	Amplified variability on the functions <to command input by pilot>, <to control power> and <to decide landing/go around>.	R5, R8, R18, R33 R34. Design the system to encourage pilots to use speed brakes if they are within the limits.
	Imprecise – Transient changes on flight path (C5).	Due to very strong wind.	That triggers the function <to decide landing/go around>, and a go-around decision was made, which resulted in an amplified impact on all functions. All functions were repeated for the second approach.	R5, R14 R35. Enhance pilot training on effective energy management.
	Acceptable – PF-corrected flight path (C8).	Situational awareness of pilots, their confidence during the flight, ability to control speed using speed brake and correct flap settings. The autopilot disengaged, and the captain took the PF role. Good communication between pilots and clear role change.	Dampened variability in the functions <control speed>, <manage sink rate> and <to configure aircraft>.	R5, R8, R16.

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Table 4. *Continued.*

Function	Variability in terms of time and precision (linked to the event case)	Context	Effects on downstream function(s)	Measures for managing variability (Recommendation (R))
	Precise – The aircraft is on the correct profile (C7).	Controlled speed, sink rate, aircraft configuration and daylight conditions with high visibility.	Dampened variability in the functions <control speed>, <manage sink rate> and <to configure aircraft>.	R3, R5, R18, R33, R34, R35
F5. To control speed	Not at all – Forgot to manage speed (C3).	Loss of situational awareness due to EFB failures on both pilots' sides. Early clearance from the ATC at the same time as EFB failures caused a distraction that resulted in forgetting to manage speed.	Resulted in a decision to go around. Amplified effect on all functions, and all functions repeated.	R5, R22, R24, R33
	Too late – late selection of managed speed (C8).	Pilot distraction.	Resulted in amplified effects on <to manage flight path>, <to manage sink rate> and <to control power>. The aircraft was stable at 300ft and landed.	R14 R36. Design system to reduce pilot distraction.
	Imprecise – Speed was below VLS (C4).	The pitch attitude is incorrect.	Resulted in amplified effects on <to manage flight path>, <to manage sink rate>, <to control power> and <to decide landing/go around>.	R5, R8, R14, R18 R37. Enhance pilot preparedness on managing low speed.

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Table 4. *Continued.*

Function	Variability in terms of time and precision (linked to the event case)	Context	Effects on downstream function(s)	Measures for managing variability (Recommendation (R))
	Acceptable – Transient speed toward and below Vapp-5 (C7).	Weather conditions.	Resulted in amplified effects on <to manage flight path>, <to manage sink rate> and <to control power>.	R38. Develop pilot training on the use of power and pitch to correct speed and flight path. R39. Support the use of automation.
F6. To configure aircraft for landing	Not at all – not configured (C3).	Distracted with events ATC – discussions with other aircraft for delayed take-off due to cumulonimbus ahead.	Resulted in amplified effects on <to control power> and <to decide landing/go around>. All functions are repeated.	R5, R8, R14, R31, R33
	Too late – Landing gear was not selected at 3.7nm, and configuration 3 and configuration full were selected late (C9).	Delayed flight back and distraction due to runway change.	Amplified variability on the function <to conduct all briefings and checklists>.	R5, R12, R33 R40. Enhance pilot preparedness by considering multiple possible issues. R41. Develop pilot training to manage time pressures and workload, especially when there are changes from ATC (e.g., shortcuts, expeditious arrivals, and altitude and speed constraints). R42. Support operators to liaise (directly or via runway safety teams) with air traffic management service providers to minimise last-minute changes or restrictions due to traffic or other operational issues and help operators confirm stable approach criteria.

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Table 4. *Continued.*

Function	Variability in terms of time and precision (linked to the event case)	Context	Effects on downstream function(s)	Measures for managing variability (Recommendation (R))
	Too early – Configured early (C3).	To allow more time for change of PF for training purposes.	Amplified variability on <to control speed> as the pilot forgot to manage speed at 4nm in all excitement and decided on a go-around.	R5, R18 R43. Ensure that changes in PF for training purposes occur earlier and before the arrival phase of the flight in order to prevent interruptions in the orderly flow of approach and landing tasks.
	Acceptable – Gear taken down at 7nm (C6).	Weather conditions – tailwind, intention to manage speed.	Dampening variability on <to control speed>.	R44. Support the use of selecting gear down within the acceptable limit as an effective strategy to manage energy and control speed.
	Imprecise – Mistakenly took flaps full out on a flap 3 landing and realised during landing checks by ECAM memo showing flaps 3 blue (C9).	Night and crew fatigue.	Amplified variability on the function <to configure aircraft> and <to conduct all briefings and checklists>.	R5, R8, R9, R14 R45. Ensure that pilots cross-check with ECAM as part of the landing check to ensure aircraft are configured as briefed for landing effectively.

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Table 4. *Continued.*

Function	Variability in terms of time and precision (linked to the event case)	Context	Effects on downstream function(s)	Measures for managing variability (Recommendation (R))
F7. To control power	Imprecise – Wrong selection of V/s increased thrust (C2).	Workload to manage flight path and speed, and PM distracted by taking 'cabin prepare for landing call' from cabin manager; lack of monitoring, ATC shortcut and rushed approach.	Amplified effects on <to control speed>, <to manage flight paths>, <to manage sink rate> and <to decide landing/go around>. All functions are repeated.	R5, R8, R9, R18, R19, R41, R42
	Imprecise – Poor energy management (C7).	A training flight for the first officer as a PF.	No impact on the rest of the functions.	R5, R8, R18, R35
	Acceptable – Power adjusted (C7).	Weather conditions (turbulent approach), rapid change in speed and sink rate warning.	Amplified effects on <to minimise heading and pitch changes>, and dampening effects on <to control speed> and <to manage flight path>.	R14 R35 R46. Create opportunities to maintain and improve pilot skills and competence. R47. Support the use of automation unless conditions dictate otherwise; if so, PF should always be prepared to take control immediately.
F8. To manage the sink rate	Imprecise – EGPWS sink rate warning activated at about 300ft (C7).	Very strong gusty crosswinds.	Amplified effects on <to control power>, <to manage flight path> <to control speed> and <to decide landing/go around.	R14, R31

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Table 4. *Continued.*

Function	Variability in terms of time and precision (linked to the event case)	Context	Effects on downstream function(s)	Measures for managing variability (Recommendation (R))
	Imprecise – A momentary sink rate of 1300fpm at 750 RA (C9).	ATC's estimate on track miles puts the aircraft high on profile, and the PM disconnects the autopilot.	Amplified effects on <to control power>, <to manage flight path> and <to control speed>.	R14, R33, R38, R47
	Acceptable – Sink rate of 800/900 ft/min (C10).	Aimed at reducing vertical speed to avoid overspeed, headwind, and wind shear.	Dampening effects on <to control speed> and <to manage flight path>.	R48. Enhance pilot competency to adjust the sink rate to manage speed and flight path.
	Acceptable – PF selects V/S 0 to capture glide (C7).	Slightly being below glide.	Dampening effects on <to control speed> and <to manage flight path>.	R48
F9. To minimise heading and pitch changes	Imprecise – Pitch attitude is incorrect (C4).	Speed below VLS target and thrust at idle.	Amplified effects on <to manage flight path> and <to decide landing/go around.	R14 R49. Enhance pilot competency in managing high deviations in pitch.
	Imprecise – Aircraft starts to pitch down (C7).	Turbulence, high speed and retracting speed brake.	Amplified effects on <to control speed> and <to manage flight path>. Results in increased speed, and increased workload. The pilot disconnected autopilot to manage pitch changes and control speed.	R14, R47, R49

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Table 4. *Continued.*

Function	Variability in terms of time and precision (linked to the event case)	Context	Effects on downstream function(s)	Measures for managing variability (Recommendation (R))
	Acceptable – PF pitched down to recapture the ground speed (C1).	PM inadvertently pulled for open climb, causing aircraft to climb.	Dampening effects on <to control speed>, <to manage flight path>, <to manage sink rate> and <to control power>.	R5, R18, R38
F10. To decide landing/go around	Imprecise: Considered going around and decided to land (C7).	The pilot feeling in control, the visual picture looks normal, and confusion over the EGPWS warning.	No variability impacts on the functions, resulting in landing.	R14 R50. Enhance pilot competency in using visual cues to perceive the altitude and distance to the runway.
	Acceptable: Called go around (C3).	Lack of time to fully configure aircraft by 100ft.	All functions are repeated with less variability.	R14, R20
	Acceptable: Called go around (C3).	The cabin was not secured at 700ft.	All functions are repeated with less variability.	R14, R20 R51. Enhance communication and coordination between pilots and cabin crew. R52. Ensure that pilots and cabin crew have a shared situational awareness. R53. Support for effective cabin crew coordination.

The following subsections discuss recommendations for managing variability (see Table 4) in a stable approach, the use of FRAM to analyse near-miss data, and the limitations of this study.

4.1 Managing variabilities in a stable approach

Performance variability can lead to both desirable and undesirable outcomes. FRAM explores variability, enabling the proposal of measures to sustain the desirable ones and mitigate the undesirable ones. This study provided numerous suggestions (Table 4) related to checklist use, situational awareness, pilot training, communication and coordination, fatigue risk management, crew rostering, pilot callouts, monitoring, equipment maintenance, energy and speed management and automation use to manage variabilities. Among these suggestions, crew resource management training, including effective communication, coordination, collaboration, monitoring, briefings and checklists, was the key factor in managing variability (see Table 4).

Effective communication, coordination and collaboration were found to be the keys to a stable approach, which requires shared situational awareness. Data analysis revealed that pilots adjust their performance when they have a shared situational awareness, which occurs when they perceive the necessary information from each other and link all the information to understand the status of the approach, despite the time pressure involved in the flying task. Routine callouts and corresponding acknowledgements are also found to play an essential role in perceiving the required information and providing feedback. All these contributed to making relevant trade-offs and decisions to ensure the stability of the approach and manage variability. Indeed, the importance of shared situational awareness between pilots and between pilots and ATCs is highly acknowledged in the literature [34, 55]. Studies have found that impaired situational awareness negatively impacts decision-making processes and is linked to poor system performance [10, 35, 37]. In this study, the authors proposed several suggestions to maintain situational awareness during flight by ensuring effective communication, enhancing pilot competencies, creating training opportunities and improving organisational culture.

Effective monitoring was found to be another factor that contributes to managing variability in a stable approach. Data analysis revealed that pilots could manage variability when effective monitoring was in place. Monitoring tasks involve monitoring pilot actions and flight instruments, as well as communicating with ATC, cabin crew and the pilot. All require cognitive efforts and the distribution of situational awareness. Monitoring tasks can be improved when effective communication and shared situational awareness exist and effective cross-checks are completed [26]. Furthermore, monitoring tasks can be enhanced by design changes and the implementation of real-time monitoring tools [6]. Based on the FRAM findings, the authors suggest improving workload management, making design changes, reducing distractions and enhancing pilot competencies to maintain adequate monitoring.

Briefings and checklists were also found to be another key factor in managing variability. The findings from the FRAM analysis showed that variabilities in the 'conduct all briefings and checklists' function (see Fig. 2) led to both dampening and amplifying impacts on downstream functions. Non-rushed briefings and checklists can increase situational awareness and mitigate risks. For instance, the landing checklist ensures that all tasks are completed safely. However, checklists and briefings are most valuable when a strong safety culture, team building and effective training are in place. The influence of safety culture on safety outcomes has been well-recognised in the literature [44, 61]. From a Safety-I perspective, improper or missed briefings and checklists are identified as contributory factors for accidents [5, 26].

In the literature, previous studies have found that speed changes, aircraft configurations and deviations in flight paths and sink rates were key factors contributing to an unstable approach [3]. This study, however, found that variability in these factors contributed to both stable and unstable approaches. Our study has also revealed the influence of external factors, such as turbulence, tailwinds, gusts and crosswinds, which contribute to undesirable outcomes. In addition, ATC requirements such as shortcuts, minimum runway time, or other aircraft or runway conditions occasionally increased the variability of the functions. In contrast, clear communication between pilots and ATC contributed to a stable approach. In

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the traditional safety approach, any variability from procedures is considered a failure, and individuals are punished when they do not comply [39]. Our findings demonstrate that not all variabilities lead to failures or undesirable outcomes. Understanding the trade-offs made by front-line staff has significant value in everyday operations [18].

In this study, there were cases, such as C3 and C5 in Fig. 4, where pilots displayed safety-conscious behaviour by initiating and conducting a go-around when they determined the approach to be unrecoverable. However, there were also some cases, such as C8, C9 and C10 in Fig. 4, where the crew continued the approach despite not meeting the SOP stable approach criteria and still completed landings within the acceptable flight data monitoring criteria. This highlights an opportunity for further research into identifying how the crew regains or maintains the approach within stability parameters that would ensure a successful landing (i.e., well within the acceptable flight data monitoring parameters). This could also allow the stable approach criteria to be redefined based on these newly developed crew skills and abilities. Here, we can question whether policies (WAI) are reflected well in the real (WAD) practical working environment. Indeed, Blajev and Curtis [3] found that pilots do not think policies reflect well in the actual practical working environment and that training does not adequately cover the challenges they face. The findings from the FRAM analysis can be used to identify the gap between the WAI and WAD, and new training scenarios can be generated.

4.2 Discussion on the use of FRAM in analysing near-miss events

In this study, the authors utilised near-miss data to conduct a FRAM analysis, exploring the unstable approach. The FRAM model successfully linked the functions involved in a stable approach, revealed the complexity of the process and enabled the identification and management of variabilities. However, here, we must mention that the use of near-miss data and the nature of the reports led the authors to primarily consider uncontrolled variability. Thus, the results revealed more variability in cases where the outputs of the functions were too late and imprecise, often due to forgetting things and making mistakes, rather than explaining trade-off cases. Recommendations were made around managing uncontrolled variabilities. This naturally led to the FRAM analysis being a combination of Safety I and Safety II. An analyst's mindset can align a traditional method with Safety II thinking [59], or the analyst can use FRAM with Safety I thinking. There may be reconsiderations on using variability types in FRAM, as current safety reports and practices are built on the Safety-I approach, focusing on how things go wrong. Prompting questions about the sources of variability can help focus on the lessons learned from good practices, which in turn raises the need to report such practices. However, it can be challenging, as variability is often unnoticed during everyday working activities and is only likely to be noticed when things go wrong [24].

While this research provided recommendations for managing variability (see Table 4), such as suggesting that airlines provide training in flight simulators on specific scenarios, some remained high-level or more akin to a requirement for a recommendation. Many of the suggestions from the FRAM analysis provided findings similar to those of other studies [3, 26]. This brings us to the considerations of how the outputs from the Safety II approach differ from the Safety-I approach. Sujan et al. [60] highlighted the issue of FRAM applications focusing on recommendations to control performance variability rather than ensure system resilience, and they suggest identifying recommendations by considering the resilience abilities of monitoring, responding, anticipating, and learning. However, despite FRAM leading the inclusion of common improvement suggestions, it can provide further suggestions around trade-offs and system interactions, which help to learn from near-miss events. This study aimed to explore unstable approaches by examining how a stable approach is typically achieved, rather than focusing solely on unstable approaches and identifying contributory factors. This approach helped to understand the complexity and context-conditioned variability.

Despite the successful applications of FRAM in various industries, the Safety II approach has been criticised [2, 8, 13, 29, 36, 66]. Karanikas and Zerguine [29] highlight that FRAM moves attention from safety to resilience, which can be criticised from a safety perspective. Leveson [36] disagrees with the

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definitions of Safety I and Safety II, highlighting that the systems approach has already been applied in safety-critical industries. Some question the empirical evidence on the validity of Safety II. Farooqi et al. [13] and Underwood and Waterson [65] identify the gap between research and practice regarding the use of FRAM. Indeed, researchers have often adjusted FRAM to improve its practical applicability. Such challenges and particular industrial needs encouraged researchers to propose suggestions for improvements to FRAM. For instance, Li et al. [38] integrated accident causation analysis and taxonomy into FRAM to provide a more systematic function identification based on control constraints, Rosa et al. [52] integrated multi-criteria decision-making methods to reduce subjectivity in identifying variability, and Patriarca et al. [49] used Monte Carlo simulation to quantify variability. Some suggestions have also been made for integrating the Safety I and II approaches to propose practical solutions to industrial problems [8, 41].

There have also been limitations identified, including the complexity of the method, difficulties in understanding its fundamentals, the resources required for analysis and the reliability of the findings [13]. However, these criticisms should not undervalue the method's strength in analysing complex systems. We believe the value of FRAM lies in its ability to explore complex systems, a claim also made by other researchers [16, 47, 53, 66]. This study revealed an additional value of using FRAM in understanding near misses.

Near misses are considered to be an opportunity to predict and analyse accidents [31, 63]. This understanding is built on very early studies with Heinrich [17] and later Salminen et al. [54] the iceberg model, providing ratios from near misses to accidents, despite later non-linear accident models explaining accidents with systemic causes [20, 63]. The latter models explain that factors can lead to successful and unsuccessful outcomes [62]. This study revealed that the variability of a function can lead to both desirable and undesirable outcomes, which aligns well with Safety II [21] and other terms, such as resilience engineering [25] and safety differently [9]. Using near-miss data to understand the impacts of variability and make performance adjustments enabled learning from near-misses, which may support the prevention of accidents. In various industries, analysing near-miss events enabled the prospective identification of causal factors of accidents [1, 33, 68]. Thoroman et al. [62] highlight the value of analysing near misses to identify the protective factors and claim that these protective factors share many properties with the causal factors identified in accidents.

In this study, using near-miss data in FRAM analysis not only identified valuable lessons learnt that traditionally could have been learnt from analysing accident data, but it also moved the focus from human error to system behaviour or 'systemic ability to do safety', which is the context of Safety II [21, 39].

4.3 Limitations

This study has limitations. Although the aviation safety reports were of great value, in several cases, the narrative/descriptive elements of the report were limited in providing a sufficient understanding and insight into the circumstances, especially regarding good practices. Moreover, event cases are provided at different levels of detail. It would be great to interview the reporter pilots and consider future studies that summarise the case debriefing with the crew, particularly regarding their actions. It would be crucial for future studies to identify critical human factors elements and access richer information from more in-depth interviews with reporter pilots, in addition to having snapshots of the flight data. This would be essential to identify those specific crew skills, behaviours and decision-making strategies that can have a positive effect on their abilities to not only operate the aircraft but also to maintain situational awareness, anticipate and decide the best course of action (i.e. abandon or continue approach) given demanding or adverse circumstances (environmental or ATC), effectively manage aircraft energy when time/distance constrained, and maintain or regain sufficient control over the stability of the approach to ensure that the landing is effected well within flight data monitoring parameters. Finally, while the FRAM model provides valuable insights into complex systems, understanding the interactions between functions requires the use of the FRAM model visualiser, as Fig. 1 does not clearly show the individual couplings. That is why the authors included Fig. 3, highlighting the couplings between 'To communicate with ATC' and other related functions.

5.0 Conclusion

This study applied FRAM as a complementary analysis to explore the issue of an unstable approach. The FRAM model enabled the exploration of complex interactions between functions involved in the approach phase by tracing how variability emerged, propagated and was dampened or amplified across functions. This analysis was based on textual aviation safety report descriptions aligned with SOP-derived functions and SME inputs. The analysis revealed that system behaviours were not observable through structured aviation safety report data alone. The study identified various sources of variability that contribute to a stable approach. Effective communication, monitoring, briefings and checklists were key factors that led to sustaining or regaining a stable approach.

This study contributes to aviation safety by revisiting the unstable approach problem and using FRAM to analyse near-miss data. The lessons learned from this study can also be used in other industries. Using FRAM in analysing near-miss data allows for a more balanced analysis that yields greater opportunities to identify what the crew did to either prevent or recover from an undesirable situation, and what specific behaviours, skills and abilities the organisation needs to reinforce further to improve safety. This creates an opportunity for further research into more accurately identifying how higher-level key human factor skills and abilities can contribute towards operational resilience. In turn, findings from such further research could form the basis of improved crew training and operational procedures, resulting in the long-awaited marked improvements in flight safety during the approach and landing phases of flights and further reducing the number of approach and landing accidents.

Furthermore, this study highlights the need to develop effective reporting systems for Safety II applications, acknowledging the practical challenges of using FRAM. Further studies can investigate the optimal application of FRAM in various industries and its long-term effects on industrial practices.

Data availability statement. Data supporting this study cannot be made available due to the confidentiality agreement with the data provider.

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