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Systemic safety analysis of complex socio-technical events: Insights from applying causal analysis based on systems theory and functional resonance analysis method

Edoardo Losi [a], Gulsum Kubra Kaya [a,*], Fanny Camelia [b], Mikela Chatzimichailidou [c], David H. Slater [d], Riccardo Patriarca [e], Mark Sujan [f]

[a] Safety and Accident Investigation Centre, Faculty of Engineering and Applied Sciences, Cranfield University, UK
[b] Centre for Defence and Security Management and Informatics, Faculty of Engineering and Applied Sciences, Cranfield University, UK
[c] Department of Civil, Environmental and Geomatic Engineering, University College London, London, UK
[d] School of Engineering, Cardiff University, United Kingdom
[e] Sapienza University of Rome, Department of Mechanical and Aerospace Engineering, Rome, Italy
[f] Centre for Assuring Autonomy, Department of Computer Science, University of York, York, UK

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ABSTRACT

Understanding safety in complex socio-technical systems requires analytical approaches that move beyond linear accident models to examine how interactions across organisational, technical and operational elements shape safety outcomes. This study applies two systemic safety analysis approaches, Causal Analysis based on Systems Theory (CAST) and the Functional Resonance Analysis Method (FRAM), using well-documented aviation investigation data. The study examines how different systemic methods model system behaviour, frame causality and performance variability, and generate different forms of safety recommendations. CAST identified cross-level control and feedback weaknesses that enabled the wrong-surface alignment under the runway-closure night configuration. FRAM showed how coupled performance variability, including missed runway-closure cueing and ambiguous visual cues, shaped the development of misalignment risk while also clarifying the recovery pathway that enabled the go-around. This study suggests that CAST and FRAM are best used as complementary lenses for systemic event analysis. CAST supports governance and assurance redesign, while FRAM informs operational guardrails and variability management under uncertainty.

1. Introduction

Aviation accident investigation is a structured process. It is conducted by designated authorities to identify contributory factors and issue safety recommendations, thereby supporting continuous improvement of aviation safety. While the International Civil Aviation Organisation (ICAO) sets procedural requirements and provides guidance on safety methodologies, it does not prescribe which accident analysis methods to apply [1]. In practice, investigative authorities employ a range of tools, many of which remain grounded in linear accident models [2], often emphasising human error mitigation [3]. However, there is a growing recognition that linear models often fall short in explaining accidents in complex socio-technical systems. They inadequately capture interdependencies among system elements, non-linear interaction effects and the uncertainty that characterises complex operations [4–6]. This has prompted a shift toward system-based methods that account for interactions, adaptations and emergent outcomes [7–9].

Within this broader shift, several approaches have been used to analyse accidents in complex socio-technical systems, including AcciMap [10,11], Human Factors Analysis and Classification System (HFACS) [12], Systems-Theoretic Accident Model and Processes (STAMP) [9], Causal Analysis based on Systems Theory (CAST) [13] and Functional Resonance Analysis Method (FRAM) [7]. These approaches all move beyond simple linear causation, but they differ in analytical emphasis. AcciMap is particularly useful for mapping contributory factors across interacting socio-technical levels [8,14–16]. HFACS provides a structured taxonomy for classifying human, organisational and

* Corresponding author.
E-mail address: kubra.kaya@cranfield.ac.uk (G.K. Kaya).

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supervisory contributors [12]. CAST treats safety as a control problem by examining how inadequate control, feedback, safety constraints and decision-making contributed to the event [13]. FRAM examines how everyday performance variability enables systems to function successfully under varying conditions, and how such variability may combine to produce unexpected outcomes [7]. Using these approaches, accidents are not viewed as the result of isolated failures, but rather as emergent outcomes of complex interactions within the socio-technical environment [17,18]. Several studies have applied system-based methods in the context of aviation accident investigation [19–22,15].

In this study, CAST and FRAM were selected to analyse the Air Canada Flight 759 (ACA759) near-miss incident, not because they are universally superior to other system-based approaches, but because they offer distinct yet complementary analytical lenses for examining complex socio-technical interactions. CAST's control-structure perspective tends to identify deficiencies in safety constraints, feedback, oversight and organisational design [23,9,13,24]. FRAM's focus on performance variability highlights how everyday work adaptations and interactions can combine to produce unexpected outcomes [7,25,26]. This contrast enables the study to examine how CAST and FRAM, when applied to the same event record, differ in their modelling of the system, their treatment of causality and performance variability, and the form of the safety recommendations they generate.

Following this introduction, Section 2 provides background on CAST and FRAM and reviews prior evaluations of accident analysis methods. Section 3 outlines the research design and details of the safety event. Sections 4 and 5 present the results of the CAST and FRAM analyses, respectively. Section 6 discusses the outputs from both methods, considering their modelling, causal framing, treatment of variability and resulting recommendations. Section 7 offers concluding reflections on the utility of these system-based approaches for safety investigations.

2. Literature review

2.1. Causal analysis based on systems theory

CAST, developed by Leveson [13], is a systems-based accident analysis method built on the Systems-Theoretic Accident Model and Processes (STAMP). It conceptualises safety as the enforcement of constraints within a dynamic system of interacting components. From this perspective, accidents are not necessarily the result of failed components but may arise from inadequate control actions, poor feedback or misaligned mental models between system actors. CAST shifts the analytical focus from "who failed" to "why the system enabled unsafe control". This orientation enables the identification of systemic contributors such as design mismatches, regulatory oversights or organisational gaps. These characteristics are particularly valuable in domains such as aviation, where operations are shaped by complex interdependencies among humans, technologies and organisations [27,28].

Several studies have applied CAST in the aviation industry [29–32]. For example, Kaya, Humphreys, et al. (2025) used it to examine passenger-boarding incidents and identified unsafe interactions in ground-handling operations. Neto et al. [32] used CAST to evaluate offshore helicopter operations, showing how regulatory and organisational layers can misalign. These studies demonstrate CAST's utility in supporting analysts in developing detailed control-structure models, explaining causality and driving comprehensive safety recommendations.

2.2. Functional resonance analysis method

The FRAM, introduced by Hollnagel [7], takes a different conceptual approach. It focuses not on failure per se but on normal work variability. In FRAM, both acceptable and unacceptable outcomes are viewed as emergent from everyday performance adjustments. Rather than modelling causality as a sequence of events, FRAM models functions, their variability and their dynamic couplings. This method reflects a resilience engineering approach. Understanding how systems succeed in the face of complexity and how small context-driven adjustments can sometimes resonate in ways that create unexpected outcomes [25,33]. This resonance does not imply malfunction, but rather the amplification of otherwise ordinary variability. Recent applied work also continues to frame FRAM as a way to analyse how local adjustments and functional couplings shape both degradation and recovery [34,35].

Several studies have applied FRAM in aviation settings [20,21,36,37]. For instance, Woltjer and Hollnagel [37] applied it to Alaska Airlines Flight 261, identifying how maintenance variability contributed to a catastrophic outcome. Similarly, a FRAM-based analysis of Comair Flight 5191 demonstrated how workload and environmental factors contributed to a runway excursion without any single failure point [20]. These applications show FRAM's ability to uncover the structure of normal operations and the boundary conditions where the aggregated variability leads to unexpected outcomes.

2.3. Accident analysis method evaluations

Several studies have evaluated accident analysis methods using criteria such as usability, reliability, theoretical grounding and utility. Benner [38] outlined ten criteria for effective investigation methodologies, including blamelessness, clarity and usability. Hollnagel & Speziali [39] categorised methods based on system characteristics such as coupling and tractability, identifying FRAM and STAMP as suitable for tightly coupled systems.

Several studies have also compared accident analysis methods across multiple domains. Stanton et al. [40] compared eight methods, including FRAM and CAST, using practical and methodological dimensions. Hulme et al. [8] compared the reliability of methods and found that STAMP-CAST had higher inter-rater reliability than AcciMap and AcciNet, although overall correlations with expert analysis remained modest. Other comparisons focused on output quality, analytical flexibility and theoretical coverage [41,31,42–44]. Yousefi et al. [16] conducted a case-based comparison of AcciMap, FRAM and STAMP, examining the outcomes and recommendations generated by each method. While they acknowledged that it was not possible to set standard comparison criteria for the outputs, as each had different types of outputs, they discussed some commonalities, such as causality, modelling and recommendations. These studies therefore emphasise reflective application and method transparency rather than rigid rankings of methods.

Overall, existing evaluations show that no single method is universally superior. Method utility depends on the system being analysed, the investigation aim, the analyst's expertise and data availability. However, less attention has been given to how different systemic methods shape the form, level and evidence traceability of safety recommendations when applied to the same aviation event record. This is the gap addressed in the present study. By applying CAST and FRAM to the ACA759 near-miss, the analysis examines how method choice influences the modelling of the system, the framing of contributory factors, and the type and specificity of the resulting recommendations.

3. Methods

This study aims to examine the outputs generated by CAST and FRAM applications for the ACA759 near-miss incident. It was investigated by the U.S. National Transportation Safety Board (NTSB). The purpose is not to reinvestigate the event, but to examine how these methods structure system modelling, frame contributory factors, treat causality and performance variability and generate safety recommendations.

3.1. Case study

In this study, the ACA759 near-miss was selected as a case study because it provides an information-rich and well-documented record of the same socio-technical interactions that would be analysed in a serious incident or accident. This makes it suitable for examining how different systemic methods interrogate a shared evidence base.

On July 7, 2017, at approximately 23:56 local time, ACA759, an Airbus A320, was cleared for a visual approach to Runway 28R at San Francisco International Airport (SFO). The adjacent Runway 28 L was closed for maintenance, and its runway lighting system had been deactivated. The closure was published via Notice to Air Missions (NOTAM) and included in the Automatic Terminal Information Service (ATIS) broadcast. However, it was not explicitly reiterated during the visual approach clearance. With Runway 28 L unlit, ACA759′s flight crew misidentified Taxiway C as the intended landing runway and aligned their approach accordingly, leading to a high-risk wrong-surface alignment near-miss.

At that time, four aircraft (UAL1, PAL115, UAL863 and UAL1118) were positioned on Taxiway C awaiting take-off clearance. As ACA759 descended through approximately 300 feet, the flight crew began to question the runway environment and contacted air traffic control to reconfirm clearance. The ATC tower repeated the clearance for Runway 28R. The approach continued until the pilot on UAL1 remarked over the frequency, "Where is this guy going? He's on the taxiway". By the time the tower instructed ACA759 to go around, the flight crew had already initiated the go-around and was starting to climb, with the instruction effectively coinciding with their action (see Appendix 1 for a chronological account of proximal events). Fig. 1 illustrates the communication between the ATC tower and ACA759, as well as the change in aircraft radio altitude over time. Aircraft passed over UAL1 at approximately 100 feet, PAL115 at 60 feet, UAL863 at 200 feet, and UAL1118 at 250 feet before climbing out.

This event was thoroughly investigated by the NTSB, which released a final report along with supplementary materials, including crew interviews and procedural documentation [45]. These documents served as the data foundation for this study.

3.2. Study design

The study followed a multi-phase expert-informed design to apply both CAST and FRAM analyses. The NTSB investigation report served as the primary data source, supplemented by materials in the publicly available docket (Appendix 2). The docket included technical appendices, flight path data, interview summaries, procedural documentation and air traffic control communications. Based on these materials, the first author initially conducted a CAST analysis, followed by an FRAM analysis. Both applications involved iterative revisions and modelling, supported by appropriate software tools: Draw.io for CAST and the FRAM Model Visualizer.

The first author reviewed the NTSB report and docket materials and used them to undertake each step of CAST and FRAM, respectively. Evidence excerpts were coded into method-specific constructs (e.g., CAST losses, hazards, safety constraints, control actions and feedback loops, responsibilities and contextual factors, and FRAM functions, aspects, couplings and variability). They were used to develop and refine the control structure and FRAM instantiation as new relationships were identified. A key step in this process was the development of the responsibilities (Appendix 3), which records the responsibilities of each component of the control structure. These responsibilities were derived through iterative review of the NTSB report and docket materials by identifying the relevant system actors or components, their roles in the event, and what they were expected to do in the analysed situation. Appendix 3 then served as the basis for identifying controllers, controlled processes, control actions and feedback relationships in CAST. The control actions informed the identification of FRAM functions by translating them into functionally meaningful descriptions of work-as-done and enabling conditions.

Model granularity was determined pragmatically in relation to the analytic purpose of the study. For CAST, the broader socio-technical architecture was preserved at a high level, with resolution increased only where finer-grained analysis of control and feedback was needed for the ACA759 event. For FRAM, the number of functions was limited to those necessary to represent the event trajectory, recovery pathway and relevant upstream-downstream couplings within the predefined system boundary. Further subdivision was avoided once added detail increased representational complexity without materially improving explanatory value or traceability.

To make the modelling choices more reproducible, candidate CAST elements and FRAM functions were retained when they met at least one of two criteria: they were directly referenced in the NTSB report or docket as shaping the ACA759 event; or they provided a necessary

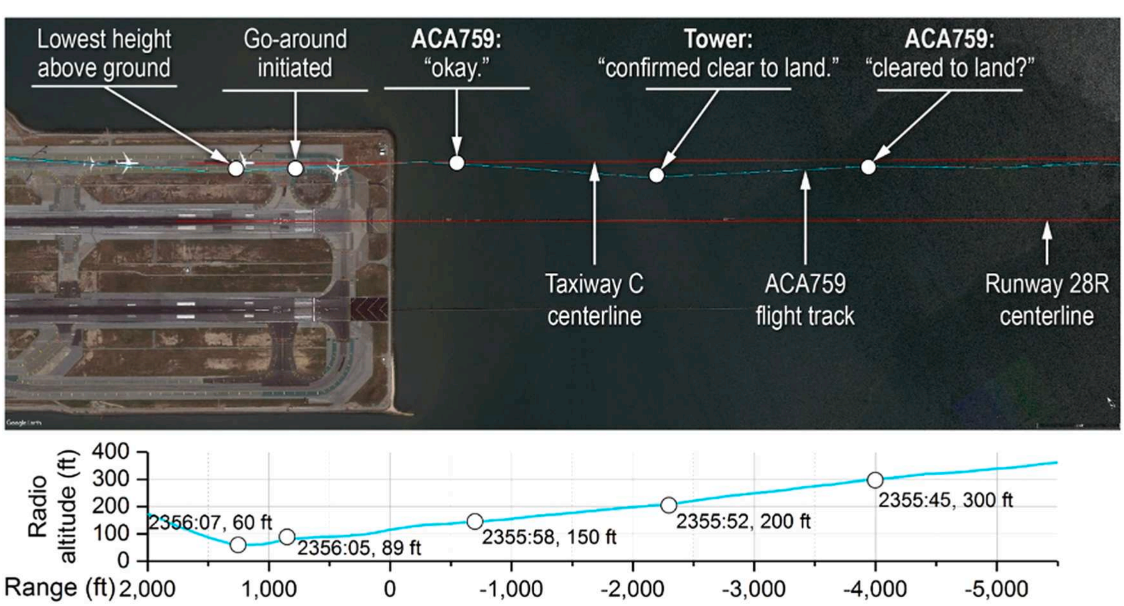

Fig. 1. ACA759 flight path over SFO and radio-altitude profile during the taxiway-overflight event (adapted from [45]).

control, feedback, resource, precondition, cue or activity for runway identification, alignment verification, monitoring, intervention or recovery. Candidate elements were excluded or merged when they duplicated another element at the same level of abstraction, fell outside the predefined system boundary, or added detail that did not change the interpretation of control flaws, functional couplings or performance variability. These criteria were used to support transparency rather than to imply that the selected CAST structure or 26 FRAM functions are the only defensible representation of the event.

Safety recommendations were generated only after the step-wise findings and models had been consolidated and were traceable to the underlying NTSB evidence through the intermediate CAST and FRAM outputs. Additionally, Author 1 explicitly defined the system boundaries in advance to include only the actors directly involved in the incident, including the airline, flight crew, SFO airport operator, tower and the national regulator. Factors outside this boundary, such as internal manufacturer design policies or international regulatory changes, were considered beyond the scope of the analysis.

Upon completing the initial analyses, Author 2 reviewed and refined the findings to enhance theoretical completeness, alignment with methodological principles and the clarity of the control structure. Four Subject-Matter Experts (SMEs) known to have substantial experience with the respective methods (two CAST experts, Authors 3 and 4, and two FRAM experts, Authors 5 and 6) were invited to provide expert review and methodological quality assurance. Experts were provided with the full working outputs, including Word tables, modelling files and figures, and were invited to comment directly on the step-by-step findings and model structure. Expert comments focused on four main checks: whether model elements were supported by the NTSB report or docket evidence; whether CAST and FRAM constructs were used consistently with their respective method guidance; whether the level of abstraction was appropriate for the study aim; and whether claims and recommendations were traceable to intermediate analytical outputs. Feedback was returned primarily as annotated comments on the Word outputs. Comments were incorporated through successive revisions to strengthen evidence-to-claim traceability and correct method-use issues. Final refinements were completed by Author 2 based on the last round of all authors' comments during the manuscript drafting process. Although this process was not intended to test inter-rater reliability, it supports the development of methodologically credible and evidence-traceable analyses. Accordingly, analyst subjectivity was managed through structured review, expert challenge, and iterative revision aimed at improving methodological fidelity and evidence-to-claim traceability.

Following this, the findings were drawn from both methods to examine their utility for analysing the ACA759 event. Specifically, four criteria were considered in reviewing the characteristics of each method's outputs: system modelling, causal framing, treatment of performance variability and the nature and scope of the resulting safety recommendations. These criteria align with prior method evaluation and comparison studies in the literature [41,43,16].

4. CAST analysis findings

The CAST analysis followed the five-step approach outlined by Leveson [13], beginning with the identification of system hazards, losses, safety constraints and a neutral event timeline. Control structure models are then developed to represent interactions among the infrastructural, operational, managerial, and regulatory levels. The key system components were subsequently examined to understand how responsibilities, assumptions and control dynamics contributed to the hazardous state. Iterative modelling and expert review were employed to refine the analysis, culminating in the identification of systemic control flaws and the development of safety recommendations.

4.1. Step 1: assembling basic information

For the analysis of the ACA759 event, the system boundary was defined to include Air Canada, SFO Air Traffic Control (ATC) Tower, SFO airport operations, airport infrastructure, tower surveillance systems, the involved aircraft positioned on Taxiway C, the flight crew and aircraft systems of ACA759. The primary losses were identified as L1: potential loss of life and L2: potential loss of or damage to aircraft or other objects.

Building on the identified losses, the main system-level hazard (H1) for the ACA759 event was defined as H1: The aircraft is not aligned with the designated landing runway during final approach. To prevent or mitigate this hazard, the following system-level Safety Constraints (SC) were derived:

- SC1: The aircraft must be aligned with the cleared runway throughout final approach.
- SC2: Visual and lighting cues must enable clear identification of the designated runway, even under degraded or ambiguous conditions.
- SC3: ATC procedures and surveillance support must enable timely detection and intervention when an aircraft shows signs of misalignment.
- SC4: Surveillance systems must detect aircraft alignment with non-landing surfaces and alert controllers in real time.
- SC5: Flight crews must actively verify runway alignment using both visual references and available instrument data during approach.

In addition, a chronological sequence of proximal events was reconstructed, and a set of guiding analytical questions was developed to support subsequent analysis. These questions were used to explore why the system allowed the hazardous state to emerge, without assigning blame to individual actors. The full list of key events and corresponding guiding questions is provided in Appendix 1.

4.2. Step 2: model the control structure

A high-level safety control structure was developed to illustrate the key system controllers and their control-feedback relationships (Fig. 2). Entities were included based on their stated influence over safety in the investigation files, whether through policy, procedures, supervision, training, infrastructure management or real-time decision-making. The control structure comprises the key controllers, control actions, controlled processes and feedback loops. To support a more focused analysis of the ACA759 event, the high-level model was refined into the detailed control structure shown in Fig. 3. The higher-resolution presentation foregrounds the components and interactions most directly implicated in the event sequence while preserving their relationships within the broader system. The purpose of this refinement is to highlight where control actions may have been inadequate or delayed, where feedback was missing or ambiguous, and where information was insufficient to prevent the misalignment. The responsibilities compiled in Appendix 3 were used to identify the controllers and their expected control and feedback relationships.

4.3. Step 3: analyse each component in loss

In Step 3, key controllers, including SFO Tower, SFO Airport Operator, Air Canada and the ACA759 Flight Crew, were used in the analysis. The analysis considered their safety responsibilities, situational context, contributions to the hazardous state, and flawed mental and process models explaining their control actions at the time. While source data informed the analysis, the resulting characterisations may reflect the analyst's interpretation of the available evidence within the CAST framework.

Table 1 illustrates the CAST component analysis for the SFO Tower. Equivalent analyses for the SFO Airport Operator, Air Canada and the

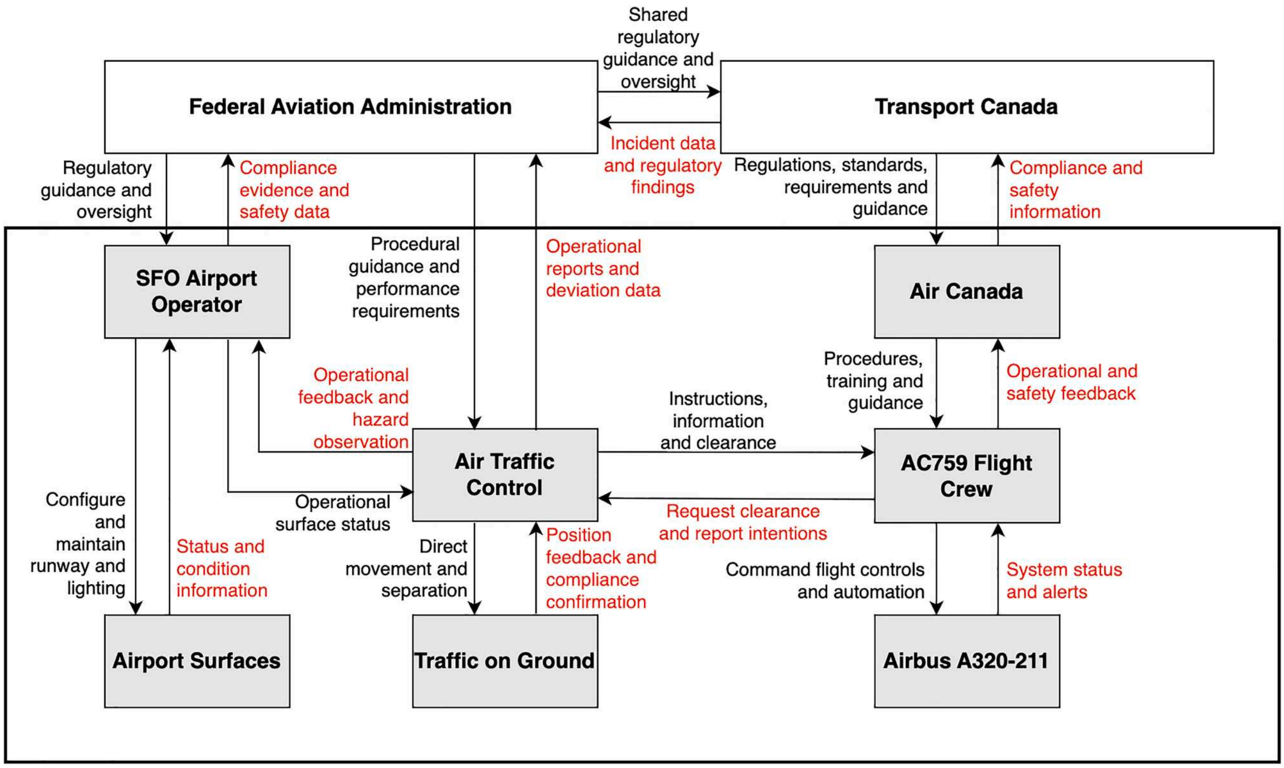

Fig. 2. High-level CAST safety control structure for the ACA759 event. Black labels indicate control actions, and red labels indicate feedback.

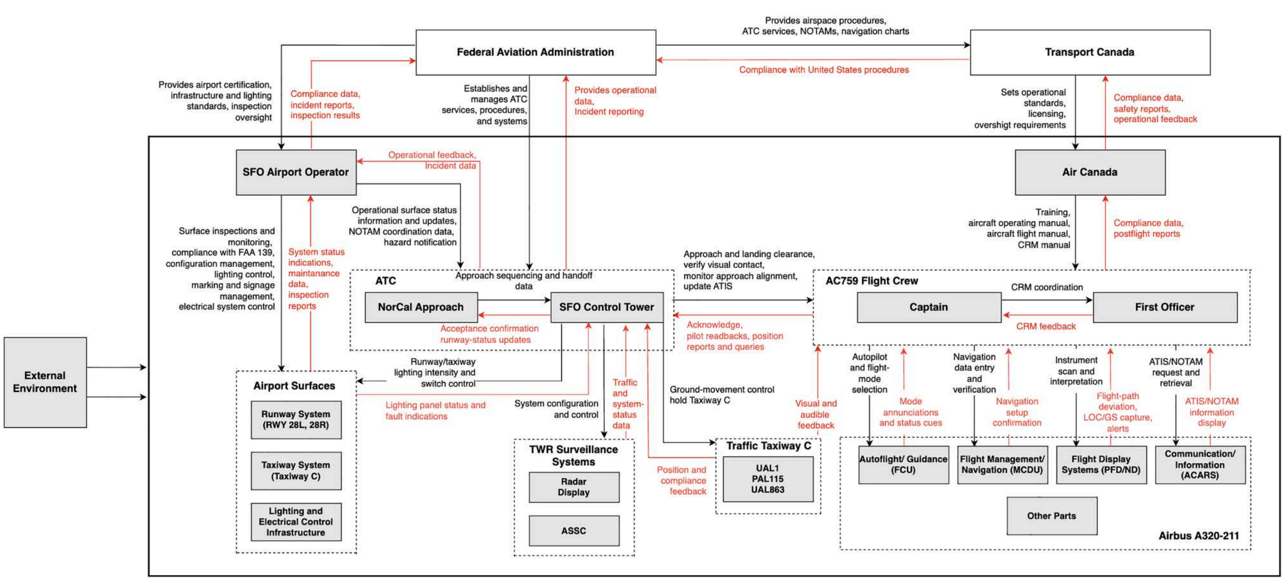

Fig. 3. Detailed CAST safety control structure for the ACA759 event. Black labels indicate control actions, and red labels indicate feedback.

ACA759 flight crew are available in Appendices 4, 5 and 6, respectively.

The SFO Tower analysis also raised several unresolved questions relevant to system learning and future control improvements. First, it questioned whether midnight-shift staffing and position-combination practices should allow single-person operations during a non-standard night-time configuration, such as a runway closure, and what operational constraints should govern such combinations. Second, it asked why existing surveillance and monitoring arrangements, including visual scan and Airport Surface Surveillance Capability (ASSC), did not support earlier recognition of wrong-surface alignment, and what additional cues, procedures or display features could improve low-light detections. Third, it highlighted limitations in ASSC and ASDE-X, which did not provide alerting for likely taxiway landings or approach misalignment. This raised questions about the feasibility of alert logic or approach-path integration without excessive nuisance alarms. Finally, it suggested reconsidering local procedures and phraseology for pilot uncertainty at very low altitude, including whether tower responses should verify runway alignment rather than runway occupancy alone.

4.4. Step 4: identify control structure flaws

In Step 4, the analysis shifts from component-specific descriptions in

Table 1
CAST component analysis for the SFO Tower.

Safety Responsibilities Inadequately Achieved

- RIA8. Ensure midnight-shift single-person and position-combination procedures are defined and followed (including what procedures must not be used when positions are combined).
- RIA9. Ensure frequency management and sectorisation preserve capacity for time-critical safety communications during combined-position operations.
- RIA10. Monitor inbound aircraft alignment using available visual and surveillance information with explicit recognition of tool limitations.
- RIA11. Ensure monitoring of inbound alignment uses available visual and surveillance information with explicit recognition of Airport Surface Surveillance Capability (ASSC) and geometry limits (e.g., coverage cone, parallax and typical Bridge Visual offset).
- RIA12. Ensure local procedures guide response to late-stage pilot uncertainty queries in a way that includes alignment verification (not only runway-occupancy confirmation) and supports precautionary intervention when needed.
- RIA13. Ensure tower and local procedures explicitly address temporarily altered airfield configurations (e.g., runway closure and traffic on a parallel taxiway at night) and specify risk-based wrong-surface monitoring and verification strategies that can be integrated into normal scan patterns and workload management (e.g., prioritised scan cues, use of available surveillance and clear escalation triggers when uncertainty arises).

Contextual Factors

- C10. A preceding arrival (DAL521) experienced difficulty distinguishing Runway 28R from Taxiway C under the same configuration and used lateral guidance to confirm alignment, indicating the visual environment was ambiguous even for an arriving crew.
- C11. Local and ground functions were combined under one controller during a midnight shift.
- C12. Night conditions, construction and airport lighting, and visual geometry (including parallax) reduced the controller's ability to visually discriminate runway vs taxiway alignment until very short final.
- C13. ASSC and Airport Surface Detection Equipment, Model X (ASDE-X) provided surface surveillance but was not designed to detect or alert on taxiway landings and misalignment, limiting automated warning support for approach alignment errors.
- C14. Multiple aircraft on Taxiway C (notably their navigation and wingtip lights) contributed to a runway-like 'string of lights' pattern from aircraft position and wingtip and landing and taxi lights, reinforcing the misperception of an active landing surface.

Contribution to the Hazardous State

- HS8. Single-person combined-position operations reduced redundancy and monitoring bandwidth, compressing the time available to detect and resolve approach-path anomalies before short final.
- HS9. A landing clearance remained in effect as the aircraft subsequently developed an offset toward Taxiway C. The misalignment was not recognised early enough to trigger an earlier corrective instruction.
- HS10. The developing misalignment was not identified in time to enable an earlier corrective instruction; recognition occurred only on very short final at low altitude, allowing the hazardous approach state to persist close to the ground.
- HS11. ATC intervention (go-around instruction) occurred only after third-party warnings and after the flight crew had begun the go-around.

Flawed Mental/Process Model

- FM9. Assumed that single-person combined-position operations and routine scanning would be adequate under the prevailing configuration, without additional support or specific prompts for wrong-surface monitoring.
- FM10. Interpreted the aircraft's apparent track and offset as consistent with the expected Bridge Visual geometry and therefore believed the aircraft was aligned with RWY 28R based on the scan and expectation.
- FM11. Assumed no abnormal alignment was developing because the observed depiction was interpreted as normal for the approach.
- FM12. Had no prior reference for how a taxiway lineup would appear visually or on ASSC (having not previously encountered a Taxiway C lineup), contributing to late recognition.

Step 3 to systemic control-structure flaws. It examines cross-layer conditions that weaken safety constraints and allow a hazardous state to develop and persist across organisational boundaries. Consistent with the CAST handbook [13], four systemic starting points were examined: communication and coordination, the safety information system, feedback loops and reporting, and changes and dynamics over time.

A cross-layer weakness was that late-stage uncertainty did not reliably trigger explicit verification and intervention between the flight deck and tower. When the crew queried ATC on short final, the controller checked runway occupancy and reconfirmed clearance to land on Runway 28R. However, the exchange did not include clear verification of runway identity and alignment. This reveals a systemic coordination gap. Communication confirmed the clearance, but did not enforce alignment confirmation as the safety-critical constraint under ambiguous cues. The vulnerability was compounded by tower frequency congestion during combined-position operations, which delayed the crew's query and reduced the time available to resolve the mismatch.

Across multiple layers, key information was present but not sufficiently salient or supportive during the non-standard night configuration. Runway-closure information was provided through preflight and arrival channels. However, it was not reliably carried forward into a clear threat picture or verification plan. Closure cues, extinguished runway lighting and lighted "X" markers met the technical requirements. However, they did not provide a strong attention-capturing cue for aircraft aligned with Taxiway C, limiting redundancy for wrong-surface detection from the approach perspective. In parallel, procedure and interface design also weakened the instrument cross-check. For the flight management system, the Bridge Visual approach and manual Instrument Landing System (ILS) tuning were required. However, it was non-routine for this fleet and not conspicuous in the approach material. As a result, the independent alignment reference was easier to miss. Finally, tower controllers used surveillance displays for monitoring, but interpretation remained largely manual. Procedures did not clearly address how to account for tool limitations or respond to uncertainty in the late stage.

The event also exposed a systemic weakness in post-event feedback pathways, particularly those needed for evidence preservation and organisational learning. Reporting requirements referred to action as "as soon as possible" but did not specify a clear time frame. This created scope for delay and reduced the likelihood that time-sensitive data (e.g., Cockpit Voice Recorder (CVR)) would be preserved before being overwritten during continued operations. From a CAST perspective, this reflects a feedback-control problem. Weak triggers and unclear escalation thresholds can delay organisational awareness, safety-function involvement and preservation actions. This, in turn, reduces the system's ability to learn from the event and strengthen its controls.

The event occurred under a temporarily altered operational configuration. Runway 28 L was closed with its lights off, while multiple aircraft queued on Taxiway C created a runway-like light pattern. Step 4 shows that the broader control structure lacked robust adaptation to configuration-change controls. These controls would need to span airport operations, ATC practices and airline approach preparation, including strengthened monitoring, verification gates and communication prompts when parallel-runway cues are disrupted at night. These dynamics also interacted with ATC tower staffing and position-combination practices, further reducing the time available for detection and intervention.

Overall, Step 4 shows that cross-layer weaknesses enabled the ACA759 event. These concerned how uncertainty was translated into verification and intervention, how safety-critical information supported cross-checking, how reporting and evidence-preservation feedback loops were triggered and time-bounded, and how controls adapted to temporary high-risk configurations.

4.5. Step 5: create improvement programme

Based on the preceding CAST findings, twenty-seven safety recommendations were developed to strengthen the system's ability to prevent, detect and recover from hazardous states. Each recommendation was traceable to specific CAST outputs, including inadequately achieved safety responsibilities (RIA), contextual factors (C), contributions to hazardous states (HS), and flawed mental or process models (FM) identified across system controllers. The recommendations address runway closure markings, airport surface configuration visibility, regulatory and industry-level standards, alerting capabilities and information design. For example, SR6 recommends enabling approach-conformance alerting in ASSC and ASDE-X and adding final-funnel and runway-centreline overlays to controller displays. This recommendation links to RIA10, RIA11, C12, C13, HS10 and FM12 in Table 1. Appendix 7 provides the full list of recommendations.

5. FRAM analysis findings

The FRAM analysis followed Hollnagel's [7] guidance and began by identifying key system functions. These functions were modelled using six characteristic aspects: Inputs, Outputs, Preconditions, Controls, Resources and Time. The analysis focused on functional variability and its aggregation. It mapped how normal operational performance under variable conditions could produce emergent outcomes, including unsafe states and recovery. Variability was then traced across coupled functions to identify resonance scenarios and develop recommendations.

5.1. Step 1: recognising the purpose of the analysis

The primary objective of applying FRAM was to examine how functional interactions and performance variability combined across flight crews, ATC, airport infrastructure and supporting systems. The analysis considered how the ACA759 event emerged despite procedural compliance and the absence of technical failures. Rather than treating the event as an anomaly, FRAM reframed it as an emergent property of routine performance under complex conditions.

5.2. Step 2: identifying and describing functions

A total of 26 system functions were identified: 15 foreground and 11 background functions. These functions were not intended to provide a single definitive decomposition of the system. Instead, they were derived iteratively from the investigation materials and the responsibilities compiled in Appendix 3. Relevant responsibilities, activities and enabling conditions were reformulated as FRAM functions within the study boundary. The resulting set was judged sufficient to approximate work-as-done as reconstructed from the investigation record. It captured both the event trajectory and the recovery pathway, while distinguishing foreground functions directly implicated in the event dynamics from background functions that provided enabling or constraining conditions. For example, the foreground function ⟨To validate and ensure alignment⟩ is presented along with its related aspects in Table 2. These aspects serve as prompts for analysing couplings; therefore, not every function requires all aspects to be explicitly developed. Appendix 8 provides the full list of functions.

Table 2
FRAM aspects for the function ⟨To validate and ensure alignment⟩.

Aspect	Description
Input(s)	Surface status displayed; approach clearance issued to flight crew; runway and taxiway lights displayed
Output(s)	Alignment with the intended landing surface verified
Precondition (s)	Shared crew mental model of threats and approach; visual contact confirmation accepted; navigation system configured
Control(s)	Airline SOPs and procedures
Time	Approach and landing phase context
Resource(s)	Runway closure marker with a lighted flashing white "X", visual references available, dispatch release, Jeppesen charts, navigation mode annunciations and prompts

A FRAM instantiation was developed to model system interactions and variability during the ACA759 event. This revealed functional couplings and showed how variability propagated across the system. The analysis identified resonance scenarios in which multiple small variations may have aligned. Because complete FRAM models can become visually dense, Fig. 4A provides a high-level overview of the instantiation. It is not a separate formal abstraction and agency model. Rather, it is a readable abstraction of the full event-specific FRAM instantiation, consistent with the principle that FRAM representations can be clarified by adjusting model abstraction and resolution [46]. Fig. 4A, therefore, foregrounds the main event-relevant functions and selected supporting background functions. These show the key cross-system interactions involved in approach management, monitoring, intervention and recovery.

In Figures 4A and 4B, colours indicate function ownership. Magenta represents the Flight Crew; blue, Northern California (NorCal) Approach; green, SFO Tower; red, the Airport Infrastructure; turquoise, the Other Aircraft on Taxiway C; white, regulatory bodies; purple, Air Canada; brown, Airport Operation; and grey represents ATC Facility Infrastructure. Foreground functions are shown as FRAM hexagons, and background functions are shown in grey boxes. The grey boxes are used only to improve visual readability. They do not change the FRAM logic of representing functions through their aspects and couplings. Because the full FRAM instantiation includes many functions and couplings, Fig. 4A provides a simplified overview, while Fig. 4B presents the complete model for traceability.

Fig. 4B presents the full FRAM instantiation for the ACA759 event, including the complete set of foreground and background functions retained within the study boundary. Function numbering in Fig. 4B supports traceability to Appendix 8 and Appendix 9 and does not imply linear sequencing.

5.3. Step 3: identification of variability

Performance variability of the outputs from the functions was identified in terms of time and precision. A detailed summary of observed variability and its aggregation across functions is provided in Appendix 9. The ACA759 event analysis illustrates how performance variability can lead to both desirable and undesirable outcomes.

For instance, the variability of the outputs from the function F1 ⟨To review operational data⟩ was imprecise, as the required information was hidden in dense text, and the crew missed the runway closure information. F3, ⟨To configure navigation systems⟩, showed variability in terms of precision (not at all), as the Instrument Landing System (ILS)/localiser for Runway 28R was not tuned. All these reduced the precision of alignment verification and increased reliance on ambiguous visual cues. However, adaptive variability was also evident. The crew's late-stage query to ATC about unexpected light marks a moment when doubt surfaced and was communicated. It was an adaptive signal that expectations were not being met and that additional verification might be required. Following the go-around and stabilisation, the crew further adapted their approach strategy. During the downwind leg for the

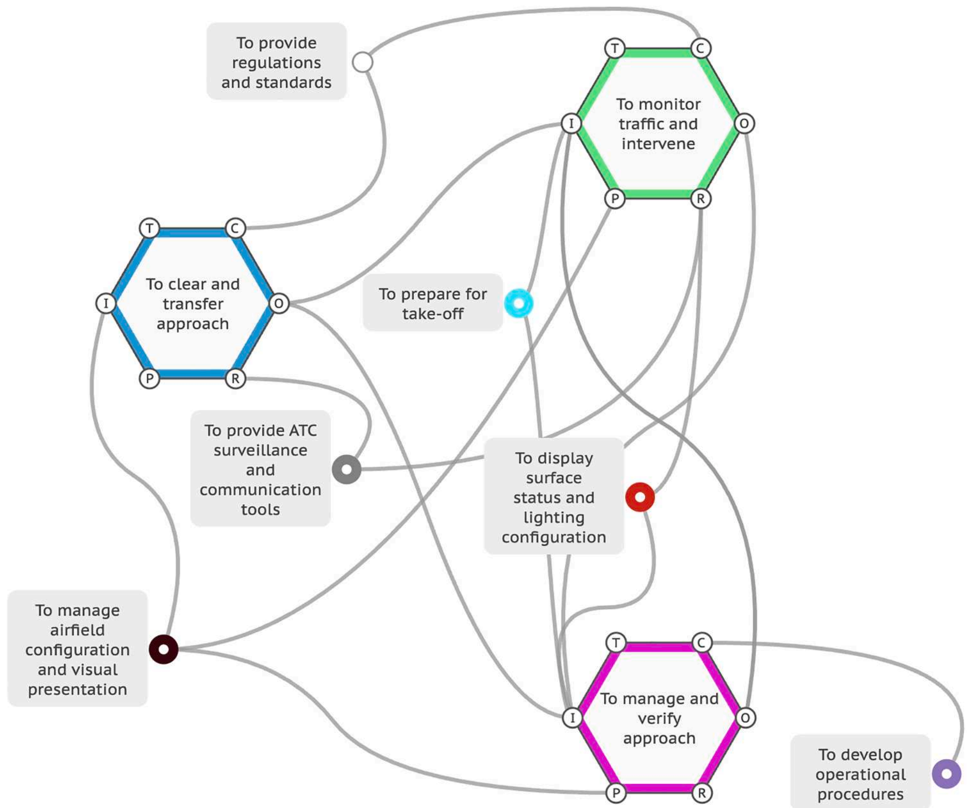

Fig. 4a. Simplified high-level FRAM overview of the ACA759 event. The figure foregrounds the main event-relevant functions and selected background functions to improve readability.

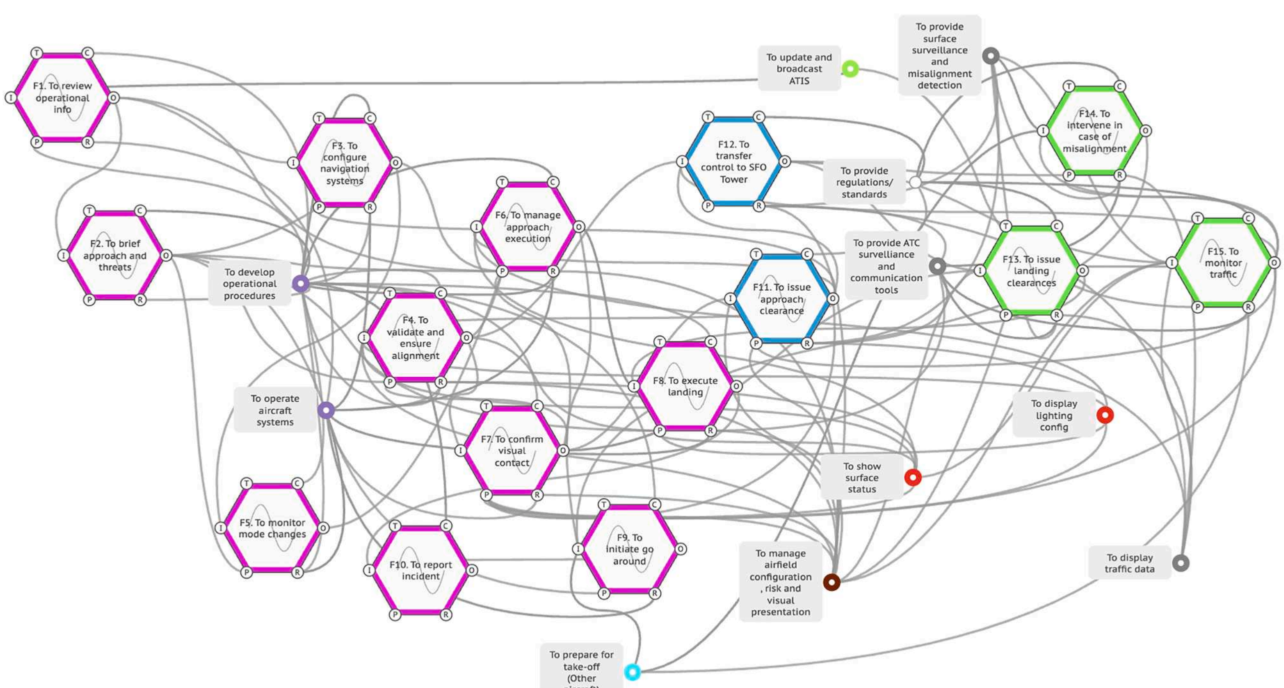

Fig. 4b. Full FRAM instantiation of the ACA759 event. Colours indicate function ownership, and grey boxes indicate background functions.

second approach, the first officer proposed tuning the ILS, and the captain agreed. The subsequent approach and landing were completed uneventfully.

Adaptive variability was also evident in ATC functions. When the inbound aircraft appeared “extremely strange” on a very short final, and after another aircraft reported that ACA759 was lined up on the taxiway, the ATC issued a go-around. By then, the flight crew had already initiated a go-around, with the ATC instruction occurring almost simultaneously. In FRAM terms, the recovery was therefore not a single late intervention. It was a tightly coupled, time-critical convergence of flight crew and ATC actions. Although both occurred late in the sequence, together they prevented a landing on Taxiway C.

Importantly, system resilience also depended on informal safety nets beyond the planned control architecture. Multiple aircraft holding on Taxiway C detected the developing misalignment and transmitted warnings, including "he's on the taxiway". Another crew increased conspicuity by switching on landing and nose lights, reportedly "dictated by instinct". These actions were not prescribed by procedures. However, they represent emergent functional couplings that introduced strong cues into the system and helped trigger the recovery path.

Beyond this case, FRAM also considers how normal functioning under similar conditions typically yields safe outcomes. The NTSB noted that nine other aircraft flew the same Bridge Visual approach and landed safely on Runway 28R after Runway 28L's closure. This indicates that the system often succeeds under the same configuration. A particularly informative comparator is the preceding arrival, Delta Air Lines Flight DAL521, which operated under the same external conditions. The crew reported confusion due to the lighting and non-standard configuration, but cross-checked Lateral Navigation (LNAV) guidance and other available aids to confirm the correct runway alignment. They also explicitly prepared to go-around if runway identity could not be confirmed ([45], pp.7–9). This additional checking and readiness to abort dampened the risk created by the ambiguous visual scene. In FRAM terms, these success cases show that safety is not achieved by eliminating variability. Instead, variability must be coupled with stabilising resources, such as electronic guidance, go-around readiness and robust monitoring, so that ambiguous visual cues are absorbed rather than allowed to resonate into hazardous states.

5.4. *Step 4: aggregation of variability*

The FRAM analysis shows how aggregated performance variability shaped the conditions in which the misaligned approach emerged and persisted. Appendix 9 provides the full analysis. Key couplings involved configuration awareness and threat framing, navigation setup and short-final monitoring capacity. Limited salience of the runway closure, the absence of ILS tuning as an independent lateral reference, and divided attention during the visual segment reduced the precision and timeliness of alignment verification and discontinuation decisions.

At the same time, the system exhibited dampening functional couplings that limited further propagation of the developing misalignment. Once the misalignment became salient across multiple functions, warning calls from aircraft holding on Taxiway C and additional conspicuity cues acted as strong signals. These cues triggered system-wide recognition. Both the ATC and the flight crew then transitioned to the discontinuation and recovery pathway. Although the go-around occurred late, it was executed successfully and prevented a collision. This highlights a key FRAM principle. The same coupled functions can either amplify risk or support recovery, depending on when and how performance variability becomes visible across the system.

Recovery mechanisms, such as the go-around, are not isolated actions. They reflect the system's real-time response to mismatches between demand and capacity. In this case, demand peaked during a time-compressed visual segment with task load, frequency congestion and degraded visual references. At the same time, monitoring capacity was reduced by attention fragmentation and the absence of redundant cues, such as untuned ILS. The decision to continue the approach reflected an Efficiency-Thoroughness Trade-Off (ETTO). Efficiency is involved in maintaining flow and completing the task, while thoroughness is involved in verifying runway identity and alignment. Such trade-offs are necessary in dynamic operational environments, but they can expose vulnerabilities when verification capacity is compromised [26]. Here, prioritising efficiency over thoroughness contributed to the misalignment persisting deep into the approach. The eventual go-around, although delayed, represented adaptive recovery under uncertainty by interrupting the efficiency-driven continuation of the approach and re-establishing the capacity needed to manage the emerging alignment mismatch.

5.5. *Step 5: managing performance variability and functional resonance*

Seventeen recommendations were developed from the FRAM findings to address the role of performance variability and functional couplings in the ACA759 event. These are organised around the four resilience engineering cornerstones: monitoring, responding, anticipating and learning. Monitoring recommendations aim to make critical information, such as runway closures and lighting changes, more salient and easier to retain. They also support alignment verification under visual conditions through improved ATIS/NOTAM delivery and navigation cross-checks. Responding recommendations aim to shorten the gap between doubt and decision. Since uncertainty was not always treated as a trigger for action, these recommendations address early go-around criteria, enhanced simulator training and clearer controller protocols during non-standard surface configurations. Anticipation recommendations seek to reduce reliance on unaided human perception, especially at night. These include increased runway closure conspicuity, onboard alerting for taxiway alignment and upgrades to ground-based surveillance tools. Learning recommendations address reporting delays and feedback gaps. These include time-bound near-miss escalation, automated data preservation, and the use of successful comparators to strengthen training and procedural adaptation. These recommendations are not isolated fixes. They respond to recurring patterns of variability and misaligned interdependencies identified across functions. Appendix 10 provides the full list.

6. Discussion

This section discusses the outputs of CAST and FRAM in relation to system modelling, causality, variability and safety recommendations. Both methods were applied based on the analyst's understanding of the ACA759 event using the NTSB report and supporting materials, and the findings were iteratively refined by SMEs. Although the case is classified as a near-miss, the insights may be relevant across event severities. The safety recommendations generated by each analysis are presented here as illustrative examples of CAST and FRAM outputs, rather than prescriptive fixes for the ACA759 event.

6.1. *Modelling*

CAST and FRAM both model the ACA759 event, but they represent interconnectedness differently. CAST uses a hierarchical control structure, where safety is framed as the enforcement of constraints through control actions and feedback across system levels (see Fig. 3). FRAM represents the system as a network of functions, defined by six aspects, with context-sensitive couplings between them (see Figures 4A and 4B). As Qiao et al. [42] and Yousefi et al. [16] note, these structural differences shape how each method conceptualises system behaviour and system safety.

CAST delineates controllers, control actions and feedback loops across a socio-technical hierarchy. FRAM does not impose a vertical structure. Instead, it traces functional dependencies through coupling types. For example, one function's output shapes another's input, precondition or resources. Reciprocal influences can appear in both models. CAST represents them through structured feedback loops, whereas FRAM captures them as conditional or emergent linkages between functions, without requiring authority relationships.

Neither method fully encodes the event sequence on its own. In FRAM, temporal order is not prescribed a priori. The relevance and sequencing of couplings depend on the situation and operating conditions being analysed. A similar qualification applies to the CAST control structure model. CAST analysis considers the event sequence when reconstructing what happened and generating analytical questions, but the control-structure diagram itself is not a timeline. It represents controllers, controlled processes, control actions and feedback relationships. In both methods, the temporal development of the event must therefore be interpreted through the event narrative and the specific model instantiation. In the ACA759 instantiation, as in other FRAM studies, functions are interpreted in relation to timing, sequence, phase-specific demands and operational time pressures [47,20]. Accordingly, some couplings become salient only during particular phases of the event, whereas others reflect more continuous activities.

The graphical readability of the models also differs. FRAM's six-aspect characterisation makes couplings explicit and can reveal indirect dependencies. However, FRAM models can become visually complex and harder to interpret unless tailored to the analytic purpose [48–50]. FRAM model visualiser software can support model development and interpretation [42]. Additional approaches, such as abstraction layering, can further improve clarity [46]. CAST models often retain greater visual clarity through hierarchical organisation. Detailed interactions are usually unpacked in the accompanying analysis rather than densely embedded in the diagram. This allows the control-structure view to remain interpretable while supporting refinement from high-level to low-level descriptions.

6.2. Causality and variability

Both CAST and FRAM provided systemic explanations of the ACA759 event, but they conceptualise causality and variability differently. CAST frames causality as inadequate specification, communication or enforcement of safety constraints through control actions, process models and feedback across socio-technical levels. In ACA759, CAST showed how reliance on visual cues by multiple actors remained insufficiently challenged during the visual approach. The control structure did not provide sufficiently robust feedback, verification triggers or independent cues to update relevant process models in response to the runway closure and changed visual environment (see Table 1 and Appendices 4–6).

FRAM does not seek to identify "causes" in the traditional sense. It identifies sources of variability and models how performance variability propagates through functional couplings. These couplings can produce locally rational actions that may lead to safe performance, successful recovery or unexpected unsafe outcomes (see Appendix 9). In the ACA759 event, FRAM showed how skipped ILS tuning, expectation bias and reliance on ambiguous lighting contributed to the wrong-surface alignment. It also showed how recovery emerged from late-stage couplings, including warnings from aircraft on Taxiway C and ATC intervention. This reflects FRAM's emphasis on the common basis of successful and unsuccessful outcomes. The same adaptive mechanisms that support everyday functioning can also contribute to risk or support recovery under different conditions [51,36,52,53,35].

These differences can be related to Safety-I, Safety-II and Safety-III debates, but only cautiously [54]. CAST, often associated with Safety-I or Safety-III, asks how the control structure allowed a hazardous state to emerge or persist. FRAM, often associated with Safety-II, asks how normal performance shaped both escalation and recovery. However, neither method should be reduced to a fixed paradigm label. CAST can support resilience-orientated redesign by strengthening monitoring, feedback and learning. FRAM can identify where adaptive performance requires more formal support, resources or constraints [7,13,33]. Recent work, therefore, cautions against labelling methods uniquely as Safety-I, Safety-II or Safety-III. They can be applied from different analytical perspectives [53] and should be evaluated in terms of their scope, assumptions and practical use [54,55].

FRAM makes variability central to the explanation. In the ACA759 event, not tuning the ILS can be understood as output variability in the function ⟨To configure navigation systems⟩. This reduced the resources available for ⟨To validate and ensure alignment⟩, increasing dependence on ambiguous visual cues. Other forms of variability then shaped both escalation and recovery. The crew's uncertainty query, warnings from aircraft on Taxiway C, increased conspicuity from PAL115, and the go-around response introduced cues and actions that interrupted the developing misalignment trajectory and supported recovery. The delayed but ultimately effective go-around was not merely a procedural recovery. It was an adaptive response shaped by attention allocation, emergent cues and judgment under uncertainty. These forms of situated resilience show how real-time adaptation can compensate for degraded cues and systemic mismatches.

CAST does not foreground variability in the same way as FRAM, but it still accounts for contextual conditions that shape control performance. In this study, expectation bias, degraded nighttime visibility, and high task load were treated as conditions affecting control actions, feedback and process models. The methods therefore operationalise systemic risk differently. CAST characterises systemic risk as inadequate specification, communication or enforcement of constraints across the control structure. FRAM characterises it in terms of how functional variability is amplified, dampened or combined through couplings. This difference also shapes how resilience is framed. Using Macrae's [56] distinction between structural, systemic and situated resilience, CAST is more closely aligned with structural and systemic forms of resilience. It examines how governance, procedures, and formal feedback mechanisms stabilise performance when conditions change. FRAM highlights situated resilience, showing how interacting system elements adapt under uncertain or unexpected conditions.

6.3. Safety recommendations

CAST and FRAM both produced safety recommendations but framed what should change differently. CAST translates systemic findings into strengthened constraints, responsibilities and control-feedback mechanisms. These can be embedded in system design, procedures and oversight. FRAM focuses on managing performance variability by modifying functional couplings. Its recommendations often take the form of verification gates, interface cues and supports for adaptive responses under uncertainty.

CAST-derived recommendations tend to be more structured, directive and aligned with system governance. This makes them easier to integrate into formal policies and assurance mechanisms. This is consistent with systems-theoretic work on leading indicators, which argues that safety signals only become effective when embedded in a risk-management structure with explicit responsibilities, triggers and pre-defined actions [57]. FRAM recommendations are typically more interpretive and context-sensitive. They aim to mitigate unwanted resonance of variability at the operational frontline. As prior studies note, FRAM outputs may need to be translated into local procedures or design requirements, especially in highly regulated environments [58,16]. One practical route is to use FRAM outputs to derive leading indicators from functions with significant variability and upstream-downstream coupling. This can turn qualitative systemic findings into structured monitoring targets [59].

In this study, FRAM recommendations were generated based on resilience engineering principles: monitor, respond, anticipate and learn. This does not mean that CAST recommendations fall outside these principles. Several CAST-derived suggestions, such as escalation triggers, strengthened feedback loops and role clarification, also support monitoring and learning. The key difference is therefore not intent, but intervention focus. CAST tends to intervene at structural and governance interfaces, while FRAM tends to intervene at functional couplings and operational decision points.

The CAST-driven safety recommendations (SR1-SR27, Appendix 7) and the FRAM-driven safety recommendations (R1-R17, Appendix 10) were cross-referenced against the NTSB's published findings and formal safety recommendations (Table 3). The comparison shows substantial

Table 3
Comparison of the safety recommendations.

NTSB findings and safety recommendations	CAST recommendations (SR)	FRAM recommendations (R)
A. Alignment to NTSB safety recommendations (A–18–23 to A–18–29)		
A–18–23 (Findings 2–3)	SR11	R3, R10
A–18–24 (Finding 9; also relates to Findings 8,10):	SR4, SR15, SR18, SR27	R1, R2
A–18–25, A–18–26 (Finding 14)	SR16	R13
A–18–27 (Finding 18)	SR6	R12
A–18–28 (Findings 8,9, 10,19)	SR1-SR3, SR7–SR9	R11
A–18–29 (Findings 12–13)	SR13, SR22	R14
B. NTSB findings without a specific NTSB safety recommendation (additional traceability)		
Finding 4	SR19, SR20, SR25, SR26	R4, R5
Finding 7	SR12, SR21, SR24, SR26	R6, R7, R17
Finding 11	SR20, SR21, SR23, SR25	R6, R7
Finding 15	SR14, SR17	R15
Finding 16	SR4, SR5, SR23	R8, R9
Finding 17	SR5	R8
C. Additional method-derived recommendation (not explicit as a standalone NTSB item)		
Real-time learning during temporary runway configurations: same-shift weak-signal feedback loops to rapidly update ATIS, procedures and mitigations while configurations remain in place.	SR10	R16

convergence with the investigation record. Common areas include runway-closure information retention, navigation verification, misalignment detection and alerting, fatigue-related readiness, and timely reporting and escalation. However, the methods package mitigations differently. CAST more often adds organisational scaffolding, such as policy, accountability structures and assurance mechanisms. FRAM more often specifies operational guardrails and information and interface changes that shape real-time cue interpretation and decision-making. These differences reflect distinct analytic affordances, not the superiority of one method over the other.

These differences align with comparative studies showing that CAST is more likely to generate comprehensive and procedurally embedded recommendations [14,40]. FRAM offers nuanced insights into how everyday variability can be harnessed or constrained to improve safety [16]. Table 3 illustrates this complementarity. Both methods identified the need to improve the retention of runway-closure information, alignment verification, misalignment detection and escalation. What is more, both methods identified an additional learning-orientated area not stated as a standalone NTSB finding or recommendation: real-time weak-signal learning during temporary configurations (SR10 and R16). This would create same-shift feedback loops so that reports of confusion from pilots and controllers can trigger updates to ATIS, local procedures and mitigations, while the configuration remains in place.

6.4. Limitations

This study has several limitations. Some relate to CAST and FRAM as qualitative systemic methods, while others arise from the case-study design.

First, both methods are interpretive. Their outputs depend on analysts' system knowledge, methodological familiarity, system boundary-setting decisions, abstraction choices and interpretations of evidence. Another analyst might therefore construct a different CAST control structure, define different FRAM functions or formulate recommendations at a different level of detail. This creates a reproducibility challenge, especially for complex events with multiple plausible interpretations. It can be mitigated by making assumptions explicit, documenting inclusion and exclusion criteria, maintaining evidence-to-claim traceability, using iterative review and, where feasible, involving multiple analysts or stakeholders in model validation.

Second, both methods are resource-intensive and lack a definitive stopping rule. CAST can expand as additional controllers, feedback paths, responsibilities and organisational influences are considered. FRAM can expand as functions are decomposed, and further couplings are represented. This creates a trade-off between analytical completeness and practical usability. Mitigation strategies include defining the analytical purpose and system boundary in advance, documenting inclusion and exclusion decisions, and stopping model expansion when additional detail no longer changes the explanation, recommendation set or evidence traceability.

CAST has specific limitations. Detailed control structure can be difficult to manage under time or data constraints [60]. Determining completeness is also challenging because CAST has a multi-level scope and relies on analyst expertise [30,32]. CAST terminology also requires careful framing. Although CAST aims to move attention away from individual blame, terms such as “responsibility”, “inadequately achieved responsibility” and “flawed mental/process model” may be misread as implying individual culpability. CAST findings should therefore be framed in terms of why the control structure allowed unsafe conditions to emerge or persist. Recommendations should also be linked to missing feedback, weak constraints, inadequate interfaces, unsupported assumptions or organisational conditions.

FRAM has different limitations. Its focus on functions, couplings and performance variability is valuable for understanding how everyday adaptations contribute to both risk escalation and recovery. However, FRAM models can become difficult to read when many functions and couplings are included. This can reduce their communicative value for investigators and operational stakeholders. Abstraction layering can help by using a high-level FRAM model to show the overall functional architecture, while lower-level sub-models examine critical function clusters in more detail [46]. FRAM also does not automatically produce prescriptive recommendations. Its outputs often describe functional couplings and variability patterns rather than direct intervention [16]. Additional translation is therefore needed to convert FRAM findings into procedures, interface improvements, monitoring cues, training or operational guardrails. This translation should involve operational stakeholders to ensure compatibility with work-as-done.

A further limitation is that qualitative systemic analyses can identify many vulnerabilities without indicating which interventions should be prioritised. They also do not show how strongly different factors contributed to risk or how findings should be compared across cases. Recent literature has responded to this challenge by combining FRAM, STPA or other systemic approaches with Bayesian, network-based or data-driven layers. These additions can support prioritisation and reduce reliance on qualitative judgement [61–64,34,65,66].

The present study also has application-specific limitations. Both analyses were conducted sequentially by the same analyst, which may have introduced carry-over effects. Insights from the CAST, such as the control structure, may have influenced the subsequent FRAM function selection, abstraction level and recommendation phrasing. Conversely, greater case familiarity may have improved the efficiency and completeness of the second analysis. Residual analyst-order bias cannot be ruled out. However, iterative author review and refinement helped reduce the risk that findings reflected only one analyst’s interpretation. Future comparative studies could use independent analyst teams, counterbalanced method orders, blind or partially blind modelling where feasible, and structured reconciliation of independently produced outputs.

The study also relied exclusively on secondary data from the NTSB docket (see Appendix 2). Although comprehensive, these materials were not collected for the present analyses. The researchers could not clarify ambiguities, probe undocumented coordination or obtain additional organisational context beyond the official record. As a result, some CAST and FRAM constructs may be underrepresented. This is a recognised limitation of secondary-data approaches, where the fit between the analytic model and available evidence can constrain inference and require explicit documentation of assumptions and abstractions [67]. Future studies could combine official investigation records with interviews, workshops, simulator reconstruction, operational data or stakeholder review, where access and ethical constraints permit.

Finally, this was a single-case comparison. The findings show how CAST and FRAM framed one information-rich aviation near miss. They should not be interpreted as a general ranking of method effectiveness. Transferability should be examined through comparative applications across multiple cases and domains.

7. Conclusion

This study applied CAST and FRAM to the ACA759 event to examine how each method supports systemic modelling, causality, variability and safety learning in complex socio-technical settings. Both methods model interactions and feedback rather than isolated failures, but through distinct lenses. CAST uses hierarchical control structures and constraint enforcement, while FRAM uses dynamic functional couplings and performance variability. Applying both methods to the same event record revealed complementary dimensions of the incident. CAST clarified how system-level controls and feedback mechanisms were insufficient to prevent or interrupt misalignment. FRAM showed how local adaptations, trade-offs and emergent couplings shaped the trajectory toward and away from danger.

The integrated findings revealed overlapping concerns, including weak runway-closure salience, degraded verification and delayed escalation. However, the methods suggested different intervention mechanisms. CAST recommendations emphasised structural reinforcement through policy, roles and assurance. FRAM recommendations focused on stabilising frontline performance through stronger monitoring cues, earlier response triggers and support for adaptation under uncertainty.

The study also shows that no single method offers a complete account. CAST was stronger in tracing responsibilities and upstream systemic constraints, but less able to explain how variability manifested and propagated in real time. FRAM captured adaptation under uncertainty but required further translation to produce actionable recommendations. Used together, the methods provide a richer understanding of safety as both system design and situated performance.

From a practical investigation perspective, CAST is useful when the focus is on constraints, control structures, responsibilities and feedback mechanisms. It is particularly suited to recommendations involving governance, assurance, accountability or institutional redesign. FRAM is useful when the focus is on performance variability, local adaptations and context-sensitive interactions, including escalation and recovery. It is particularly suited to recommendations that strengthen frontline monitoring, anticipation, response and variability management. Where resources permit, the methods can be used together without merging them into a single hybrid method. CAST may be applied first to structure the socio-technical control problem, followed by FRAM to examine how local variability and functional couplings shaped the event trajectory. Alternatively, where work-as-done is poorly understood, FRAM may be applied first, followed by CAST to translate recurring vulnerabilities into formal control, feedback and accountability requirements.

Future work should examine how CAST and FRAM can be incorporated into investigation and recommendation workflows. Digital tools may help improve traceability and reduce analytic overhead. Further comparative studies across domains, event types and practitioner groups are also needed to assess reproducibility, feasibility and implementation. The transferability of the present findings is strongest at the methodological level. Although the specific recommendations remain tied to ACA759, the complementary perspectives may be useful in other high-risk socio-technical domains where safety depends on both structural resilience and adaptive capacity.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the authors used ChatGPT (OpenAI), including GPT-5 and GPT-5.5, to improve the language and clarity of the manuscript (e.g., grammar, phrasing and readability). After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

CRediT authorship contribution statement

Edoardo Losi: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Conceptualization. **Gulsum Kubra Kaya:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Conceptualization. **Fanny Camelia:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Mikela Chatzimichailidou:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **David H. Slater:** Validation, Supervision, Methodology. **Riccardo Patriarca:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Mark Sujan:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Riccardo Patriarca and Mark Sujan are members of the Editorial Board of Reliability Engineering & System Safety. They were not involved in the review or decision process for this manuscript. The other 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.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ress.2026.113115.

Data availability

All source data are publicly available (see References). The full FRAM and CAST outputs are included in the supplementary materials (appendices).

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