ERGONOMICS
https://doi.org/10.1080/00140139.2025.2516060

Taylor & Francis
Taylor & Francis Group

RESEARCH ARTICLE

OPEN ACCESS Check for updates

Integrating causal analysis based on system theory with network modelling to enhance accident analysis

Gulsum Kubra Kaya[a], Mark Humphreys[a], Fanny Camelia[b] and Mikela Chatzimichailidou[c]

[a]Faculty of Engineering and Applied Science, Safety and Accident Investigation Centre, Cranfield University, Cranfield, UK; [b]Centre of Excellence for Complex Systems, Centre for Systems, Simulation, and Analysis, Cranfield University, Cranfield, UK; [c]Dept of Civil, Environmental and Geomatic Engineering, University College London, London, UK

ABSTRACT

This study integrates Causal Analysis based on System Theory (CAST) with network modelling to enhance accident analysis in aviation ground handling. Using 117 Passenger Boarding Steps (PBS)-related incident reports, the CAST analysis identified 74 flaws across 40 control actions, leading to four loss types. Approaching, inspecting, adjusting, and repositioning PBS were the most critical control actions contributing to incidents. Key contributory factors included issues around training, workload management, situational awareness, performance management, recruitment, organisational culture, procedures, equipment maintenance, and financial constraints. The integration of network modelling into CAST enhanced accident analysis by visualising complex interactions, offering deeper insights into accident causation and identifying critical nodes. This study demonstrates that combining CAST with network modelling enhances the understanding of accidents and safety risks, supporting evidence-based decision-making for aviation safety professionals and improving ground handling risk management strategies.

Practitioner Summary: This study integrates CAST with network modelling to enhance accident analysis in aviation ground handling. Analysing 117 passenger boarding steps incidents, the study identifies critical control actions and contributory factors. Network modelling enhances CAST by revealing complex interactions, providing deeper insights into incidents, and supporting improved risk management strategies.

ARTICLE HISTORY
Received 1 February 2025
Accepted 26 May 2025

KEYWORDS
Accident analysis; network modelling; CAST; ground handling; systems approach

1. Introduction

Safety on the apron is considered one of the top five critical risks in commercial aviation (Studic et al. 2017). The vast majority of ground damage incidents, greater than sixty per cent, are caused when the ground support equipment (GSE) is positioned on or disengaging from the aircraft and moves around the aircraft (Alonso Tabares and Mora-Camino 2019; Balk 2008; IATA 2020). In seventy-five per cent of cases, the cause is identified as human-related (Alonso Tabares and Mora-Camino 2019; Sumwalt and Lemos 2010). Most significantly, procedural non-compliance or drift has been identified as a causal factor in many aviation accidents. However, despite the corrective actions being introduced to prevent recurrences, there have been no significant changes in ground handling safety since the beginning of commercial aircraft operations (Alonso Tabares and Mora-Camino 2019). One of the reasons would be that ground-handling incidents do not often lead to catastrophic accidents or severe injuries despite resulting in significant financial loss. Despite the absence of major accidents, on-the-ground incidents contribute to increased direct and indirect costs and airport congestion. With these costs estimated at $10 billion annually, the rising congestion and a concerning negative trend in risk could lead to further cost increases. These include the costs associated with disruptions to the planned flight schedule, repositioning of aircraft and crew, compensation to passengers and the less quantifiable cost of reputational damage, all of which fall onto the airline's balance sheet (Allianz Global Corporate & Speciality 2020).

Another reason is that the apron system is a complex sociotechnical system, but it is often managed in a simple and linear manner (Chikha and Skorupski 2022; Musa and Isha 2021; Studic et al. 2017). Aircraft ground handling operations comprise many layers that result in complex interactions; this complexity moves any

CONTACT Gulsum Kubra Kaya kubra.kaya@cranfield.ac.uk Faculty of Engineering and Applied Science, Safety and Accident Investigation Centre, Cranfield University, College Road, Wharley End, Martell House, Cranfield MK43 0AL, UK
© 2025 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group
This is an Open Access article distributed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives License (http://creativecommons.org/licenses/by-nc-nd/4.0/), which permits non-commercial re-use, distribution, and reproduction in any medium, provided the original work is properly cited, and is not altered, transformed, or built upon in any way. The terms on which this article has been published allow the posting of the Accepted Manuscript in a repository by the author(s) or with their consent.

accident analysis away from linear investigation. The interactions occur between human operators (e.g. ground staff and flight crew), between human operators and procedures (e.g. airport bye-laws, airline manuals, IATA regulations and standard operating procedures), and between human operators and GSE (e.g. high loaders, belt loaders, passenger steps, baggage tugs, fuel vehicles, catering vehicles, coaches and minibuses) (Studic et al. 2017). This creates a highly complex, intractable, socio-technical system, of which the layers form tightly coupled systems characterised by fast response time, high impact, and rigid adherence to process. Studic et al. (2017) demonstrated this in their systemic modelling of ground handling for their hybrid Total Apron Safety Management Framework, modelling daily operations carried out on the apron. While systems-based methods such as Accimap, the Functional Resonance Analysis Method (FRAM), and Causal Analysis based on System Theory (CAST) provide valuable insights for analysing complex accident causation, they remain largely qualitative and lack mechanisms for quantifying and prioritising risk factors. To address this, various extensions have been proposed to introduce quantification (Bensaci et al. 2023; Chen et al. 2024; Sun et al. 2022), such as Bayesian Network (BN) (Liu et al. 2020; Qiao et al. 2023; Xu et al. 2022). However, BN often impose rigid, one-directional and acyclic structures that limit their ability to capture multi-directional interactions inherent in socio-technical systems. Network modelling, on the other hand, enables identification of system structure, interactions and behaviour, and dynamics of real-world networks, including non-linear relationships, in a flexible and multi-directional manner. Integrating CAST with network modelling offers a way to visualise both vertical and lateral system relationships, quantify interdependencies, and identify critical nodes based on network centrality, thus enhancing both analytical depth and practical utility.

In this study, we apply this integrated approach to a dataset of 117 ground damage incidents involving Passenger Boarding Steps (PBS) at a low-cost airline. PBS-related events were selected due to their frequency and operational impact, making them a high-priority target for safety improvements. By combining CAST with network modelling, we aim to reveal underlying systemic interactions, identify the critical nodes in the model and support more informed, data-driven interventions in ground handling safety.

2. Insights into research gaps: a literature review

In aviation, safety experts traditionally analyse accidents using expert judgements and methods like fault tree analysis, event tree analysis and bow-tie models (Bills, Costello, and Cattani 2023; Mogles, Padget, and Bosse 2018). These methods explain accidents as a linear chain of events, limiting understanding of complex systems. This linear perspective promotes looking for something that has failed or gone wrong in the sequence of events before the accident. For example, Heinrich's Domino model of accident causation represents accident sequence as a causal chain of events, dominoes that topple in a chain reaction (Heinrich 1931). Similarly, Reason's Swiss Cheese model depicts barriers as slices of cheese and the holes representing weaknesses in the control measures, which, if they align, allow the hazard to occur (Reason 1997). The stopping point for the investigation is often arbitrarily identified at this point of failure or where there was an identifiable error, especially with hindsight bias (Leveson 2011b), so unless we look further, we limit the opportunity for learning and almost certainly guarantee future accidents involving the same related factors.

Systems thinking extends the understanding of complex interactions between the system components and supports a more comprehensive accident analysis (Leveson 2011a). Systems thinking methods have been popular for 25 years and have been applied to various sociotechnical systems (Hulme et al. 2019). In accident analysis, Systems-Theoretic Accident Model and Process (STAMP), Human Factors Analysis and Class System (HFACS), AcciMap and FRAM are widely used system-based methods in various industries (Patriarca et al. 2022; Underwood, Waterson, and Braithwaite 2016), including transportation (Dong et al. 2024; Li et al. 2019; Revell et al. 2019) and healthcare (King et al. 2024; Mason-Blakley et al. 2017).

While each method has different strengths and weaknesses, studies suggest that STAMP, AcciMap and FRAM have more value from a systems perspective (Hulme et al. 2021, 2024; McCormack et al. 2023; Qiao, Li, and Liu 2019; Stanton et al. 2019; Staton et al. 2023). Here, it should be noted that no single method outrates others under all categories, such as time and resource requirement, usability and repeatability of the findings. Selecting a technique is subject to trade-offs made by the analysts (Underwood and Waterson 2014). However, several studies have demonstrated the benefits of using systemic instead of linear methods (Altabbakh et al. 2014; Mogles, Padget, and Bosse 2018; Studic et al. 2017).

In particular, studies have highlighted that adopting STAMP-based methods, including Systems-Theoretic Process Analysis (STPA) for hazard analysis and CAST for accident analysis, results in a more comprehensive analysis. These methods identify a greater number of

causal factors and recommendations, and they are considered more reliable due to the similarity of causal factors identified by different analysts compared to other methods and models (Hulme et al. 2021; Kaya 2021; Yousefi, Rodriguez Hernandez, and Lopez Peña 2019). Therefore, CAST, which was developed by Leveson (2019), was chosen to be explored in this study.

CAST is an accident/incident analysis method that identifies the causal factors of accidents. This approach aims to identify questions that need to be answered to fully understand why an accident occurred and questions that are not asked when using traditional accident investigation techniques. The model of causality underlying CAST treats safety as a control problem, not a failure problem. In this model, the underlying cause is always that the control structure and controls constructed to prevent the hazard were not effective in preventing the hazard. The primary goal is to determine why and how they might be improved (Leveson 2019).

One of the common points in systems thinking methods for safety, including CAST, STPA, Accimap and FRAM, is that they have all been developed to address the limitations of the linearity of traditional accident analysis methods. Another commonality is their qualitative nature. However, although their qualitative nature helps the analyst understand the system's complexity without focusing on assumptions and probabilities, practical applications often require quantification to prioritise risks, measure performance, identify the key factors and manage safety. Therefore, several studies proposed an integration of quantitative approaches into these methods. For example, Monte Carlo simulations have been integrated into FRAM to quantify performance variability (Kaya, Ozturk, and Sariguzel 2021; Patriarca, Di Gravio, and Costantino 2017), and the best-worst method and CREAM have been incorporated into STPA to quantify risks (Chen et al. 2024; Wang et al. 2024). The BN is integrated into STPA to quantify risks and improve assessment reliability (Liu et al. 2025); although studies that integrated BN into STPA provided a linear explanation of how accidents occurred by explaining how unsafe control actions (UCAs) contributed to the occurrence of hazards, which led to accidents that result in losses. These models typically provide one-way directional links and ignore the links between the items on the same level of nodes (such as links between UCAs) (Basnet et al. 2023; Johansen and Utne 2022).

Network modelling, on the other hand, can analyse relationships among the nodes on the same level (as in UCAs), which reveals the non-linear relationship between the contributory factors and how they lead to accidents. This, in turn, helps better understand the critical factors in the analysis. Network modelling is built on graph theory and is used to identify system structure, interactions and behaviour, and dynamics of real-world networks (Barnes and Harary 1983; Yan et al. 2023). A network model comprises nodes representing entities and edges representing relationships between entities (Bloch, Jackson, and Tebaldi 2023; Mohan and Pramod 2019). Network modelling has been used in various fields, such as biology and social sciences, for multiple purposes, including risk and accident analysis (Feng et al. 2023; Griffin, Young, and Stanton 2010; Guo et al. 2021; Li et al. 2024; Li et al. 2025; Suo et al. 2021; Wang et al. 2023; Yan et al. 2023). For example, Feng et al. (2023) developed an accident chain network to explain accidents, and Wang et al. (2023) used complex network theory to identify critical accident causation factors. Yan et al. (2023) used complex network models in accident analysis using safety control structure components to build the network model. This study aims to analyse historical ground damage incidents, focusing on Passenger Boarding Steps (PBS)-related incidents and integrating CAST with network modelling. This study uses all CAST findings to build the network model and calculates centrality measures to identify the most critical nodes on the model.

3. Methods

3.1. Study design

This study collected an airline's operations manual and incident data to analyse passenger boarding steps (PBS)-related incidents. The authors applied CAST to near-miss incidents and used CAST findings to develop the network modelling (see Figure 1). Ethical approval was gained from Cranfield University Research Ethics System (CURES/18149/2023) to undertake this study.

The CAST analysis contains five steps: (1) assembling the basic information, (2) modelling the safety control structure, (3) analysing each component in loss, (4) identifying control structure flaws, and (5) creating an improvement programme (Leveson 2019). In this study, the CAST analysis revealed losses, hazards, control actions and contributory factors to accidents, including control structure flaws, contextual factors and light conditions.

This study used data-driven network modelling, using the CAST findings. Network modelling comprises nodes and edges. In this study, nodes contain losses, hazards, control actions, control action flaws, flaw

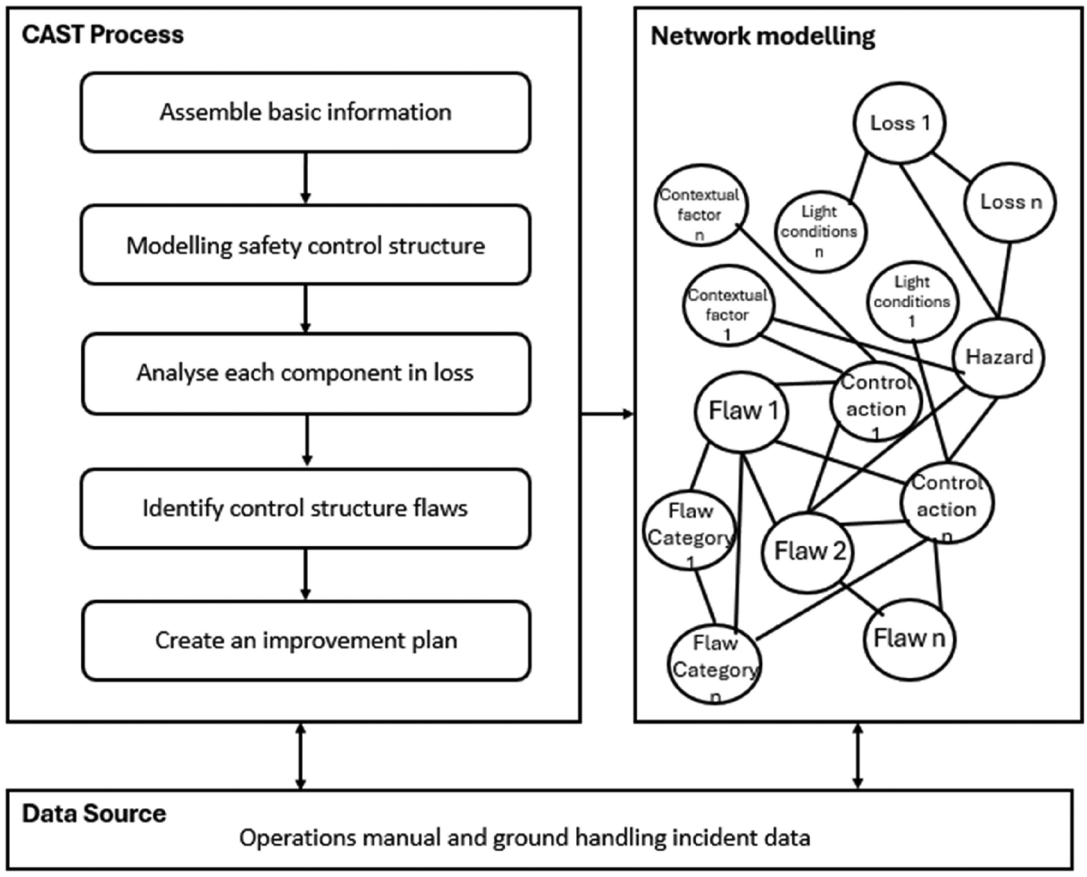

Figure 1. Study design for the enhanced accident analysis.

categories, contextual factors and light conditions. The edges are identified using the incident data.

3.2. Data collection

The authors accessed the airline's operations manual–ground handling and safety investigation manual and collected 65,179 safety incident reports for events between 2012 and 2023 from a multinational low-cost airline. The reports include data on causal factors, event details, event questions and answers, ground-damaged equipment colliding, ground-damaged part struck, MOR and operational outcomes. The dataset comprised some or all of the following: witness statements, submitted incident reports, incident photographs, engineering reports, mandatory occurrence reports, damage/inspection/repair reports, maintenance records, briefing notes, post-incident corrective actions, safety alerts and tech log entries.

In this study, the authors used the event details file as a core dataset and merged all seven files by referencing the Form IDs listed on the event details file. The authors removed any event data that had a missing value in any of the other datasets. The incident data, whilst comprehensive, was not complete. Not every recorded incident was fully investigated; some events provided no information. The authors ended up with 482 complete data points, including incidents related to airbridge, ambulift, baggage tug, belt loader, car/van, catering vehicle, de-icing unit, ground power unit, pushback tug, refuelling vehicle, steps, toilet/water and others. The authors selected the most recurrent equipment collision: step-related incidents, with 189 incident data, and the passenger door was the most affected part struck with 117 incidents. This study used 117 incident data to analyse aircraft Passenger Boarding Steps (PBS) incidents. Figure 2 shows the data inclusion process for this study. There were 60 features for each incident in the merged dataset (see Appendix A). Features represent information on the merged dataset; each column is identified as a feature, such as a form ID, event description and light condition.

3.3. CAST analysis

This study included 117 incident data points, having 60 features, in the analysis. The authors used the

airline's operations manual to identify the controllers, their responsibilities and control actions, and the control structure was built accordingly. The authors also used their experience in safety to conduct the CAST analysis. This study focused on four key high-level controllers: ground handling, airline, airport and ground support equipment manufacturer and maintenance.

The authors created an Excel sheet containing incident data and inserted additional columns for the CAST analysis. These additional columns included hazard, context, inadequate decisions and control actions, process model flaws and recommendations for four key high-level controllers. The authors set up two online workshops, each taking four hours, to discuss and initiate the data analysis. During these workshops, the authors agreed on the review process, familiarised themselves with data, set a standard for data extraction, and initiated extracting relevant information into the designed columns.

Then, two authors have independently analysed the whole dataset. This was to reduce confirmation bias. The authors reviewed each incident's data to identify the related hazard, incident context, control structure flaws, including inadequate decisions and control actions, process model flaws, and recommendations. The authors identified all these for four controllers. The authors also used the predefined information from the dataset, including light conditions and losses. After the completion, the two authors combined the findings and agreed on any differences in their review findings. The other two authors reviewed the combined dataset to ensure that relevant data were extracted for CAST analysis. After completing the data extraction and review, the authors identified flaw categories based on the findings of inadequate decision and control actions and mental model flaws, indicating the controller's internal understanding of the system state, environment, or procedures, and then linked them with the control actions.

3.4. Network modelling

The findings from the CAST analysis were used to construct the network model using Python 3.12 (see Appendix B for the pseudo-code). The CAST analysis identified 74 flaws in the control-feedback loop, which

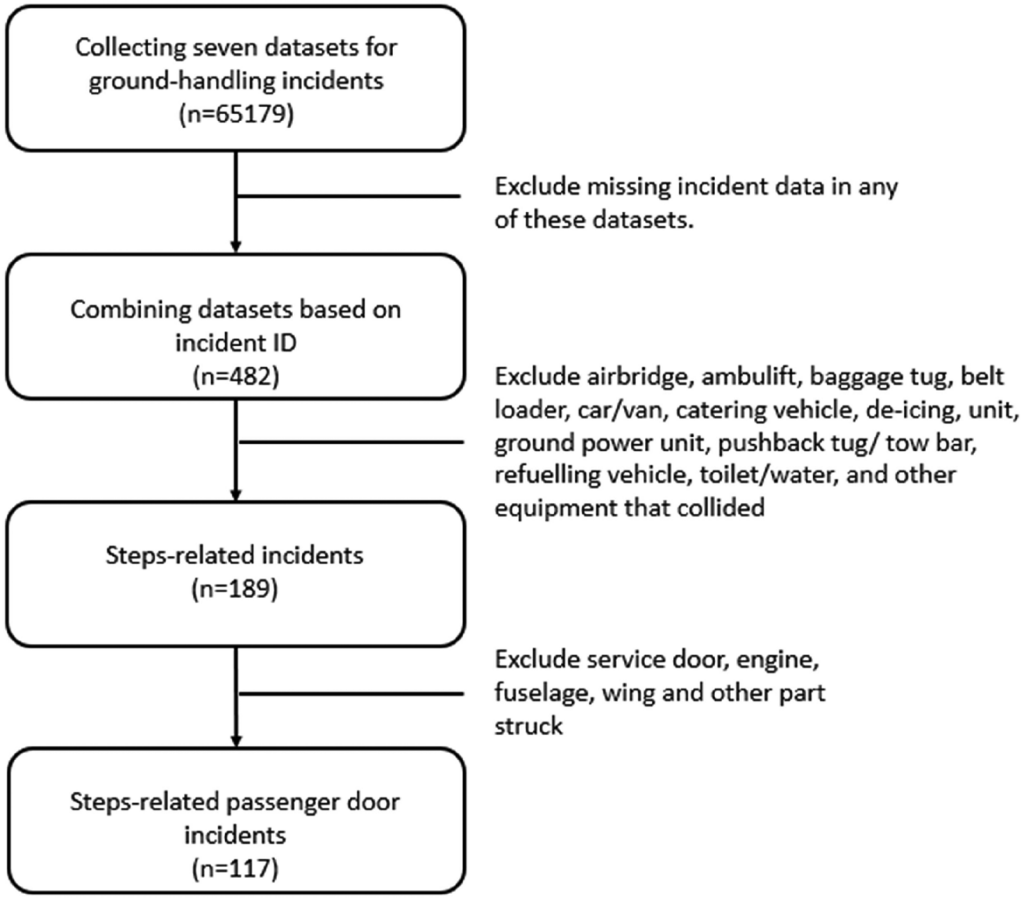

Figure 2. Data inclusion process for this study.

were grouped into 10 categories, along with 40 inadequate control actions, 4 loss types, 1 hazard, 7 context categories, and 4 lighting condition categories, resulting in a total of 140 features. Each incident report (n = 117) was treated as a separate data entry, and a binary feature matrix was created to represent the presence (1) or absence (0) of each CAST-derived feature within each incident. This approach is a practical and consistent means of quantifying qualitative CAST findings by highlighting the presence or absence of safety-relevant interactions across 117 incidents without subjective weighting or assumptions about interaction strength. It helps to preserve multi-level and lateral interactions via connections across and within categories (e.g. flaws linked to multiple control actions, contextual factors linked to multiple outcomes).

To analyse relationships among these features, Spearman's rank correlation (ρ) (Spearman 1904) was computed across all feature pairs. This nonparametric method is suitable for binary data and captures the strength and direction of co-occurrence patterns across the incident dataset. The resulting correlation matrix served as the basis for network construction. An edge was created between two nodes when the absolute correlation between them was at or above $\rho \geq 0.3$ and statistically significant ($p \leq 0.05$). A threshold of $\rho \geq 0.3$ ($p \leq 0.05$) was selected to capture weak-to-moderate correlations (Hinkle, Wiersma, and Jurs 2003; Xiao et al. 2016). This level of association was intentionally chosen to reflect the complexity of accident data, where strong relationships are uncommon and contributory factors often interact in subtle, non-linear, or indirect ways. The threshold supports the inclusion of less frequent, but potentially significant, systemic patterns. A threshold sensitivity analysis ($\rho \geq 0.4$ and $\rho \geq 0.6$) was also conducted to assess robustness, and the results are presented in Appendix C.

Once the network is established, the authors calculate four common centrality measures to identify the critical nodes. These measures are: (1) degree centrality, revealing the number of direct connections a node with other nodes; (2) betweenness centrality, measuring the number of times a node acts as a bridge and connects two other nodes; (3) closeness centrality indicating the closeness of a node to all other nodes in terms of shortest path distance and (4) eigenvector centrality identifying the influence of a node based on its importance to its neighbouring nodes (Bloch, Jackson, and Tebaldi 2023; Feng et al. 2023; Yang et al. 2019). These quantitative metrics extend the qualitative insights from CAST and help identify critical leverage points for safety interventions.

4. Results

4.1. CAST analysis

This study analysed 117 PBS-related incidents during ground handling operations. The incident dataset revealed four losses: aircraft damage ($n = 23$), delay ($n = 24$), maintenance ($n = 6$) and no impact on operation ($n = 64$). A system-level hazard leading to the losses and a safety constraint were identified:

- *Hazard. PBS does not maintain a safe distance from the aircraft,*
- *Safety Constraint. PBS must maintain a safe distance from the aircraft.*

The control structure was built with six key controllers: UK government, UK CAA, GSE manufacturer, airport, airline and ground handling controlling the PBS operations (see Figure 3). Responsibilities were identified considering these controllers, and control actions were refined from the responsibilities (see Table 1). Figure 4 shows the detailed control structure derived from the airline's operations manual. In this figure, control actions are represented by numbers, which can be cross-referenced in Table 1.

The incident dataset was used to analyse each component in loss and identifying flaws, which resulted in identifying 74 contributing factors leading to the hazardous state, categorised under 10 items: equipment failure, failure to follow procedure, inadequate checks, monitoring and supervision, inadequate door closure/opening, inadequate handrail and platform adjustment/setting, inadequate reporting, inadequate resources allocation, inadequate steps positioning, lack of communication, and misjudgement/misperception (see Appendix D). While we could extract valuable information for some controllers, the incident dataset provided no information regarding the UK government and UK CAA, with only contextual information regarding the airport, which was about a slight gradient stand and the lack of light on the isolated stand. In other words, the contributory factors were mainly identified regarding ground handling, airline, GSE manufacturer and maintenance provider.

When looking at the recommendations provided in the dataset, the review showed that recommendations were mainly concerned with the controllers at the sharp end, such as ramp agents. Over half of the recommendations were about briefing and reminding, training and issuing an alert, notice, bulletin and instructions (see Figure 5), aiming to fit the staff at the sharp end into the ground handling task. For

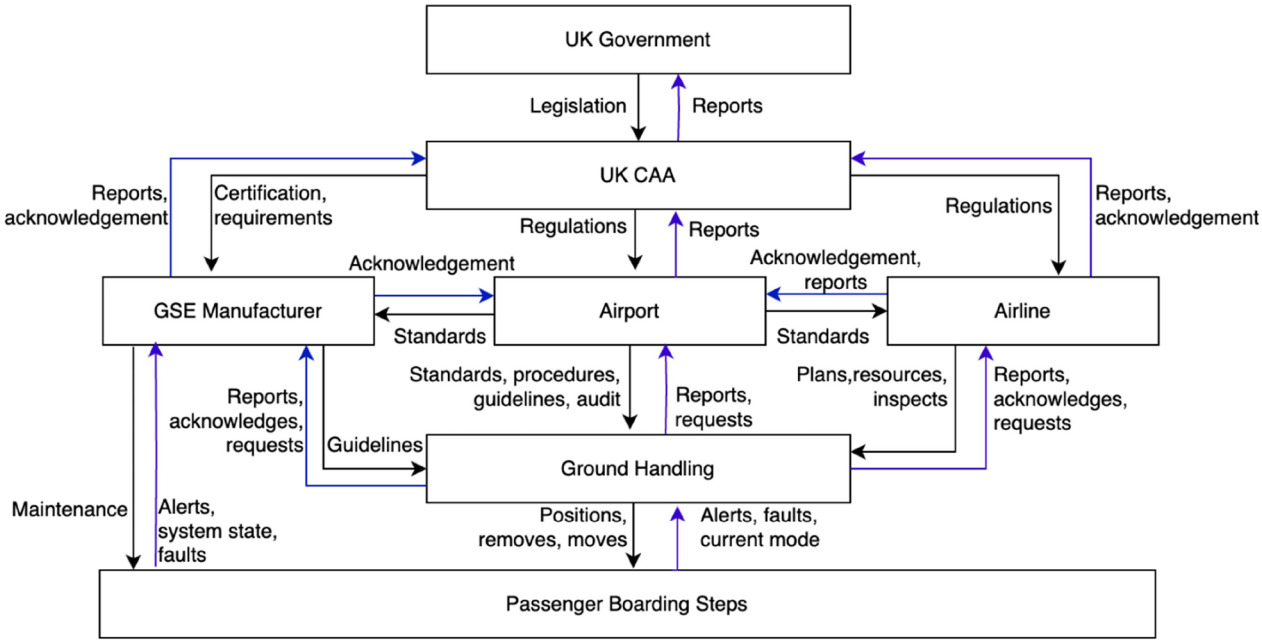

Figure 3. The high-level safety control structure.

instance, recommendations were given as '*TCO has been personally debriefed about the correct arrival procedure and an SLS red bulletin has been issued and disseminated to any dispatchers to remind all the mandatory steps to take during the walkaround procedure to ensure a robust reporting culture in place*', '*All ramp staff will be retrained on how to use and position covered steps*', and '*Operator can disseminate a bulletin to remind all the mandatory steps to take during the walkaround procedure to ensure a robust reporting culture in place.*' While briefing, training, and issuing alerts are necessary to ensure safety, delivering the same fixed training programme and reminding the operating procedures over and over will not help the industry prevent things from happening again and again. This highlights the need for innovative interventions beyond procedural reminders.

4.1.1. Ground handling

The findings from the CAST analysis identified 74 different types of flaws, and the flaws were identified under 10 categories. Among these, the flaw categories were as follows: (1) Inadequate resource allocation ($n=2$), (2) lack of communication ($n=13$), (3) inadequate checks, monitoring and supervision ($n=32$), (4) equipment failure ($n=13$), (5) inadequate reporting ($n=17$), (6) inadequate handrail and platform adjustment/setting ($n=12$), (7) inadequate steps positioning ($n=51$), (8) inadequate door closure/opening ($n=3$), (9) failure to follow the procedure ($n=13$) and (10) misjudgement/misperception ($n=17$).

Incident data identified the ground handler and the supervisor as key controllers contributing to the PBS-related incidents. Considering the control actions, 'approach and position PBS' (C35) ($n=53$), 'inspect and monitor' (C27) ($n=53$), and 'inspect PBS position' (C42) ($n=47$) were the top three control actions that flaws were related to. The most recurrent case in the incident data was the ground handler failing to position the PBS. This was a circumstance mostly when the ground handler lacked experience, had low visibility, or had action taken under a lack of supervision. For example, an incident is explained as: '*Steps to the rear door had been left with a gap of approx. 70 cm to the fuselage. From the bottom of the steps, it was not apparent that they were not correctly positioned to the fuselage. Given the light conditions at the time, it was very possible that the gap would not have been noticed by someone entering by the rear door*'. Table 2 provides the CAST findings for ground handling.

4.1.2. Airline

CAST analysis showed that airline-related flaws appeared the least. Among these, flaws were concerning inadequate door closure/opening, failure to follow procedures, lack of communication, misjudgement/misperception and inadequate reporting. These flaws mainly indicate inadequate actions on 'follow procedures' (C13) ($n=7$), 'close door' (C12) ($n=4$) and 'open door' (C11) ($n=2$). Most related cases were due to the lack of communication between the ground handler and the cabin crew. For example, an incident event

Table 1. Controllers, responsibilities and control actions for passenger boarding steps operations.

Controller	Responsibilities (R)	Control Actions (C)
UK Government	R1. Setting regulation for the manufacture and supply of GSE with legislation (PUWER, LOLER etc)	C1. Legislation
UK CAA	R2. Regulates safety and security arrangements at Airports	C2. Regulation
Airport	R3. Ensuring safe operations in airport and establishing standards.	C3. Provide standards, guidelines and procedures
	R4. Conducting regular inspections of the equipment.	C4. Inspect and audit
	R5. Ensuring that apron services are maintained in good conditioning.	C5. Maintain apron services
	R6. Ensuring that foreign object debris (FOD) is cleared from the stands prior to aircraft arrival.	C6. Clear FOD
	R7. Ensuring that all apron markings are clear and complete, identifying equipment restraint area (ERA), Back of Stand (BOS) and Head of Stand (HOS).	C7. Maintain apron marking
	R8. Communication with airline and ground handling service provider	C8. Contact with ground handling
Airline	R9. Ensuring all required resources available.	C9. Provide resources
	R10. Recruiting skilled crew and providing crew training	C10. Recruit and train
	R11. Opening the door from inside.	C11. Open door
	R12. Closing the door.	C12. Close door
	R13. Following procedures	C13. Follow procedures
	R14. Reporting into tech log	C14. Report
	R15. Communication with ground handling personnel.	C15. Contact with ground handling
GSE manufacturing and maintenance	R16. Manufacturing high quality equipment	C16. Manufacture products
	R17. Addressing regulatory and safety requirements.	C17. Provide standards, guidelines and procedures
	R18. PBS are maintained in accordance with manufacturer's schedule based on hours use (A B C services).	C18. Maintain PBS
	R19. Controls on PBS are clearly marked with action and direction. Marking of a visual indicator on PBS to show distance from bottom of aircraft door and the 'safety' height.	C19. Control marking on PBS and marking visual indicator on PBS
	R20. Communicates with ground handling provider.	C20. Contact with ground handling
Ground handling	R21. Assuring that operations are in accordance with Quality, Safety, Health and Environment standards.	C21. Assuring QHSE standards
	R22. Ensures recruitment and retention of the staff	C22. Recruitment and retention
	R23. PBS operator is trained for each type of PBS to be used. Training is refreshed in accordance with schedule.	C23. Provide standards, guidelines and procedures
		C24. Train PBS operator
	R24. Ensuring that sufficient trained personnel is allocated to aircraft prior to arrival or departure in accordance with the service level agreement (SLA) agreed with airline to complete all tasks required.	C25. Allocate personnel
	R25. Plans and coordinates safe operations, and reporting damages, marks, dents, and scratches.	C26. Plan, coordinate and report
	R26. Inspects and monitors the operation	C27. Inspect and monitor
	R27. Personnel inspecting FOD and clearing FOD if any found.	C28. Inspect and clear FOD
	R28. Personnel arriving on stand prior to aircraft arrival, and conducting pre-arrival briefing.	C29. Conduct pre-arrival briefing and follow procedures
	R29. PBS is inspected for serviceability and any issues prior to each use (360° review) by trained operator.	C30. Inspect PBS for serviceability
	R30. PBS is removed to be repaired if any identified issues are 'red tagged'	C31. Remove PBS
	R31. Ensuring that all equipment is stagged outside of ERA prior to aircraft arrival in a prepared state; PBS siderails and canopies are fully retracted, and brakes are applied.	C32. Stag equipment outside of ERA
	R32. Ensuring the path that PBS moving has been inspected and is clear of all hazards.	C33. Inspect path for PBS moving
	R33. Moving PBS towards aircraft only after Anti-Collision Beacons (ACB) are extinguished, aircraft is chocked, periphery cones are in place, Team Leader (TL) or Turnaround Coordinator (TRC) has completed 360° inspection of fuselage to identify damage found on arrival and indicates that turnaround process can start.	C34. Move PBS
	R34. Moving PBS around the aircraft outside the cones in place with clearance to avoid collision.	
	R35. Ensuring that all movement within the area that surrounds the parked aircraft, ERA, is at walking pace, avoiding any aircraft sensors or protrusions.	
	R36. Ensuring that PBS are positioned in accordance with SLA on L1, L2 or both doors. Approaching PBS to aircraft at 90° to the door and positioning, not in contact with fuselage (2–4″ gap) in accordance with no touch policy with door central to the platform. Where required, such as operator vision being restricting, a banksman is used to indicate to operator that PBS clearance from fuselage is correct.	C35. Approach and Position PBS
	R37. Disconnecting towable PBS from towable vehicle and positioning manually at the aircraft.	C36. Disconnect towable PBS
	R38. Applying brakes and deploying stabiliser, and then adjusting the platform to a level below bottom of door (4–6″).	C37. Apply brake
		C38. Deploy stabiliser
		C39. Adjust platform
	R39. Contacting with crew for door to be opened from inside.	C40. Contact with crew
	R40. Left handrail on platform is fully retracted to prevent contact with door when opened. Left handrail is repositioned to provide safe main platform after door fully opened.	C41. Reposition handrail
	R41. PBS position is inspected (every 15 mins) by operator throughout the turnaround process.	C42. Inspect PBS position
	R42. Adjusting and repositioning the PBS when required (aircraft raises during offload, and lowers during onload). If PBS are fitted with auto leveller, no checking required.	C43. Adjust and repositioning PBS
	R43. Retracting the left handrail and canopy after completion of offload and onload activities in coordination with crew.	C44. Retract handrail and canopy
	R44. Removing PBS after door is closed, and a confirmation given by the crew.	C45. Remove PBS
	R45. Reversing PBS away from aircraft and positioning in the ESA with brakes applied.	
	R46. Removing towable PBS to a suitable location before attachment to towing vehicle.	
	R47. Inspecting PBS after use for FOD and making it ready for the next use. PBS remains in place for any other activities.	C46. Inspect PBS after use
	R48. Communicating with other ground handlers	C47. Contact with other ground handlers

was explained as '*The aft steps (normally powered) were broken down on the way to the aircraft and, thus, the steps were pushed manually. As only 83 pax were onboard, it was decided to board only on the front and remove the aft steps before boarding to protect OTP. However, there was still significant rubbish on the top deck of the steps, and the step permit was handed over as it was being picked up. While still in the process of doing this, the cabin crew closed the door. Luckily, it did not hit the extended guardrail, but it was a close call.*

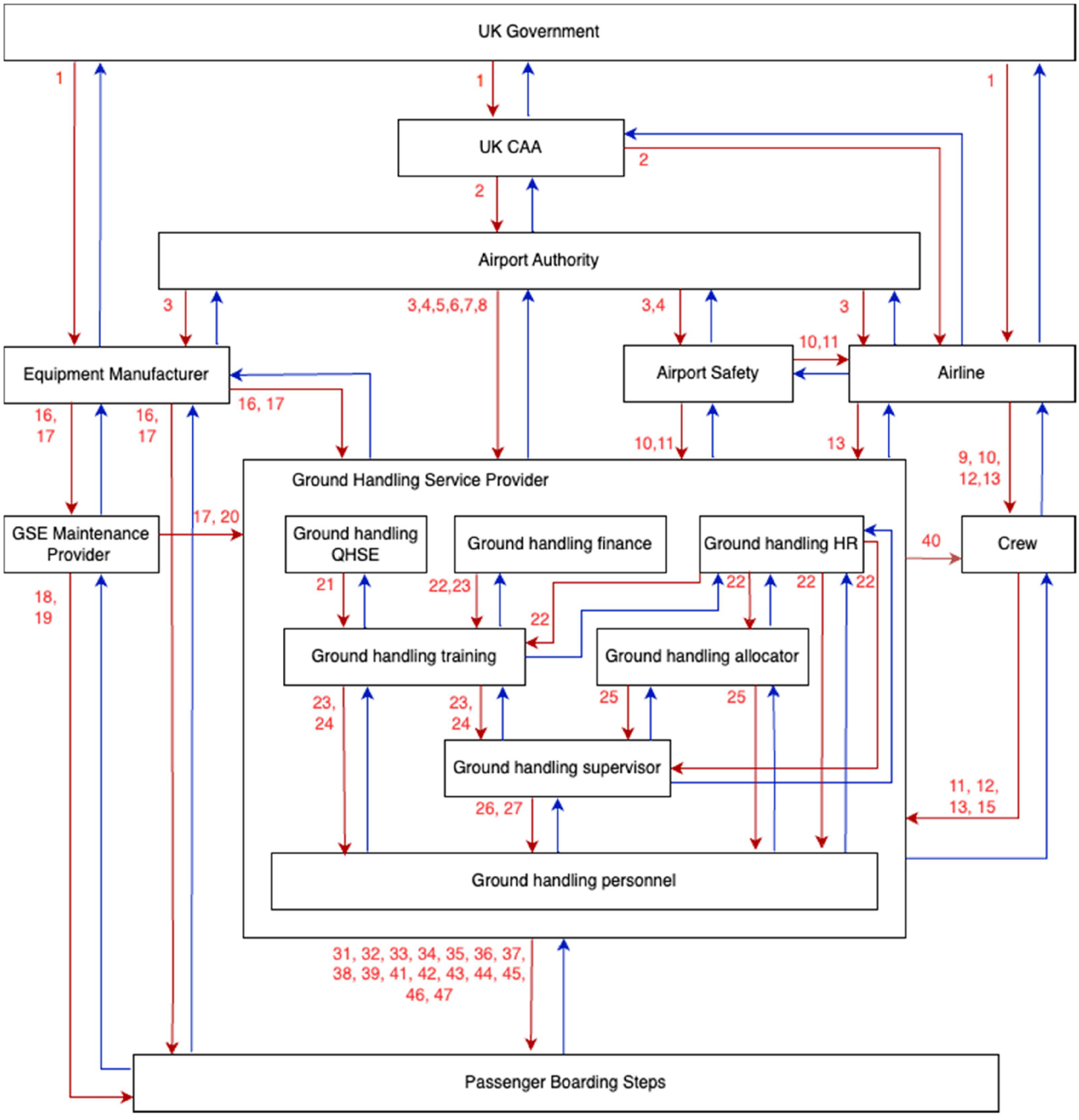

Figure 4. Detailed safety control structure derived from the operational safety manual.

They should have waited until this was retracted before closing up.' Data also revealed that aircraft context-related factors contributed to the flaws and hazards, especially in the A320 case. Table 3 provides the CAST findings for the airline.

4.1.3. Ground support equipment manufacturer and maintenance

All flaws except one were about the equipment failure, and one was about step positioning. Among these flaws, inadequate actions primarily concerned the 'maintain PBS' (C18) ($n = 11$) and 'inspect PBS for serviceability' (C30) ($n = 7$). For example, an incident event was explained as follows: '*While positioning the front steps, the driver did the 6-meter check, but the brakes failed on the 3-meter check, so he reversed to avoid the impact, resulting in a very slight hit to the aircraft fuselage with the steps' buffer.*' Table 4 provides the CAST findings for the GSE manufacturer and maintenance.

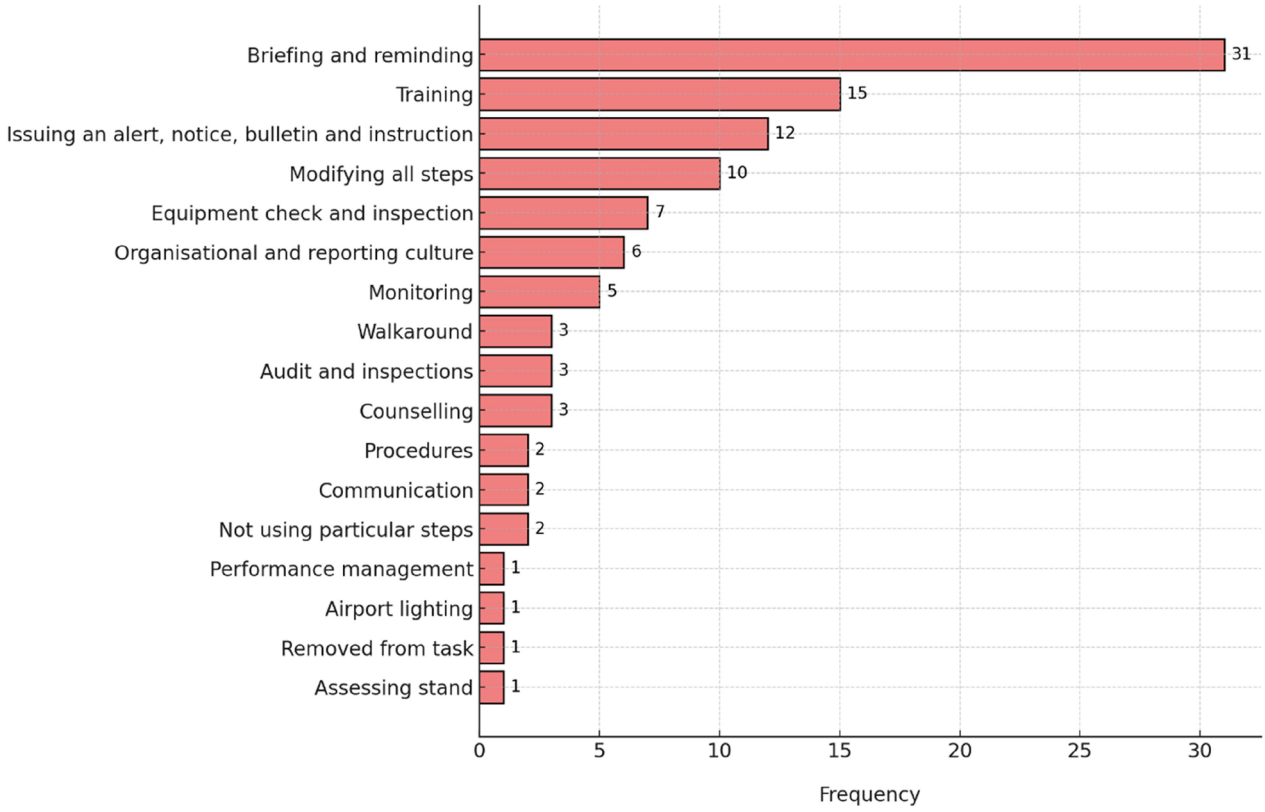

Figure 5. Recommendation categories identified from the incident dataset.

4.2. Network modelling

The network model was built on the findings of CAST analysis, setting a threshold of 0.3 (see Figure 6). The network model has 140 nodes (features), including 74 flaws, 10 flaw categories, 40 inadequate control actions, 4 light conditions, 7 contextual factor categories, a hazard and 4 loss types. The network model created 503 edges (links) between the nodes. After comparing thresholds of $\rho \geq 0.3$, 0.4, and 0.6 in the sensitivity analysis (see Appendix C), the 0.3 threshold was considered the most appropriate for this study. Higher thresholds highlighted only the stronger correlations, which resulted in a much sparser and fragmented network. This may exclude weaker but still meaningful connections, and the fragmentation can affect the interpretation of the network's cohesiveness.

Figure 7 presents the correlation matrix that reveals the correlation between the nodes. There are varying degrees of relationships between the hazard and different control actions, flaws, conditions and contextual factors. Hazard is moderately correlated with 'approach and position PBS' (C35) ($r=0.56$), 'inspect PBS position' (C42) ($r=0.53$) and 'step positioning' (flaw category 7) ($r=0.54$), and the hazard is weakly correlated with 'incorrect step positioning' (flaw 4) ($r=0.37$), 'missed detecting dents/marks/scratches/damages' (flaw25) ($r = -0.34$), 'missed reporting dents/marks/scratches/damages' flaw53 ($r = -0.35$), 'inadequate reporting' (flaw category 5) ($r = -0.33$), 'adjust and reposition PBS' (C43) ($r=0.42$), no impact on operation (loss type 4) ($r = -0.35$), and infrastructure context ($r=0.3$).

Considering individual loss types, nodes had weak to moderate correlations with the individual loss types. Delay is moderately correlated ($r = -0.56$) with no impact on operations and has weak to no correlations with other nodes. Maintenance action has a weak correlation ($r=0.39$) with flaws 5, 23 and 43. Aircraft damage is moderately correlated ($r = -0.54$) with no impact on operations. No impact on operations has a weak correlation ($r=0.3$) with flaw category 7 and hazard. The results are not listed for any correlation having an r value smaller than 0.3.

Centrality measures are calculated on the overall network model. Table 5 reveals the most critical ten nodes based on degree centrality measures: the higher the value, the more critical the node. 'Failure to follow the procedure' (Flaw category 9) was considered the most critical node, followed by 'Lack of communication' (Flaw category 2). The top 2 nodes had a degree centrality equal to or more than 0.2, so they can be considered the core hubs, dominating the network model. The inadequate control action of 'Follow procedures' (C13) was connected to 16.5% of the nodes (degree centrality),

Table 2. CAST analysis for ground handling.

Safety requirement and constraints violated

- Must allocate trained personnel; must plan and coordinate safe operations; must inspect and monitor the operation; must inspect and clear FOD; must inspect PBS for serviceability; must ensure PBS positioned in accordance with SLA; must approach and position PBS in accordance with no touch policy; must apply brakes and deploy stabiliser; must retracted/reposition handrail/platform; and must inspect PBS.

Contextual Factors

- The staff involved is hired with a fixed term contract; the ramp team concentrated on the height of the step while communicating with the cabin crew; two staff were sent to cover short notice sickness; the overall poor reporting culture of ramp staff; the aircraft was scheduled for a long ground time; the agent was freshly trained; agent is new in its role and did not have a lot of experience with steps positioning; colleague was rushing to help the TCO; and the dispatcher was doing 2 flights spaced by 10 minutes.

Inadequate decisions and control actions

- Boarding passengers with left handrail not in place
- Communication breakdown
- Disengaging pawl locks
- Failed to manoeuvring equipment around the aircraft
- Failed to follow SOP/procedure/policy
- Step positioning without communication
- Ground crew not stopping passengers climbing to the steps when the door was closed
- Guard rail not removed when opening door
- Inadequate post- arrival checks and pre-departure walkaround checks
- Inadequate ramp staff allocation system- poor information on responsibilities
- Inadequate supervision and/or monitoring
- Incorrect descriptor was entered by the reporter
- Incorrect flight number was entered by the reporter
- Incorrect steps positioning
- Instead of lifting step stabiliser, lifting the platform.
- Crew did not check the tech log to verify the dent spotted
- Left handrail was opened before a/c door was opened.
- Misjudgement on the step positioning action.
- Misjudgement on the time of knocking on the door
- Missed arrival walkaround
- Missed banksman allocation during positioning
- Missed detecting the dents/marks/scratches/damages.
- Missed FOD check.
- Missed reporting dents/marks/scratches/damages
- Missed repositioning of steps
- Missed visual checks/inspections during positioning
- No permit requested when repositioning
- Not checking the vertical gap between door frame and platform
- Repositioning steps while the door was open
- Safety rails too close to the fuselage
- Stairs positioned too much on the rear of the aircraft.
- Steps leaving a large gap, positioned too close or too high
- Steps positioned to be in touch with a/c
- The guard rail on rear steps was not totally retracted.
- The ramp agent left the key in the 'on' position.
- The stabs were not down and the handbrake not on
- The steps were not completely aligned to the fuselage.
- Top platform being too close to the bottom of the door
- Unsafe actions by leaving steps without securing the safety straps
- Wrong marshalling

Mental model flaws

- Forgot the steps procedure
- Inconsistent procedural knowledge and poor reporting culture

acted as a bridge 6.2% of the shortest path between other nodes (betweenness centrality), had a closeness centrality score of 35.8% (indicating its relative reachability to all other nodes) and was considered the third most influential nodes due to its connections to other highly central nodes (eigenvector centrality). This is followed by 'Assuring QHSE standards' (C21), 'Failed to follow SOP/policy/procedure' (flaw 63) and 'Open door' (C11).

5. Discussions

This study conducted a CAST analysis integrated with network modelling using an airline's incident dataset. The findings showed that the PBS-related incidents often occurred due to inadequate positioning, adjusting, repositioning and inspection of passenger boarding steps and a lack of ramp agents' supervision and team coordination. The findings align well with previous GSE-related accident analysis studies; the equipment's positioning is still a key influential factor (Balk 2008; Balk and Bossenbroek 2010; Studic et al. 2017). This study, however, provides a contribution by giving more insights into a particular GSE, PBS, which has not been as extensively explored in previous studies.

Looking in more detail, the CAST analysis revealed issues with a lack of communication between the ramp team or between the ramp and crew team, a lack of supervision of the ramp team, equipment

Table 3. CAST analysis for the airline.

Safety requirement and constraints violated
• Must open and close the doors according to the SOP
• Must recruit and train the crew
• Must report into the tech log
• Must communicate with ground handling
Contextual Factors
• The inbound load was light, but the out bound load was heavy and likely the cause of the settlement.
• There is always an aircraft vertical movement issue with A320 with 186 seats capacity, despite all SOPs followed on the ground.
• Aircraft having arrived from its previous sector approximately 3 hours late due to disruption earlier in the day.
• As the aircraft was very tail-heavy because of a lot of weight in the aft hold and as all passengers onboarded by the front door.
• Aircraft diverted due to the crosswind
• The aircraft squatting during pax/bags offloading and boarding
Inadequate decisions and control actions
• Cabin crew action (closing and/or opening the door) without communication
• Cabin crew closed the door before guardrail could be retracted.
• Cabin crew member did not follow procedure
• Cabin crew misjudgement on the step positioning.
• Communication breakdown between crew and ground handlers
• Crew did not check the tech log to verify the dent spotted
• The door was not secured in the ned lock.
• Aircraft started boarding without confirming the rear door opened
• Crew missed reporting of delays in disembarking
Mental model flaws
• Crew thought that they were doing the right thing.

Table 4. CAST analysis for ground support equipment manufacturer and maintenance.

Safety requirement and constraints violated
• Must manufacture high quality products
• Must maintain PBS in accordance with manufacturer's schedule based on hours use
• Must control action and direction marking and visual indicator on PBS
Contextual Factors
• Recurrent aircraft movement issues with the use of particular steps.
• The aft steps (normally powered) broken down on way to aircraft and were pushed on manually.
Inadequate decisions and control actions
• Brakes failed during steps positioning
• Improper design (spacing) of the pawl locks.
• Metal bar holding the rubber was bent in steps.
• Not having visual aid sticker on steps
• Rubber part of steps touched aircraft
• Motor failure of the platform
• The shape of the canopy leaving a gap
• The step top gate had fallen
• Steps malfunctioning- auto level system failure with no warning lights
• Steps malfunctioning- rolling forward
• Steps moved during passenger disembarkation

failure, failure to follow procedures, and poor markings and signs on the steps. During the analysis, the authors asked further questions, including '*Why do some agents experience spatial disorientation in positioning the steps?*', '*Why is there a lack of communication?*', '*Why is the supervisor not monitoring the team?*', '*Why are ramp teams in some airports more likely to fail and report less?*', '*Why is the equipment inspected and not well marked or labelled*?', '*Why does training not help with agents' learning?*', '*Why do accidents occur more on particular stands and aircraft types*?', and '*Why are ramp teams exposed to high workload?*'. Responses to these questions highlighted issues around training, workload management, situational awareness, performance management, recruitment, organisational culture, procedures, finance and communication.

Accidents are often claimed to have occurred due to human error, primarily due to the failure to follow procedures, and, in turn, recommendations are given to provide more rules and training. With the increased complexity of the systems, human error cannot be solely prevented by providing training and procedures (Kontogiannis and Malakis 2012). The term human error has actually evolved in the literature, moving from treating human error as a cause to a consequence (Read et al. 2021). However, we still need to acknowledge that training, which is correlated to competency, impacts attitudes; staff with better competency skills tend to have more positive attitudes in dealing with safety (Musa and Isha 2021). This study showed that staff who received adequate training also failed, as multiple other factors contributed to their actions. There were occasions when, indeed, staff did not receive an acceptable level of training and failed. So, while training would impact attitudes and behaviours, training alone might not be enough to ensure safe attitudes and behaviours. The individual, task, organisational and environmental factors should be considered, and the tasks should be designed to consider human fallibility without blaming the individuals, where human factors and systems-based analysis methods enable these considerations.

Would fatigue affect attitudes, workload, and performance? Fatigue reduces the performance of individuals (Muecklich et al. 2023). In the aviation industry, fatigue management studies are mostly concerned with pilots and air traffic controllers (Pruchnicki, Wu, and Belenky 2011), with less attention being paid to ground handler fatigue. Ground handler fatigue management can help measure performance and redesign tasks to ensure the handler's well-being and the operations' efficiency and safety. How about the cognitive process? As questioned: '*Why do some agents experience spatial disorientation in positioning the steps?*'. This often leads to considerations of situational awareness and links back to fatigue, workload, time pressure and environmental factors. Workload and time pressure were identified as reasons for the lack of supervision and monitoring due to scheduling and task allocation.

The performance of the ground handler has a significant impact on the quality of the ground handling operations. Interestingly, despite heavily relying on ground handler performance, recruiting ground handlers requires fewer specifications or qualifications to address the staff shortages (Chikha and Skorupski 2022; Wandelt and Wang 2024). Ground handlers are trained by the ground handling service

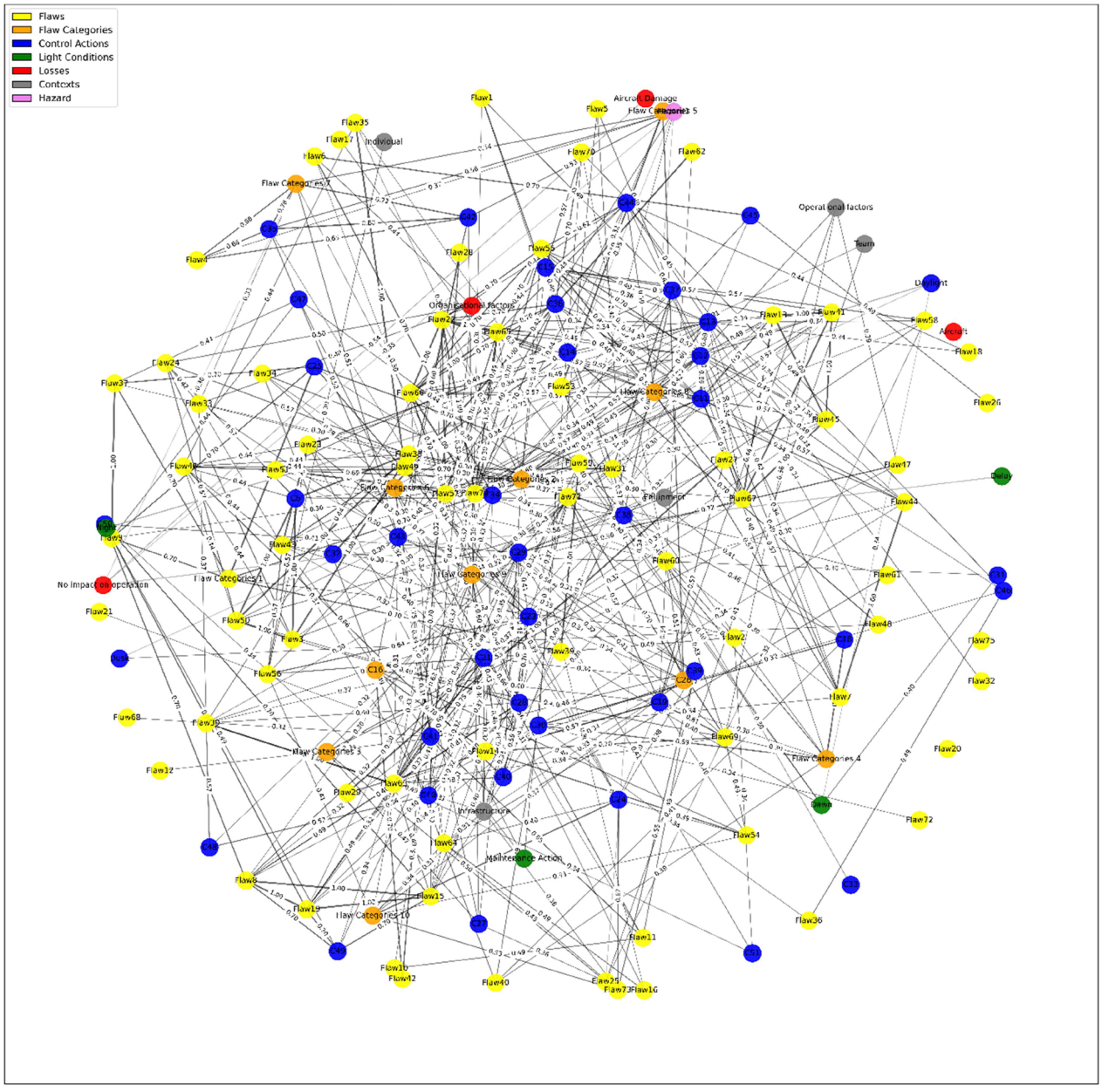

Figure 6. CAST findings network model.

providers and are expected to deliver a high level of performance. The challenge continues to keep the ground handlers in the organisation; job satisfaction, well-being, work-life balance, stress and management and leadership impact the retention of experienced staff (Kossivi, Xu, and Kalgora 2016; Wandelt and Wang 2024).

Incident reporting is one of the components that form the foundation of safety. Reporting is considered a communication channel, and a reporting culture positively impacts understanding accidents and near misses (Kaya et al. 2023; Musa and Isha 2021; Wiegmann et al. 2004). In this study, a complete lack or poor quality of reporting was considered one of the most common issues, possibly due to the reporting culture and organisational culture. Ground handlers might have concerns about being held accountable (i.e. blame culture) for the incidents and thus are not willing to report incidents. Indeed, Dobrowolska, Stasiła-Sieradzka, and Kozuba (2020) claimed that ground handlers feel threatened by losing their jobs, which prevents building a positive safety culture. The incident data showed occasions where the ground handler was taken away from the job until retraining and refresher training, and a few received disciplinary action under the suspension policy. Just culture should take blame-free approaches and respond to the anxiety of the blame and accountability, including

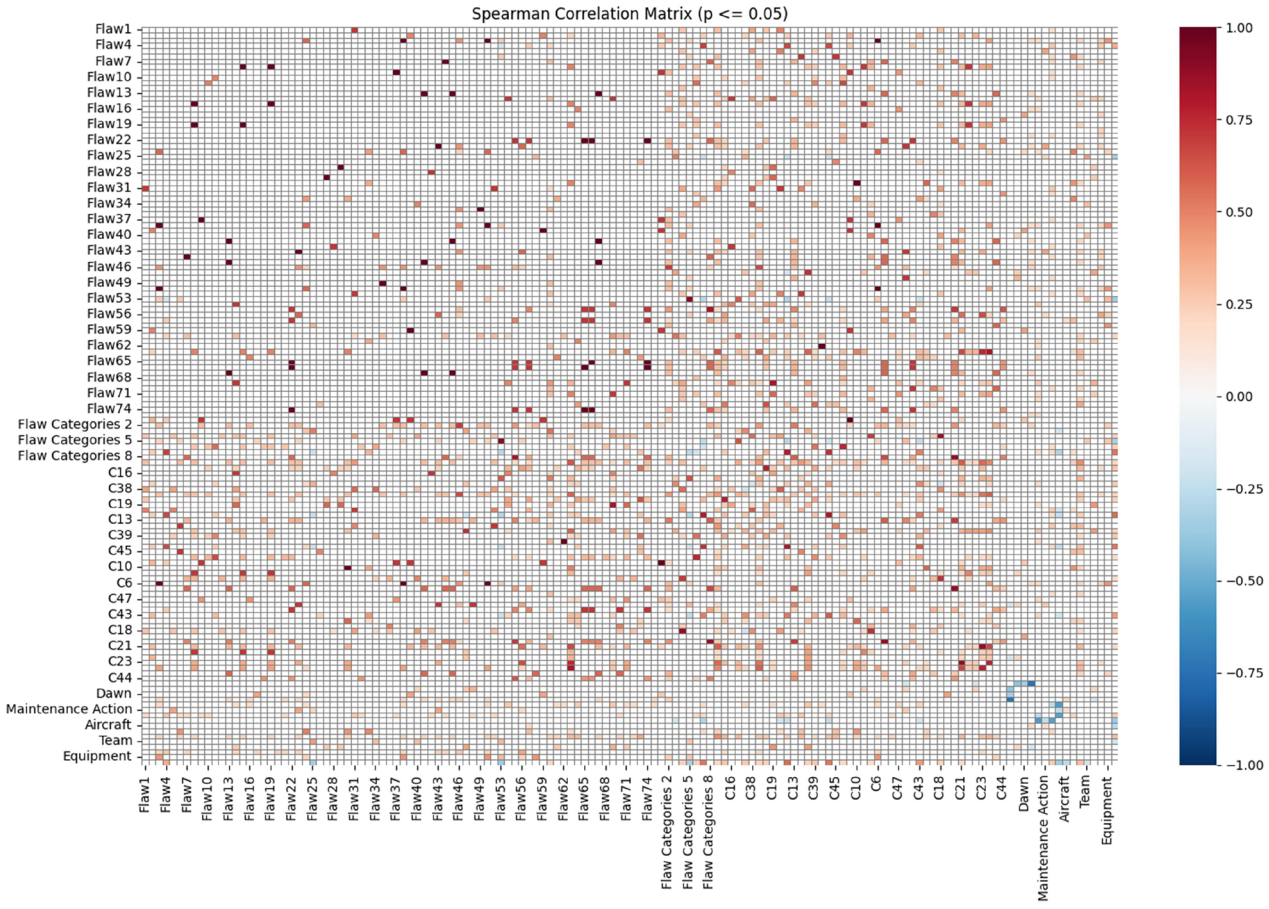

Figure 7. Correlation matrix including all features (flaws, flaw categories, control actions, light conditions, losses, contextual factors and the hazard).

Table 5. Centrality measures for the top 10 critical nodes (based on degree centrality).

Node	Degree Centrality	Closeness Centrality	Betweenness Centrality	Eigenvector Centrality
Flaw Categories 9	0.216	0.432	0.133	0.256
Flaw Categories 2	0.201	0.367	0.086	0.263
C13	0.165	0.358	0.062	0.258
C21	0.165	0.417	0.097	0.172
Flaw63	0.137	0.407	0.051	0.120
C11	0.137	0.378	0.014	0.264
C12	0.129	0.348	0.010	0.247
C28	0.122	0.388	0.042	0.118
C23	0.122	0.396	0.024	0.125
Flaw60	0.115	0.372	0.115	0.038

restorative, substantive and procedural justice. Restorative justice should heal the individuals at the sharp end who felt hurt because of error and violation. Substantive justice enables fair and legitimate regulations, rules and procedures, and procedural justice establishes legitimate procedures to identify rule violations, provides protections for the accused, and specifies who is authorised to make these decisions (Dekker and Breakey 2016).

The dataset indicated that failure to follow procedures was not only one of the most frequently reported contributory factors but also emerged as the most central node in the network model, highlighting its critical role in accident causation. However, this finding should not be interpreted as mere procedural non-compliance at the individual level. Instead, it often reflects systemic issues embedded in the design, communication, and applicability of the procedures themselves. Standard Operating Procedures (SOPs) are frequently developed without adequate input from frontline staff, leading to documents that may be inaccessible, overly complex, misaligned with operational constraints, or poorly adapted to context-specific scenarios. Moreover, the practice might differ from the prescribed work. This discrepancy is particularly pronounced in high-pressure, time-sensitive environments such as ground handling. Indeed, studies found gaps between work-as-done (practice) and work-as-imagined (procedures) in various industries (Clay-Williams, Hounsgaard, and Hollnagel 2015; Patriarca, Gravio, and Costantino 2016; Underwood and Waterson 2013). Such gaps can result in procedural drift, where staff

adapt or bypass procedures in order to maintain workflow efficiency. While this performance variability is often necessary to keep operations running smoothly, it becomes visible primarily when it contributes to adverse outcomes (Hollnagel 2017; Kontogiannis and Malakis 2012). For example, one of the incidents in the dataset (Appendix A) involved passengers boarding via steps with a guard rail missing, and a cabin crew member closed the aircraft door without issuing the required step permit, both of which actions violate SOPs. The SOPs mandate passenger boarding only after putting the guard rail in place, and the crew closing the door in coordination with the ramp agent. From the crew's point of view, the individual was familiar with the procedure and believed to act safely, thinking that the steps were positioned too low. This highlights several systemic vulnerabilities: the crew and ramp teams lacked a shared mental model of the situation, and the responsibility for verifying the safe configuration of the boarding equipment was ambiguously distributed. This shows that procedural failures often signal deeper issues in organisational design, such as weak cross-role communication protocols and a lack of mechanisms for verifying task interdependencies during high-tempo operations.

In addition, it is claimed that there is a lack of international and national safety requirements for ground-handling service providers despite ground-handling-related airport regulations. Therefore, ground handling providers adjust their practices based on the airline's needs and the specific airport's requirements. It is suggested that internal and external audits should be performed to ensure safety, which can be promoted using internal, national and international channels like safety bulletins and alerts and national and international safety groups (Studic et al. 2017). However, the varying levels of international requirements could result in differences in the quality of the services provided by ground-handling organisations. When the ground support is provided by a third party, which is often the case with other options of self-handling and airport-provided, the airline must contract with different third-party providers at various airports, which results in varying quality of service received at different airports. Some of the reporting issues could likely be due to the service provider's safety management system and reporting culture.

Many airlines complain about the monopolies of the ground handling providers at airports and their poor and expensive services (Castro, 2022), in which national and international regulations and standards can assure quality. However, there is a dilemma here; airlines tend to make contracts with the cheapest service providers, where 80% of their costs are due to labour costs, increasing the pressure on the ground handlers and leading to low-quality service (Harvey, Turnbull, and Wintersberger 2019; Wandelt and Wang 2024). So, while most of the efforts are focused on the service provider, airlines can work with different providers. Also, international standards can be established to ensure acceptable quality in ground handling operations delivered worldwide.

Furthermore, the CAST analysis revealed issues around communication between the controllers, including between the ground handler and crew, between ground handlers, between the ground handling provider and GSE maintenance provider, and between the ground handling provider and airline. These issues were actions taken without communication, such as the crew opening the door without communicating with ground handlers, misunderstandings by misinterpreting or not receiving the necessary information, or actions not taken due to the lack of communication. For instance, the lack of communication between the ground handling service provider and the GSE maintenance provider contributed to the failure to maintain the GSE. In turn, markings and signs on the GSE were not renewed/provided. Ultimately, this affected the ground handler's performance on positioning steps and the airline, resulting in delayed operations, aircraft damage, or maintenance actions. The network modelling demonstrated the complexity of the problem, as multiple factors interact with each other, and all these contribute to the incident.

In this study, CAST enabled the exploration of the 'why' and revealed the necessity of human factors. The performance of ground handlers should be measured to design customised training. Ground-handling providers should establish a 'Just culture' or 'Restorative culture' and support the well-being of their staff and reduce fear-driven underreporting. Balk, Stroeve, and BossenBroek (2011) identifies indicators for just culture in relation to safety reporting by following three ASC-IT safety culture indicators (Piers, Montijn, and Balk 2009): justness (evaluating unsafe behaviour, passing of responsibility and perception of evaluation), information (communication, reporting system, willingness to report and consequences of safety reports) and adaptability, referring to actions after safety occurrences. EUROCONTROL (2008) suggests that fostering a Just Culture can be supported through several key practices: implementing de-identified or anonymous reporting systems to protect individuals; clearly defining the boundaries between acceptable and unacceptable behaviour; providing structured training for

managers and supervisors on fair, non-punitive response strategies; and establishing transparent feedback mechanisms to ensure that staff understand how reported information contributes to safety improvements. Monitoring trends in reporting behaviour can also serve as a cultural indicator of progress.

Ground-handling providers can improve their recruitment process by recruiting skilled ground handlers and making the job more attractive with financial benefits. Airlines should specify safety requirements in their contracts with the ground handling service providers. Better communication channels should be built between the ground handling service providers, airlines and airports. Airports should set an acceptable level of quality standards for the service provider. International bodies or organisations should set quality and safety standards for ground handling operations. Lessons learned should be shared globally. In addition, recommendations can consider building resilient controls in the ground handling operations, considering technological advancements. Would automation be part of a solution? Chen, Ermiş, and Sharpanskykh (2023) modelled automated ground handling processes to ensure efficient task allocation and path planning for safe GSE movement. How about integrating ML to predict accidents (Tselentis, Papadimitriou, and van Gelder 2023) or continuously monitor human performance using objective measurements (Charles and Nixon 2019; Park, Jeong, and Myung 2018; Salmon et al. 2009)?

It is essential to discuss the value of CAST in accident analysis. CAST is often used to analyse an individual accident; in this study, the authors followed a different approach to apply CAST to analyse 117 PBS-related incidents in ground handling operations. On the one hand, applying CAST allowed us to explore the recurrent problems in the passenger boarding steps operations. On the other hand, focusing on multiple incidents might prevent the analyst from conducting an in-depth analysis. However, developing a network model and exploring the importance of features, another key contribution of this paper, enabled the enhancement of the analysis and the focus on the critical parts that re-occurred across several incidents. In addition, the flexibility in CAST prevented the authors from concentrating on one direction and focusing on all key questions, exploring the why. However, at the same time, this could lead authors to select some questions or confuse their users about when to complete the analysis or if all questions are asked during the analysis. Further studies can be conducted to develop a validation framework for CAST, as it was developed for STPA (Sadeghi and Goerlandt 2023). While the authors identified challenges for using CAST, it should be noted that some of these challenges are also valid for using any other methods.

The network modelling of the CAST findings demonstrated the complex interactions between contributory factors, control actions, hazards, and losses, which were not evident from the airline's incident investigation details. It provides an overall pattern of accidents, revealing how these factors contribute to incidents. The authors integrated network modelling into CAST to enhance the accident analysis. Similarly, attempts have been made to enhance accident or risk analysis in the literature using Bayesian networks (Basnet et al. 2023; Johansen and Utne 2022; Qiao et al. 2023; Xu et al. 2022) and network models (Feng et al. 2023; Li et al. 2024; Suo et al. 2021; Wang et al. 2023; Yan et al. 2023). For instance, the Bayesian network is integrated into STPA; however, Bayesian network models use a directed acyclic graph-edge pointing one direction, and so no cycles are allowed, limiting the exploration of complexity, whereas network modelling enables the demonstration of the complex interactions with cycles. Network models are mostly used to explain accident causality without building the study based on systems-based methods, except Yan et al. (2023) for building the network model based on the system components of the control structure. While network models explain how accidents occur in complex systems, the model itself cannot be used to detect certain links, as the links overlap on the network model due to its presentation. At this point, the correlation matrix enables understanding the exact interactions between the nodes and provides insights into areas of greater concern. In addition, the centrality measures are used to reveal the most critical nodes in the network model. However, it should be noted that, in this study, the critical nodes were not necessarily meant to be the most critical contributing factor to the incident as the model contained losses, hazards, control actions, external factors and contributory factors; critical nodes presented the most influential element based on their connectivity among all nodes.

In this study, integrating network modelling was shown to add value to the CAST analysis, including exploring how accidents occur further, revealing the interactions, and identifying critical factors (nodes). However, the limitations of this study should be mentioned. One limitation of this study lies in the inherent constraints of the incident data, which, as with many accident reporting systems, may lack complete context or detail. While the authors used their safety engineering expertise and consulted operational manuals and relevant literature to support the CAST analysis, it is

possible that some contributory factors were not fully captured. There is also a possibility of selective bias as the authors analysed the near-miss data that have been collected. Secondly, the process of converting qualitative CAST findings into a binary dataset introduces an abstraction layer that may not reflect the full complexity of system behaviour. However, this simplification enables consistent comparison across incidents and supports scalable analysis. It is important to acknowledge that accidents in complex systems rarely follow identical patterns, and any quantitative approach risks overgeneralisation. Nonetheless, the identification of recurring structures and high-centrality nodes provides valuable insight for guiding resource prioritisation and system improvement. As with any method, the utility of this approach lies in its integration with expert judgement and an understanding of its boundaries. Thirdly, this study used centrality measures to calculate the most critical node, which has limitations, as different measures might suggest different results in their ranking order. That is why researchers suggested integrating MCDM methods to rank node importance (Yang et al. 2019). However, the same problem might occur using different MCDM methods (Kaya 2020). Also, our findings indicate the same node outrating in all measurement categories, and centrality measures are widely used despite their limitations (Feng et al. 2023; Yang et al. 2019). Additionally, although the network was constructed from a weighted correlation matrix using Spearman's rank correlation, the final structure involved thresholding ($\rho \geq 0.3$) to generate a binary adjacency matrix. This introduces simplification by discarding the full range of correlation strengths. Also, the chosen threshold reflects weak-to-moderate associations, which may increase the density of the network. This choice was deliberate, given the complexity and subtlety of contributory relationships in accident data, where strong linear associations are often absent. Nonetheless, we acknowledge that alternative thresholds or edge-weighting schemes (e.g. raw co-occurrence counts or mutual information) could offer complementary insights and should be explored in future research. What is more, this study used the data collected from a single airline, in which the airline's organisational and safety culture, as well as their specific operational processes, might have influenced the findings. While this might limit the generalisability of the findings, airline operators follow global standards and regulations, and, therefore, we would expect to see similar findings in other operators by acknowledging that every incident has its own unique features, while also still having the possibility of recurring issues. In addition, the findings from this study align with the industrial reports. Finally, as with other qualitative methods, CAST relies on human judgement, which may introduce bias or inconsistency in the findings. To mitigate this, two analysts independently conducted the initial review, followed by consensus discussions and an independent validation by two other analysts. This approach was intended to balance diverse perspectives while reducing the risks of confirmation bias and groupthink.

6. Conclusion

This study provided a unique application of CAST by integrating network modelling to enhance accident analysis. The CAST analysis enabled the consideration of issues that were not reported and led to the consideration of improvement suggestions moving beyond the standard recommendations. Network modelling revealed the complex interactions among the contributory factors. This study contributes to safety science by proposing an integrated method to analyse accidents and the aviation industry by providing a comprehensive accident analysis on ground handling passenger boarding steps-related incidents. A similar approach proposed in this work could be followed for analysing incidents in other industries, especially those of high frequency but low impact/severity. As systems become more complex and interactions become more latent, predicting the impacts of incidents becomes more complex. Developing a methodology that focuses on understanding 'why' incidents occur, visualises relationships between flaws, inadequate control actions, contextual factors, hazards and losses and provides traceability is invaluable.

While this study focused on retrospective analysis, future work could build on this foundation by incorporating real-time data streams from ground equipment (e.g. IoT-enabled PBS monitoring) to support live network updates and early warning systems. Additionally, machine learning classifiers could be trained on CAST-derived features to support the prioritisation of contributory factors, potentially validating and complementing centrality-based insights. These directions reflect the increasing convergence of safety analysis with predictive analytics and offer opportunities for further improving risk detection and intervention strategies in ground handling operations.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

The author(s) reported there is no funding associated with the work featured in this article.

Data availability statement

Data supporting this study cannot be made available due to legal and commercial restrictions.

References

Allianz Global Corporate & Speciality. 2020. *Aviation Risk 2020 Safety and The State of the Notion*. https://commercial.allianz.com/news-and-insights/reports/aviation-risk-report.html

Alonso Tabares, D., and F. Mora-Camino. 2019. "Aircraft Ground Operations: steps towards Automation." *CEAS Aeronautical Journal 10* (3): 965–974. doi:10.1007/s13272-019-00390-5.

Altabbakh, H., M. A. AlKazimi, S. Murray, and K. Grantham. 2014. "STAMP- Holistic System Safety Approach or Just Another Risk Model?" *Journal of Loss Prevention in the Process Industries 32*: 109–119. doi:10.1016/j.jlp.2014.07.010.

Balk, A. D. 2008. "Safety of Ground Handling." Nasional Aerospace Laboratory NLR 46 https://www.skytanking.com/fileadmin/user_upload/downloads/Skytanking_Case-Study-Bangalore.pdf.

Balk, A. D., and J. W. Bossenbroek. 2010. "Aircraft Ground Handling and Human Factors: A Comparative Study of the Perceptions by Ramp Staff and Management." https://www.easa.europa.eu/essi/documents/HFreportfinal_000.pdf

Balk, A. D., S. H. Stroeve, and J. W. BossenBroek. 2011. *Just Culture and Human Factors Training in Ground Service Providers*, 1–22. Amsterdam: NLR Air Transport Safety Institute.

Barnes, J. A., and F. Harary. 1983. "Graph Theory in Network Analysis." *Social Networks 5* (2): 235–244. doi:10.1016/0378-8733(83)90026-6.

Basnet, S., A. BahooToroody, M. Chaal, J. Lahtinen, V. Bolbot, and O. A. Valdez Banda. 2023. "Risk Analysis Methodology Using STPA-Based Bayesian Network- Applied to Remote Pilotage Operation." *Ocean Engineering 270*: 113569. doi:10.1016/j.oceaneng.2022.113569.

Bensaci, C., Y. Zennir, D. Pomorski, F. Innal, and M. A. Lundteigen. 2023. "Collision Hazard Modeling and Analysis in a Multi-Mobile Robots System Transportation Task with STPA and SPN." *Reliability Engineering & System Safety 234*: 109138. doi:10.1016/j.ress.2023.109138.

Bills, K., L. Costello, and M. Cattani. 2023. "Major Aviation Accident Investigation Methodologies Used by ITSA Members." *Safety Science 168*: 106315. doi:10.1016/j.ssci.2023.106315.

Bloch, F., M. O. Jackson, and P. Tebaldi. 2023. "Centrality Measures in Networks." *Social Choice and Welfare* 61 (2): 413–453. doi:10.1007/s00355-023-01456-4.

Castro, P. 2022. "EU Airport Ground Handling Directive or When Discretion Interferes with Public Duty: A Proposal on How to save Portugal's Transposition from Discretion." *Case Studies on Transport Policy 10* (3): 1473–1482. doi: 10.1016/j.cstp.2022.05.014.

Charles, R. L., and J. Nixon. 2019. "Measuring Mental Workload Using Physiological Measures: A Systematic Review." *Applied Ergonomics 74*: 221–232. doi:10.1016/j.apergo.2018.08.028.

Chen, J., B. Yao, Q. Lu, X. Wang, P. Yu, and H. Ge. 2024. "A Safety Dynamic Evaluation Method for Missile Mission Based on Multi-Layered Safety Control Structure Model." *Reliability Engineering & System Safety 241*: 109678. doi:10.1016/j.ress.2023.109678.

Chen, S. T., G. Ermiş, and A. Sharpanskykh. 2023. "Multi-Agent Planning and Coordination for Automated Aircraft Ground Handling." *Robotics and Autonomous Systems 167*: 104480. doi:10.1016/j.robot.2023.104480.

Chikha, P., and J. Skorupski. 2022. "The Risk of an Airport Traffic Accident in the Context of the Ground Handling Personnel Performance." *Journal of Air Transport Management 105*: 102295. doi:10.1016/j.jairtraman.2022.102295.

Clay-Williams, R., J. Hounsgaard, and E. Hollnagel. 2015. "Where the Rubber Meets the Road: using FRAM to Align Work-as-Imagined with Work-as-Done When Implementing Clinical Guidelines." *Implementation Science 10* (1): 125. doi:10.1186/s13012-015-0317-y.

Dekker, S. W. A., and H. Breakey. 2016. "Just Culture:" Improving Safety by Achieving Substantive, Procedural and Restorative Justice." *Safety Science 85*: 187–193. doi:10.1016/j.ssci.2016.01.018.

Dobrowolska, M., M. Stasiła-Sieradzka, and J. Kozuba. 2020. "Safety Attitude as a Predictor of the Sense of Threat in the Workplace, Using the Example of Airport Ground Staff." *Sustainability 12* (16): 6569. doi:10.3390/su12166569.

Dong, C., Y. Zhang, Z. Wang, J. Liu, and J. Zhang. 2024. "The Hybrid Systems Method Integrating STAMP and HFACS for the Causal Analysis of the Road Traffic Accident." *Ergonomics 67* (7): 971–994. doi:10.1080/00140139.2023.2270783.

EUROCONTROL. 2008. European Air Traffic Management. London: Routledge. doi:10.4324/9781315256030.

Feng, J. R., M. Zhao, G. Yu, J. Zhang, and S. Lu. 2023. "Dynamic Risk Analysis of Accidents Chain and System Protection Strategy Based on Complex Network and Node Structure Importance." *Reliability Engineering & System Safety 238*: 109413. doi:10.1016/j.ress.2023.109413.

Griffin, T. G. C., M. S. Young, and N. A. Stanton. 2010. "Investigating Accident Causation through Information Network Modeling." *Ergonomics 53* (2): 198–210. doi:10.1080/00140130903125165.

Guo, S., B. Tang, K. Liang, X. Zhou, and J. Li. 2021. "Comparative Analysis of the Patterns of Unsafe Behaviors in Accidents between Building Construction and Urban Railway Construction." *Journal of Construction Engineering and Management 147* (5): 04021027. doi:10.1061/(ASCE)CO.1943-7862.0002013.

Harvey, G., P. Turnbull, and D. Wintersberger. 2019. "Speaking of Contradiction." *Work, Employment and Society 33* (4): 719–730. doi:10.1177/0950017018759204.

Heinrich, H. 1931. *Industrial Accident Prevention: A Scientific Approach*. New York: McGraw-Hill.

Hinkle, DE., W. Wiersma, and S. Jurs. 2003. *Applied Statistics for the Behavioral Sciences* (5th ed.). Boston: Houghton Mifflin.

Hollnagel, E. 2017. *The ETTO Principle: Efficiency-Thoroughness Trade-Off*. Boca Raton: CRC Press. http://onlinelibrary.wiley.com/doi/10.1111/j.1539-6924.2009.01333.x/abstract

Hulme, A., N. A. Stanton, G. H. Walker, P. Waterson, and P. M. Salmon. 2019. "What Do Applications of Systems Thinking Accident Analysis Methods Tell us about Accident Causation? A Systematic Review of Applications between 1990 and 2018." *Safety Science 117*: 164–183. doi:10.1016/j.ssci.2019.04.016.

Hulme, A., N. A. Stanton, G. H. Walker, P. Waterson, and P. M. Salmon. 2021. "Are Accident Analysis Methods Fit for Purpose? Testing the Criterion-Referenced Concurrent Validity of AcciMap, STAMP-CAST and AcciNet." *Safety Science 144*: 105454. doi:10.1016/j.ssci.2021.105454.

Hulme, A., N. A. Stanton, G. H. Walker, P. Waterson, and P. M. Salmon. 2024. "Testing the Reliability of Accident Analysis Methods: A Comparison of AcciMap, STAMP-CAST and AcciNet." *Ergonomics 67* (5): 695–715. doi:10.1080/00140139.2023.2240048.

IATA. 2020. Ground Damage Report: The Case for Enhanced Ground Support Equipment. https://www.iata.org/en/programs/ops-infra/ground-operations/ground-damage-report/.

Johansen, T., and I. B. Utne. 2022. "Supervisory Risk Control of Autonomous Surface Ships." *Ocean Engineering 251*: 111045. doi:10.1016/j.oceaneng.2022.111045.

Kaya, G. K. 2020. "The Use of Multi-Criteria Decision-Making Methods to Support Risk Prioritisation.". *5th International Conference on Industrial Engineering and Operations Management*.

Kaya, G. K. 2021. "A System Safety Approach to Assessing Risks in the Sepsis Treatment Process." *Applied Ergonomics 94*: 103408. doi:10.1016/j.apergo.2021.103408.

Kaya, G. K., F. Ozturk, and E. E. Sariguzel. 2021. "System-Based Risk Analysis in a Tram Operating System: Integrating Monte Carlo Simulation with the Functional Resonance Analysis Method." *Reliability Engineering & System Safety 215*: 107835. doi:10.1016/j.ress.2021.107835.

Kaya, G. K., S. Ustebay, J. Nixon, C. Pilbeam, and M. Sujan. 2023. "Exploring the Impact of Safety Culture on Incident Reporting: Lessons Learned from Machine Learning Analysis of NHS England Staff Survey and Incident Data." *Safety Science 166*: 106260. doi:10.1016/j.ssci.2023.106260.

King, B. J., G. J. M. Read, A. Hulme, S. Chari, R. Clay-Williams, K. L. Plant, L. McCormack, M. Tresillian, and P. M. Salmon. 2024. "Evaluating the Use of Systems Thinking Methods in Healthcare: A RE-AIM Analysis of AcciMap and Net-HARMS." *Ergonomics*: 1–19. doi:10.1080/00140139.2024.2423170.

Kontogiannis, T., and S. Malakis. 2012. "Recursive Modeling of Loss of Control in Human and Organizational Processes: A Systemic Model for Accident Analysis." *Accident; Analysis and Prevention 48*: 303–316. doi:10.1016/j.aap.2012.01.029.

Kossivi, B., M. Xu, and B. Kalgora. 2016. "Study on Determining Factors of Employee Retention." *Open Journal of Social Sciences 04* (05): 261–268. doi:10.4236/jss.2016.45029.

Leveson, N. 2011a. "Applying Systems Thinking to Analyze and Learn from Events." *Safety Science 49* (1): 55–64. doi:10.1016/j.ssci.2009.12.021.

Leveson, N. 2011b. *Engineering a Safer World: Systems Thinking Applied to Safety*. Cambridge: The MIT Press.

Leveson, N. G. 2019. *CAST Handbook: How to Learn More from Incidents and Accidents*. https://psas.scripts.mit.edu/home/books-and-handbooks/.

Li, C., T. Tang, M. M. Chatzimichailidou, G. T. Jun, and P. Waterson. 2019. "A Hybrid Human and Organisational Analysis Method for Railway Accidents Based on STAMP-HFACS and Human Information Processing." *Applied Ergonomics 79*: 122–142. doi:10.1016/j.apergo.2018.12.011.

Li, J., Z. Yang, H. He, C. Guo, Y. Chen, and Y. Zhang. 2024. "Risk Causation Analysis and Prevention Strategy of Working Fluid Systems Based on Accident Data and Complex Network Theory." *Reliability Engineering & System Safety 252*: 110445. doi:10.1016/j.ress.2024.110445.

Li, S., G. Chen, L. Zhou, Y. Zhao, Q. Xu, and J. Zhao. 2025. "Complex Network Analysis for Accident Causes Modelling to Enhance Process Safety in Chemical Enterprises." *The Canadian Journal of Chemical Engineering* 103 (2): 679–696. doi:10.1002/cjce.25443.

Liu, Q., K. Sun, W. Liu, Y. Li, X. Zheng, C. Cao, J. Li, and W. Qin. 2025. "Quantitative Risk Assessment for Connected Automated Vehicles: Integrating Improved STPA-SafeSec and Bayesian Network." *Reliability Engineering & System Safety 253*: 110528. doi:10.1016/j.ress.2024.110528.

Liu, X., Z. Zhao, H. Li, C. Liu, and S. Wang. 2020. "Defect Prediction of Radar System Software Based on Bug Repositories and Behavior Models." *International Journal of Performability Engineering 16* (2): 284–296. doi:10.23940/ijpe.20.02.p11.284296.

Mason-Blakley, F., R. Habibi, J. Weber, and M. Price. 2017. "Assessing STAMP EMR with Electronic Medical Record Related Incident Reports: Case Study: Manufacturer and User Facility Device Experience Database.". *Proceedings - 2017 IEEE International Conference on Healthcare Informatics, ICHI 2017*, 114–123. doi:10.1109/ICHI.2017.97.

McCormack, P., G. J. M. Read, A. Hulme, B. R. Lane, S. McLean, and P. M. Salmon. 2023. "Using Systems Thinking-Based Risk Assessment Methods to Assess Hazardous Manual Tasks: A Comparison of Net-HARMS, EAST-BL, FRAM and STPA." *Ergonomics 66* (5): 609–626. doi:10.1080/00140139.2022.2105959.

Mogles, N., J. Padget, and T. Bosse. 2018. "Systemic Approaches to Incident Analysis in Aviation: Comparison of STAMP, Agent-Based Modelling and Institutions." *Safety Science 108*: 59–71. doi:10.1016/j.ssci.2018.04.009.

Mohan, A., and K. V. Pramod. 2019. "Network Representation Learning: models, Methods and Applications." *SN Applied Sciences 1* (9): 1–23. doi:10.1007/s42452-019-1044-9.

Muecklich, N., I. Sikora, A. Paraskevas, and A. Padhra. 2023. "The Role of Human Factors in Aviation Ground Operation-Related Accidents/Incidents: A Human Error Analysis Approach." *Transportation Engineering 13*: 100184. doi:10.1016/j.treng.2023.100184.

Musa, M., and A. S. N. Isha. 2021. "Holistic View of Safety Culture in Aircraft Ground Handling: Integrating Qualitative and Quantitative Methods with Data Triangulation." *Journal of Air Transport Management 92*: 102019. doi:10.1016/j.jairtraman.2021.102019.

Park, S., S. Jeong, and R. Myung. 2018. "Modeling of Multiple Sources of Workload and Time Pressure Effect with ACT-R." *International Journal of Industrial Ergonomics 63*: 37–48. doi:10.1016/j.ergon.2017.07.003.

Patriarca, R., G. Di Gravio, and F. Costantino. 2016. "Resilience Engineering to Assess Risks for the Air Traffic Management System: A New Systemic Method." *International Journal of Reliability and Safety 10* (4): 323–345. doi:10.1504/IJRS.2016.084477.

Patriarca, R., G. Di Gravio, and F. Costantino. 2017. "A Monte Carlo Evolution of the Functional Resonance Analysis Method (FRAM) to Assess Performance Variability in Complex Systems." *Safety Science 91*: 49–60. doi:10.1016/j.ssci.2016.07.016.

Patriarca, R., M. Chatzimichailidou, N. Karanikas, and G. Di Gravio. 2022. "The past and Present of System-Theoretic Accident Model and Processes (STAMP) and Its Associated Techniques: A Scoping Review." *Safety Science 146*: 105566. doi:10.1016/j.ssci.2021.105566.

Piers, M., C. Montijn, and A. Balk. 2009. "Safety Management System and Safety Culture Working Group (SMS WG):

Safety Culture Framework for the ECAST SMS-WG." In ECAST: European Strategic Safety Initiatives.

Pruchnicki, S. A., L. J. Wu, and G. Belenky. 2011. "An Exploration of the Utility of Mathematical Modeling Predicting Fatigue from Sleep/Wake History and Circadian Phase Applied in Accident Analysis and Prevention: The Crash of Comair Flight 5191." *Accident; Analysis and Prevention 43* (3): 1056–1061. doi:10.1016/j.aap.2010.12.010.

Qiao, W., E. Huang, H. Guo, C. Lian, H. Chen, and X. Ma. 2023. "On the Causation Analysis for Hazards Involved in the Engine Room Fire-Fighting System by Integrating STPA and BN." *Ocean Engineering 288* (P2): 116073. doi:10.1016/j.oceaneng.2023.116073.

Qiao, W., X. Li, and Q. Liu. 2019. "Systemic Approaches to Incident Analysis in Coal Mines: Comparison of the STAMP, FRAM and "2–4" Models." *Resources Policy 63*: 101453. doi:10.1016/j.resourpol.2019.101453.

Read, G. J. M., S. Shorrock, G. H. Walker, and P. M. Salmon. 2021. "State of Science: evolving Perspectives on 'Human Error." *Ergonomics 64* (9): 1091–1114. doi:10.1080/00140139.2021.1953615.

Reason, J. 1997. *Managing the Risks of Organisational Accidents*. London: Routledge.

Revell, K. M. A., C. Allison, R. Sears, and N. A. Stanton. 2019. "Modelling Distributed Crewing in Commercial Aircraft with STAMP for a Rapid Decompression Hazard." *Ergonomics 62* (2): 156–170. doi:10.1080/00140139.2018.1514467.

Sadeghi, R., and F. Goerlandt. 2023. "Reasonableness of a Proposed System Theoretic Process Analysis (STPA) Validation Framework: An Interview Study." *Journal of Loss Prevention in the Process Industries 83*: 105064. doi:10.1016/j.jlp.2023.105064.

Salmon, P. M., N. A. Stanton, G. H. Walker, D. Jenkins, D. Ladva, L. Rafferty, and M. Young. 2009. "Measuring Situation Awareness in Complex Systems: Comparison of Measures Study." *International Journal of Industrial Ergonomics 39* (3): 490–500. doi:10.1016/j.ergon.2008.10.010.

Spearman, C. 1904. "The Proof and Measurement of Association between Two Things." *The American Journal of Psychology 15* (1): 72–101. doi:10.2307/1412159.

Stanton, N. A., P. M. Salmon, G. H. Walker, and M. Stanton. 2019. "Models and Methods for Collision Analysis: A Comparison Study Based on the Uber Collision with a Pedestrian." *Safety Science 120*: 117–128. doi:10.1016/j.ssci.2019.06.008.

Staton, M., J. Barnes, A. Morris, and P. Waterson. 2023. "Learning Not Blaming: Investigating Ten Fatal Road Traffic Collisions Using STAMP-CAST." *Transportation Research Interdisciplinary Perspectives 21*: 100912. doi:10.1016/j.trip.2023.100912.

Studic, M., A. Majumdar, W. Schuster, and W. Y. Ochieng. 2017. "A Systemic Modelling of Ground Handling Services Using the Functional Resonance Analysis Method." *Transportation Research Part C: Emerging Technologies 74*: 245–260. doi:10.1016/j.trc.2016.11.004.

Sumwalt, R. L., and K. A. Lemos. 2010. "Chapter 16 - The Accident Investigator's Perspective." In *Crew Resource Management*, edited by B. G. Kanki, R. L. Helmreich, & J. Anca, 2nd ed., 399–423. Boston: Academic Press.

Sun, H., H. Wang, M. Yang, and G. Reniers. 2022. "A STAMP-Based Approach to Quantitative Resilience Assessment of Chemical Process Systems." *Reliability Engineering & System Safety 222*: 108397. doi:10.1016/j.ress.2022.108397.

Suo, Q., L. Wang, T. Yao, and Z. Wang. 2021. "Promoting Metro Operation Safety by Exploring Metro Operation Accident Network." *Journal of Systems Science and Information 9* (4): 455–468. doi:10.21078/JSSI-2021-455-14.

Tselentis, D. I., E. Papadimitriou, and P. van Gelder. 2023. "The Usefulness of Artificial Intelligence for Safety Assessment of Different Transport Modes." *Accident; Analysis and Prevention 186*: 107034. doi:10.1016/j.aap.2023.107034.

Underwood, P., and P. Waterson. 2013. "Systemic Accident Analysis: examining the Gap between Research and Practice." *Accident; Analysis and Prevention 55*: 154–164. doi:10.1016/j.aap.2013.02.041.

Underwood, P., and P. Waterson. 2014. "Systems Thinking, the Swiss Cheese Model and Accident Analysis: A Comparative Systemic Analysis of the Grayrigg Train Derailment Using the ATSB, AcciMap and STAMP Models." *Accident; Analysis and Prevention 68*: 75–94. doi:10.1016/j.aap.2013.07.027.

Underwood, P., P. Waterson, and G. Braithwaite. 2016. "Accident Investigation in the Wild" - A Small-Scale, Field-Based Evaluation of the STAMP Method for Accident Analysis." *Safety Science 82*: 129–143. doi:10.1016/j.ssci.2015.08.014.

Wandelt, S., and K. Wang. 2024. "Towards Solving the Airport Ground Workforce Dilemma: A Literature Review on Hiring, Scheduling, Retention, and Digitalization in the Airport Industry." *Journal of the Air Transport Research Society 2*: 100004. doi:10.1016/j.jatrs.2024.100004.

Wang, J., M. Qi, S. Liu, and D. Zhao. 2024. "Comprehensive Safety Assessment of a Hydrogen Liquefaction System Based on an Integrated System-Theoretic Process Analysis (STPA) and Best-Worst Method (BWM)." *International Journal of Hydrogen Energy 66*: 479–489. doi:10.1016/j.ijhydene.2024.04.082.

Wang, W., Y. Wang, G. Wang, M. Li, and L. Jia. 2023. "Identification of the Critical Accident Causative Factors in the Urban Rail Transit System by Complex Network Theory." *Physica A: Statistical Mechanics and Its Applications 610*: 128404. doi:10.1016/j.physa.2022.128404.

Wiegmann, D. A., H. Zhang, T. L. Von Thaden, G. Sharma, and A. M. Gibbons. 2004. "Safety Culture: An Integrative Review." *The International Journal of Aviation Psychology 14* (2): 117–134. doi:10.1207/s15327108ijap1402_1.

Xiao, C., J. Ye, R. M. Esteves, and C. Rong. 2016. "Using Spearman's Correlation Coefficients for Exploratory Data Analysis on Big Dataset." *Concurrency and Computation: Practice and Experience 28* (14): 3866–3878. doi:10.1002/cpe.

Xu, J., W. Tian, L. Kan, and Y. Chen. 2022. "Safety Assessment of Transport Aircraft Heavy Equipment Airdrop: An Improved STPA-BN Mechanism." *IEEE Access*. *10*: 87522–87534. doi:10.1109/ACCESS.2022.3199740.

Yan, K., Y. Wang, W. Wang, C. Qiao, B. Chen, and L. Jia. 2023. "A System-Theory and Complex Network-Fused Approach to Analyze Vessel–Wind Turbine Allisions in Offshore Wind Farm Waters." *Journal of Marine Science and Engineering*, *11* (7): 1306. doi:10.3390/jmse11071306.

Yang, Y., L. Yu, Z. Zhou, Y. Chen, and T. Kou. 2019. "Node Importance Ranking in Complex Networks Based on Multicriteria Decision Making." *Mathematical Problems in Engineering 2019*: 9728742. doi:10.1155/2019/9728742.

Yousefi, A., M. Rodriguez Hernandez, and V. Lopez Peña. 2019. "Systemic Accident Analysis Models: A Comparison Study between AcciMap, FRAM, and STAMP." Process Safety Progress, *38* (2): 12002. doi:10.1002/prs.12002.

Appendix A

Table A1. An example of the merged incident data.

FormID	Xxxxxx
Causal Factor Group	People
Causal Factor SubGroup	Human Factors
Causal Factor Detail	Lack Of Attention/Vigilance
Reference	Xxxxxxx
Status	Closed
Distribution Status	Distributed
Red Flag Event	0
Reported Date	2012-03-07 10:33:12.283
Incident Date	2012-03-06 14:35:00.000
Investigation Open Date	2012-03-09 16:46:39.427
Investigation Close Date	2012-04-11 09:58:23.880
Investigation Rejected Date	
Title	Rear door closed/Steps Guardrail not in place during boarding
Event Description	During the departure of xxxx flight to xxx at 1435 xxxx on stand 9, the rear steps were used by the boarding passengers with the left hand guard rail not in place. The passenger door had been closed during the turn round by the crew according to the ramp staff. A ramp agent who was at the front, noticed that the passengers were queuing up the steps and the door was closed and went to investigate this with the cabin crew. The crew commented to him that they shut the door because the steps were too low. The ramp agent then led the passengers back down the steps who then queued for the front steps.
Event Location	LTN
Investigation Title	Lead Investigation
Summary and Conclusions	Root Cause - cabin crew member failed to follow procedure and issue the step permit to initiate the steps being removed and re-positioned. Secondary cause - steps perceived as being too low and required adjustment. Secondary cause - no one including the CM was aware that the no2 had closed the rear door.
Investigation Preventative	There was no fault found with the rear steps and they were at the correct height when boarding commenced. No further action to be taken with the steps although staff are reminded to ensure vigilance when positioning steps and to ensure they check the height before boarding commences. Peer reviewer has confirmed that the cabin crew member involved is fully aware of the SOP and believed she was acting in the interest of safety. However, in future she will consider redirecting passengers and leave the door open until she gets the attention of a staff member who can assist in closing the door. She is adamant that the rail was in place when boarding but she was also able to close the door without moving the rail.
Investigation Feedback	This matter has been investigated fully by both cabin services and ground operations and the appropriate corrective actions are now in place.
Aircraft Registration	Xxxxxx
Aicraft Type	Airbus A319-111
Departure	Xxx
Arrival	Xxx
Route	xxx – xxx
AOC	Xxxxxx
Your Location	LTN
Flight Phase	Parked
Event at Departure/Arrival	At departure
Updated Descriptor Category	Ramp operations
Updated Descriptor Type	Ground Servicing Equipment/Positioning/Operations
Updated Descriptor Name	Guard rails (GSE)
Updated Credible Outcome	Major accident
Updated Remaining Barrier Effectiveness	Limited
Updated Event Risk Classification Score	21
Suggested Recommendations/Corrective Action	
Apron Conditions	
Details of Equipment/Aircraft and Damage Sustained	
Stand No	9
Wx Condition Icing	–
Wx Condition Snow	–
Wx Condition Hail	–
Wx Condition Rain	–
Wx Condition Fog	–
Wx Condition Wind	–
Wx Condition Turbulence	–
Wx Condition Windshear	–
Light Conditon	Daylight
Ramp/Apron State	
Ground Damage	1

(*Continued*)

Table A1. Continued.

Was Damage Caused?	No (confirmed by Engineers)
Were the Captain/Engineers informed of the event?	Yes
Is the damage you are reporting already known/documented in the aircraft Tech Log?	No
Was the aircraft declared AOG/repair required before departure?	No
Event Question	–
Event Question Answer	–
Equipment Collided	Steps
Part Struck	Door – Passenger
Date Sent to Authority	2012-03-09 15:59
Authority	Civil Aviation Authority
Immediate Operational Outcome	None - no impact on operation

Appendix B. Pseudo-code for data pre-processing and analysis

1. ***Start***
2. ***Data Preprocessing: Generate Binary Columns for Unique Values***
   - ***Load Excel file:***
     - *Read the dataset from the original Excel file (containing columns like FormID, Revised Flaws, Flaw Categories, etc.) into a DataFrame.*
   - ***Initialise a new DataFrame:***
     - *Create a new DataFrame containing only the FormID column.*
   - ***Process each column that needs binary transformation (e.g. Revised Flaws, Flaw Categories, Control Actions):***
     - ***Extract unique values:***
       - *Split the cell contents by commas to get individual items (if multiple exist).*
     - ***For each unique value in the column:***
       - *Create a new binary column with the format ColumnName_UniqueValue.*
       - *Loop through each row:*
         - *If the unique value exists in that row, assign 1 to the binary column.*
         - *Otherwise, assign 0.*
   - ***Save the binary matrix:***
     - *Write the resulting binary DataFrame to a new Excel file (e.g. Cleaned_Data.xlsx).*
3. ***Load Preprocessed Data for Correlation Analysis***
   - ***Load binary matrix file:***
     - *Read the preprocessed Excel file (Cleaned_Data.xlsx) into a DataFrame for further analysis.*
4. ***Calculate Correlation Matrix***
   - ***Compute pairwise correlations:***
     - *Use pandas to calculate the correlation matrix for all binary columns.*
     - *Store the correlation values in a matrix.*
5. ***Initialise a Network Graph Object***
   - *Create an empty undirected graph object using NetworkX.*
6. ***Add Nodes to the Graph***
   - *Loop through each feature (binary column) in the correlation matrix:*
     - *Add each feature as a node in the graph.*
7. ***Add Edges Based on Correlation Values***
   - ***Set a correlation threshold* (e.g. 0.3) to filter significant correlations.**
   - ***Loop through the correlation matrix:***
     - *For each pair of features:*
       - *If the absolute correlation value is greater than the threshold:*
         - *Add an edge between the two features in the graph.*
         - *Assign the correlation value as the edge weight.*
8. ***Ensure Specific Features are Present***
   - *Ensure that specific columns (No impact on operation, Delay, Maintenance Action, Aircraft Damage) are present as nodes:*
     - *If any are missing from the graph, add them as standalone nodes.*
9. **Assign Node Colours Based on Feature Groups**
   - ***Define colour groups** based on column ranges or categories:*
     - *Example: Assign yellow for the first 11 columns, blue for the next 40, green for time-related columns, etc.*
   - ***Map node colours:***
     - *For each node (feature), assign a colour based on its group.*
     - *Apply the colour mapping to the graph.*
10. ***Visualise the Network Diagram***
    - ***Set the plot size** to ensure the graph is readable.*
    - ***Position the nodes** using a spring layout:*
      - *Use a spring layout to evenly distribute the nodes and avoid overlap.*
    - ***Draw the nodes** with their assigned colours.*
    - ***Draw edges** with varying widths based on the edge weights (correlation values).*
    - ***Label the nodes** with feature names.*
    - ***Label the edges** with correlation values.*
11. ***Calculate and Display Centrality Measures***
    - ***Calculate centrality measures** (Degree Centrality, Betweenness Centrality, Closeness Centrality, Eigenvector Centrality) for the nodes.*
    - ***Sort nodes by Degree Centrality** to identify the most connected nodes.*
    - ***Print the top 10 nodes** based on Degree Centrality.*
12. **Save and Display the Network Diagram**
    - ***Save the graph** as a PNG file.*
    - ***Display the network plot.***
    - ***Save centrality measures** to a CSV file.*
13. ***End***

Appendix C

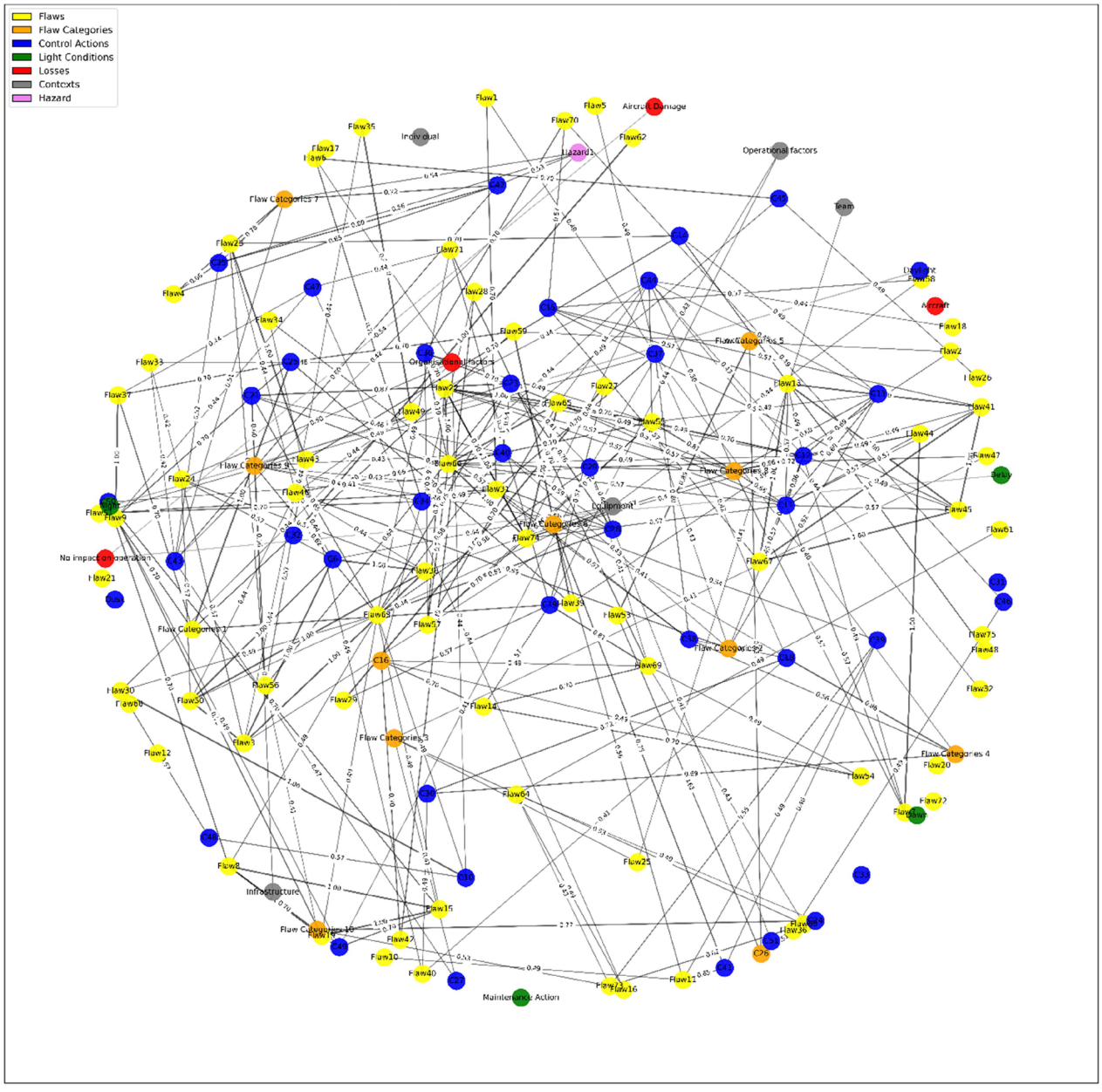

Figure C1. CAST findings network model for threshold >0.4.

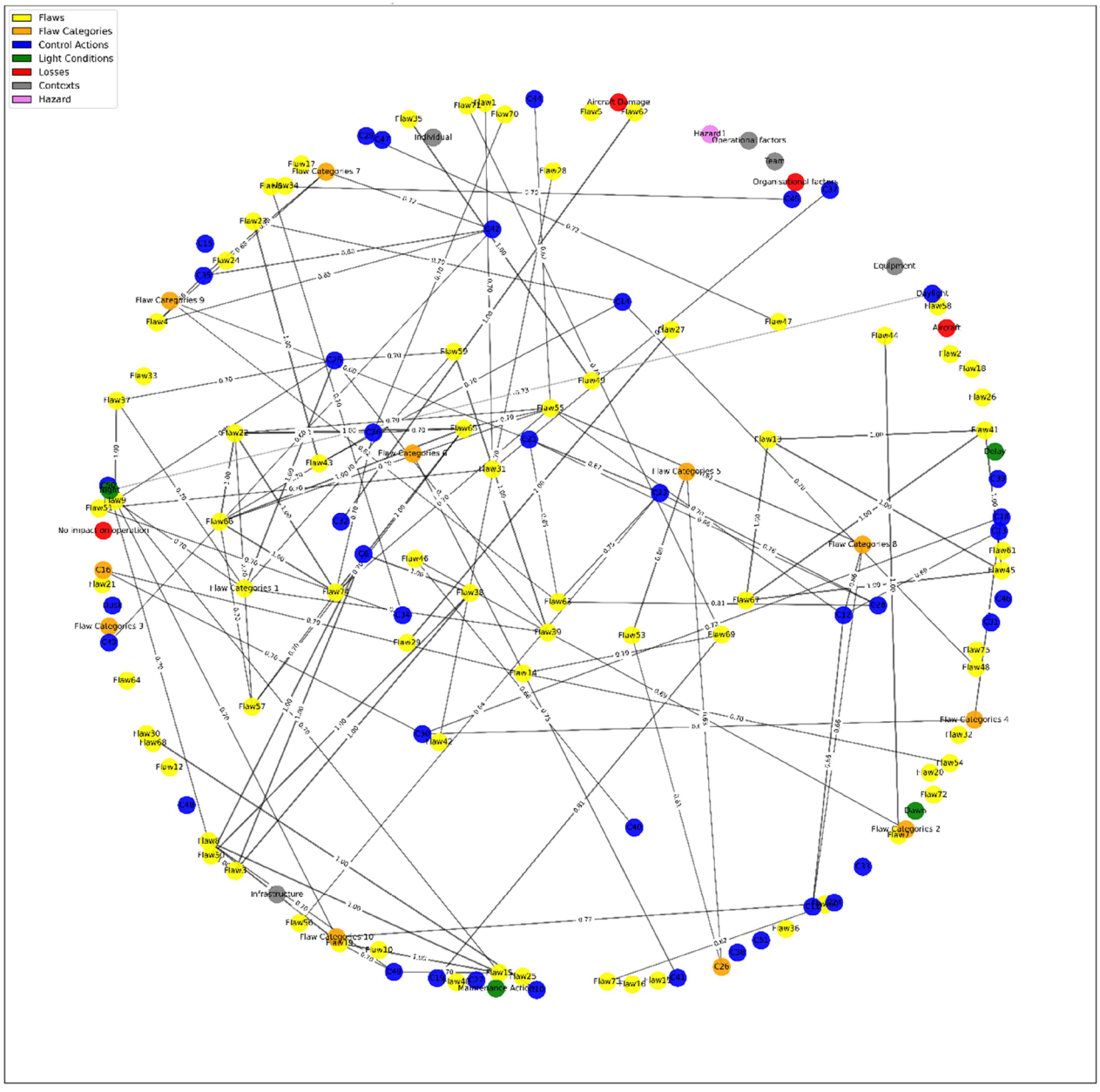

Figure C2. CAST findings network model for threshold >0.6.

Appendix D

Table D1. Flaws and flaw categories identified in the dataset.

ID	Flow Categories and Flaws	Frequency
Flow Category 1	Inadequate resource allocation	2
Flaw9	Missed banksman allocation during positioning	1
Flaw39	Inadequate ramp staff allocation system- poor information on responsibilities	1
Flow Category 2	Lack of communication	13
Flaw45	Aircraft started boarding without confirming the rear door opened	1
Flaw65	Cabin crew action (closing and/or opening the door) without communication	1
Flaw67	Communication breakdown between cabin crew and ground handlers	1
Flaw58	Communication breakdown between captain and ground handlers on reported damage in tech log	1
Flaw37	Communication breakdown between coach driver and ground handlers	1
Flaw16	Communication breakdown between ramp agent and supervisor	1
Flaw38	Ground crew action (steps positioning) without communication	1
Flaw35	No permit requested when repositioning	1
Flaw46	Poor communication between ground handler and cabin crew/pilot	5
Flow Category 3	Inadequate checks, monitoring and supervision	32
Flaw47	Inadequate post- arrival checks and pre-departure walkaround checks	6
Flaw60	Inadequate supervision and/or monitoring	10
Flaw50	Missed arrival walkaround	1
Flaw25	Missed detecting the dents/marks/scratches/damages.	9
Flaw3	Missed FOD check.	1
Flaw24	Missed visual checks/inspections during positioning	4
Flaw20	Wrong marshalling	1
Flow Category 4	Equipment failure	13
Flaw69	Not having visual aid sticker on steps	2
Flaw14	Improper design (spacing) of the pawl locks.	1
Flaw19	Motor failure of the platform	1
Flaw31	Steps malfunctioning- rolling forward	2
Flaw72	Steps malfunctioning- auto level system failure with no warning lights	1
Flaw5	Steps moved during passenger disembarkation	1
Flaw70	Metal bar holding the rubber was bent in steps.	1
Flaw40	Rubber part of steps touched aircraft	2
Flaw12	The step top gate had fallen	1
Flaw36	Brakes failed during steps positioning	1
Flow Category 5	Inadequate reporting	17
Flaw48	Crew missed reporting of delays in disembarking	1
Flaw23	Incorrect descriptor was entered by the reporter	1
Flaw17	Incorrect flight number was entered by the reporter	1
Flaw53	Missed reporting dents/marks/scratches/damages	14
Flow Category 6	Inadequate handrail and platform adjustment/setting	12
Flaw15	Disengaging pawl locks	1
Flaw21	Guard rail not removed when opening door	1
Flaw34	Instead of lifting up step stabiliser, lifting the platform.	1
Flaw18	Left handrail was not fully extended	1
Flaw68	Left handrail was opened before a/c door was opened.	1
Flaw71	Not engaging pawl locks.	1
Flaw11	Safety rails too close to the fuselage	4
Flaw32	The guard rail on rear steps was not totally retracted.	1
Flaw8	Top platform being too close to the bottom of the door	1
Flow Category 7	Inadequate steps positioning	51
Flaw4	Incorrect steps positioning	24
Flaw59	Incorrect steps positioning- poor vision	1
Flaw49	Incorrect steps repositioning	1
Flaw33	Missed repositioning of steps	7
Flaw27	Not checking the vertical gap between door frame and platform	1
Flaw66	Repositioned the steps too late.	1
Flaw7	Repositioning steps while the door was open	1
Flaw62	Stairs positioned too much on the rear of the aircraft.	1
Flaw2	Steps leaving a large gap	4
Flaw75	Steps positioned to be in touch with a/c	1
Flaw26	Steps positioned too close	2
Flaw64	Steps positioned too high	4
Flaw42	The shape of the canopy leaving a gap	1
Flaw28	The steps were not completely aligned to the fuselage.	2
Flow Category 8	Inadequate door closure/opening	3
Flaw55	Cabin crew closed the door before guardrail could be retracted.	2
Flaw44	The door was not secured in the ned lock.	1
Flow Category 9	Failure to follow the procedure	13
Flaw22	Boarding passengers with the left hand guard rail not in place.	1

(*Continued*)

Table D1. Continued.

ID	Flow Categories and Flaws	Frequency
Flaw74	Cabin crew member did not follow procedure	1
Flaw63	Failed to follow SOP/policy/procedure	5
Flaw51	The stabs were not down and the handbrake not on	1
Flaw1	The ramp agent left the key in the "on" position.	1
Flaw43	Crew did not check the tech log to verify the dent spotted	1
Flaw6	Fail to manoeuvring equipment around aircraft	1
Flaw41	Ground crew not stopping passengers climbing to the steps when the door was closed	1
Flaw13	Unsafe actions by leaving steps without securing the safety straps	1
Flow Category 10	Misjudgement/misperception	17
Flaw30	Cabin crew misjudgement on the step positioning.	1
Flaw61	Forgot the steps procedures	1
Flaw56	Inconsistent procedural knowledge and poor reporting culture	3
Flaw29	Misjudgement on the stairs positioning action- confusing height reference mark	1
Flaw57	Misjudgement on the step positioning action.	3
Flaw54	Misjudgement on the steps positioning action- aircraft load factor	2
Flaw73	Misjudgement on the steps positioning action-spatial judgement	5
Flaw10	Misjudgement on the time of knocking on the door	1

https://dspace.org/

Integrating causal analysis based on system theory with network modelling to enhance accident analysis

Kaya, Gulsum Kubra; Humphreys, Mark; Camelia, Fanny; Chatzimichailidou, Mikela

2025-12-31
Taylor & Francis
https://doi.org/10.1080/00140139.2025.2516060
Kaya GK, Humphreys M, Camelia F, Chatzimichailidou M. (2025) Integrating causal analysis based on system theory with network modelling to enhance accident analysis. Ergonomics, Available online 17 June 2025

Downloaded from a DSpace repository. https://dspace.org/