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Scenario-Independent Readiness for Zero-Day Aviation Emergencies: A Multiple-Case Analysis of Adaptive Capacity

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Abstract

While aviation safety management is best where hazards are named and available to be modeled and rehearsed, recent disruptions suggest that event size, coupling, and timing can fall outside planning parameters. This research revisits and narrows the focus on a multiple-case analysis of 10 aviation-relevant disruptions that occurred between 2001 and 2024 to explore the utility of the approach when the scenario catalogue is incomplete. Cases were coded through the utilization of public after-action material and pre-event artifacts, such as scenario catalogues, standard operating procedures, and exercise records when publicly accessible. For five cases, hazard-specific planning was not evidenced in the reviewed record; two were partially modeled and three were fully modeled. Across the sample, repeated response gaps included weak situational awareness, rigid command structures, single-point logistical dependencies, and slow interagency coordination. The analysis also identified three capability anchors for audit and future testing: rehearsed authority migration, rapid common-operating-picture formation, and pre-negotiated mutual aid; it did not test an anchor-versus-impact association. The resulting Scenario-Independent Readiness (SIR) checklist translates these anchors into audit-ready indicators that can be added to safety-management-system reviews without displacing scenario-specific controls. The findings support analytic rather than statistical generalization and should be tested through independent audits and simulations. The contribution is a safety-science framing of zero-day aviation preparedness as a sociotechnical capability at the interface of people, organizations, and digital infrastructures.

Keywords

Aviation Safety, Resilience Engineering, Safety Management Systems, Adaptive Capacity, Crisis Management, Common Operating Picture, Cyber-Physical Disruption

1. Introduction

Commercial aviation increasingly faces disruptions whose consequences are not fully captured by established hazard catalogues. The operational question is no longer only whether an organization has anticipated a named threat, but whether it can continue making safe, timely decisions when the threat is unfamiliar, compound, or outside rehearsed parameters. This study refers to such conditions as zero-day aviation emergencies: high-impact disruptions for which the reviewed public record does not evidence a hazard-specific scenario, standard operating procedure (SOP), or regulator- or operator-led drill in the preceding 24 months. This wording describes the available evidence and does not claim that inaccessible organizational records contain no such planning artifacts.

The language of black swans, grey swans, dragon kings, and perfect storms has been used to describe rare and extreme events, but recent risk scholarship cautions that these terms must be defined around knowledge and predictability rather than used as rhetorical labels [1]. For this article, an event is "unmodeled" only when available pre-event artifacts show no explicit inclusion of the hazard constellation; "partially modeled" when an analogous hazard existed, but key scale, duration, or coupling parameters were absent; and "fully modeled" when scenario, SOP, and exercise evidence existed before the event. This artifact-based boundary prevents hindsight from turning every disruption into something that "should have been obvious". In reporting case results, the article uses "not evidenced in the reviewed record" for cases without publicly located planning artifacts and does not infer absence from inaccessible records.

Within Journal of Air Transport Management, this work is explicitly sociotechnical. A zero-day aviation emergency not only stresses aircraft, fuel systems, software, and airports; it also stresses information flows, decision rights, mutual-aid agreements, and the relation between work-as-imagined and work-as-done. Recent resilience literature describes resilience as a contextual capacity for dealing with unspecified and possibly unforeseen disruptions [2], while systematic reviews of resilience engineering indicators highlight top-management commitment, awareness, learning, and flexibility as recurring safety-management indicators [3].

Recent safety-science literature sharpens this framing. Resilience training research argues that crisis-response capability must be enacted and embedded in work rather than treated as a generic personal attribute [4]. Aviation research on hidden workarounds shows that frontline adaptation can improve safety, but can also produce ethical and organizational trade-offs when systems rely on unsupported improvisation [5]. Air-traffic-management research likewise frames mindful organizing as a team capability to anticipate, detect, contain, and recover from emerging problems [6]. These strands indicate that preparedness for zero day is not necessarily reflected in a longer scenario list, but in the capacity to adapt, which is measurable.

The study asks: What is the level of readiness of aviation organizations, and what capabilities seem to help them adapt in the context of zero-day emergencies? A qualitative multiple-case analysis of 10 aviation-relevant disruptions, including terror, volcanic ash, radiation fallout, unexplained aircraft loss, mechanical failure, pandemic shock, cyber-logistics disruption, extreme weather, and software failure, was conducted to answer the question. The contribution is a framework termed Scenario-Independent Readiness (SIR), which aims to support, but not supersede, conventional Safety Management System (SMS) controls. The article emphasizes the intersections of technology, people, and organizations and articulates zero-day preparedness as a safety-management capability rather than a forecast-accuracy problem. It emphasizes auditable evidence, conservative descriptive metrics, and peer-reviewed open-access support for each major claim area.

2. Literature Review

2.1. Model-Breaking Disruption and Epistemic Uncertainty

The core weakness of scenario-bound safety management is not that scenarios are useless. Scenarios are indispensable for hazard identification, training, and regulatory assurance. The weakness is that scenario catalogues can create a false sense of completeness when the next disruption is unfamiliar or when multiple familiar hazards combine in unfamiliar ways. Glette-Iversen and Aven's synthesis of black swans, grey swans, dragon kings, and perfect storms shows why definitional precision matters: predictability and knowledge differ across events, and the same event can be surprising for one actor but not another [1].

Critical-infrastructure resilience research makes the same point in practical terms. Mentges *et al.* define resilience as the ability of a system to deal with impacts of unspecific and possibly unforeseen disruptive events, and emphasize that resilience terminology varies widely unless bounded by context [2]. The relevance for aviation lies in the aviation business, which relies on closely integrated infrastructures of the aircraft, airport, air traffic management, digital notification networks, crew management, passenger traffic, fuel supply, and external emergency services. One disruption can lead to another subsystem for which a full diagnosis may be unavailable.

2.2. Resilience Engineering and Adaptive Capacity

Resilience engineering moves attention away from the prediction of all hazards to the capabilities that enable work to continue safely in the face of uncertainty. The systematic survey of the resilience engineering indicators identified a few indicators that appear in all high-risk industries, such as awareness, learning, flexibility, and top-management commitment [3]. These indicators are supported by evidence that is directly relevant to aviation SMS audits, such as drill records, decision logs, communication redundancy, and implementation of lessons learnt, and not only making a generic "we are ready" statement.

A second implication arises out of research on resilience training. Resilience should not be thought of as a general psychological trait, but rather as a situational capability, training critical-situation management should focus on that capability, as was found by Ketelaars *et al.* [4]. In a zero-day aviation emergency, this equates to an emergency drill where leadership is transferred, where teams establish a common operating picture, and by which mutual aid is called when there is insufficient time to comply with normal escalation protocols. Roud's research on collective improvisation in emergency response also points to a connection between joint training, organizational memory, interorganizational trust, communication, and information sharing and improvisational capability [7].

2.3. Aviation as a Sociotechnical Zero-Day Setting

While aviation is often described as being 'procedurally mature', maturity can sometimes make things brittle when there are differences between work-as-imagined and work-as-done. Steen *et al.* suggest that what adaptive capacity encompasses for pilots and safety organizations can differ, and this capability may be both a friend and a foe at the same time [5]. The implication for the present study is not that rules should be relaxed. Disciplined deviation must be planned, practiced, and tested in advance of the emergency, so that deviation will not be ad hoc, but in an emergency, there must be a safety intention.

A related issue is for air traffic management. Mezentseva *et al.* conceptualize mindful organizing as a collective ability to predict, identify, and manage existing issues and challenges, and bounce back from them, considering safety climate as mediator of the relationship between empowering leadership and mindful organizing [6]. To be ready for a zero-day, technical systems therefore must be in place, but so also must organizational conditions—teams should not be left in a vacuum, they should have authority to act on incomplete information and be held accountable in terms of the procedures they follow.

Recent aviation-disruption literature illustrates the domain breadth. COVID-19 literature reports an aviation shock that was thought to be historic in size and produced a substantial number of policy and operational research documents [8]. Network analyses of the pandemic indicate that aviation networks can lose demand while maintaining connectivity and that robust networks can come at a price in terms of efficiency and environmental impacts [9] [10]. The research areas of aviation cybersecurity focus on the growing dependence of aviation on digital technologies, regulatory requirements, threat detection, training for users, plans for incident response, and secure cyber-physical interactions [11] [12].

2.4. Common Operating Pictures, Linked Infrastructures, and Mutual Aid

Unlike several zero-day events, not all aviation-impacting events are aviationoriginating events. Airport infrastructure relies on interdependent critical infrastructure, including power systems, telecom, fuel distribution, and physical and cyber strategies. Piekert *et al.* report that adversarial activities in connected infrastructure can also result in impacts to the operation of the airport and that "early awareness" and collaboration in an airport operations center are still research needs to be addressed [13].

The common operating picture (COP) is the real-life link between ambiguous signals and joint action. Recent disaster-management research defines a COP as a shared display of information that improves situational awareness, decision-making, and coordination among stakeholders, and illustrates how digital twins can support a COP during response [14]. For aviation, the COP need not be a complex digital twin at first implementation; the audit question is whether critical feeds can be fused fast enough to support safe cross-functional decisions.

2.5. Synthesis and Conceptual Model

The literature supports a structured yet flexible model of scenario-independent readiness. Epistemic uncertainty requires explicit classification of what is known, what is partially known, and what is unmodeled [1]. Resilience engineering requires measurable indicators of awareness, learning, flexibility, and commitment [3]. Aviation research requires sensitivity to the tensions between compliance and adaptive work [5]. Emergency-response research shows that improvisation improves when it is trained, trusted, and connected across organizations [7]. Together, these ideas motivate Scenario-Independent Readiness (SIR): a capability set that is independent of any one hazard but auditable within existing SMS routines.

SIR is built around three capabilities. First, authority migration: the practiced ability to move decision rights to the person or team closest to the most reliable information while preserving accountability. Second, COP formation: the ability to assemble a shared, time-stamped operational picture quickly enough to guide safe decisions. Third, boundary-spanning mutual aid: the ability to activate pre-negotiated resources across airports, airlines, air navigation service providers, fuel suppliers, and public agencies without renegotiating roles during the incident.

3. Methods

3.1. Research Design

A qualitative multiple-case design was employed to investigate the processes by which aviation organisations prepare themselves and react in the event of disruption beyond the scope of what had been previously thought possible through their scenarios. This design is suitable because zero-day emergency response is context-dependent, multi-actor, and not easily ethically or practically reproduced in experimental form. The design was reinforced by transparent case-selection criteria, consistent coding rules, and conservative interpretation of descriptive statistics. Case-study rigor was sought via construct clarity, triangulation of public documentation, and through a documented audit trail, consistent with recent guidance of methodological rigor to enhance validity and reliability of case-study research [15]. The analysis is secondary-data based. No primary interview evidence is employed as the available evidence package has no verifiable interview transcript, nor any interview protocol, ethics approvals, or participant documentation. All claims thus covered are, therefore, restricted to structured secondary evidence and public documentation.

3.2. Case Selection and Definitions

Ten incidents were selected because they had direct implications for aviation operations, involved a period of at least 12 hours, caused losses of more than USD 100 million, or were said at the time to be unprecedented or unusually disruptive to the aviation organizations involved. The sample was intentionally selected for maximum variation and not for statistical representativeness, including terrorism, natural hazard, technological disaster, aircraft-accident response, unexplained loss, pandemic onset, software failure, cyber-logistics disruption, mechanical failure, and extreme weather. Appendix A identifies the organizational unit assessed in each disruption and shows how each case met the inclusion criteria.

Prior-modeling status was coded from publicly accessible pre-event artifacts. "Not evidenced in the reviewed record" was assigned when the retained public record contained no hazard-specific scenario, SOP, or regulator- or operator-led drill from the preceding 24 months; it does not prove organizational absence. "Partially modeled" required a similar hazard in risk registers or tabletop materials but no evidence that critical scale, duration, cascading, or interdependency parameters had been exercised. "Fully modeled" required an explicit scenario, relevant SOPs, and a documented exercise or activation within the preceding 24 months. This evidence-bounded definition distinguishes zero-day from partially expected hazards while preserving uncertainty about inaccessible records.

3.3. Data Sources and Coding

Evidence included a structured secondary data source consisting of official after-action reports, public regulatory documents, aviation-sector summaries, accident/incident documentation, public operational reports, and congressional or governmental records where applicable. The retained record included the 9/11 Commission, NTSB, FAA and U.S. Department of Transportation, EUROCONTROL, ICAO and ATSB, WHO and CDC, IAEA and Japanese government records, and CISA and FBI materials. Searches combined the incident name and year with aviation, after-action, emergency plan, exercise, SOP, regulator, operator, disruption, and response. Proprietary, internal, paywalled, or inaccessible documents were not treated as absent. Each case was represented by standardized fields covering event type, location, prior-modeling evidence, response gaps, consequences, and post-event improvements.

Open coding was conducted on qualitative fields to assess gaps in response and improvements post-event. The retained materials do not identify the number or composition of independently double-coded cases or text units, the full codes included in the calculation, a coder-by-code agreement table, or how disagreements were reconciled. Cohen's kappa = 0.84 therefore cannot be independently assessed or replicated and is not retained as a reliability result. In qualitative research, intercoder reliability is a debated but useful transparency device for checking coding consistency [16]. A future replication should register its coding unit, double-code all cases or a named subset, report the full agreement table and code prevalence, and document reconciliation before calculating kappa.

The original preparedness ratings were intentionally coarse. "Low" indicated that relevant plans, exercises, and cross-functional coordination evidence were absent or weak. "Moderate" indicated some prior exercise, scenario coverage, or mobilization pathway that could be adapted during response. No case was rated "High" because the dataset did not include independent regulator-certified readiness scores or sufficient internal evidence to support a high-confidence rating. Because those indicators overlap with prior-modeling evidence, the ratings are not retained in the current analysis and no comparison between the two constructs is reported. Table 1 summarizes the rubric used to classify prior-modeling evidence.

Table 1. Coding rubric for prior-modeling evidence.

Coding dimension	Classification rule	Primary evidence
Not evidenced in reviewed record	No hazard-specific scenario, SOP, or regulator/operator drill was located in the reviewed public record for the preceding 24 months; this does not establish absence from inaccessible records.	Public pre-event scenario catalogues, SOP repositories, exercise logs, regulator/operator records, and official repositories where accessible.
Partially modeled	An analogous hazard appeared in the reviewed risk register, tabletop, or plan, but critical scale, duration, coupling, or cascading parameters were not evidenced as exercised.	Risk registers, tabletop materials, emergency-plan excerpts, and after-action documentation describing pre-event planning scope.
Fully modeled	The reviewed record evidenced an explicit scenario, hazard-specific SOP, and documented exercise or activation in the preceding 24 months.	Exercise records, SOPs, activation records, and regulator/operator documentation.

Note. The rubric was applied before outcome interpretation to reduce hindsight bias. Categories are deliberately coarse because the evidence base is secondary and varies by case.

3.4. Analysis and Safeguards

Descriptive statistics were calculated from the structured fields. Prior-modeling coverage was reported as the percentage of cases classified as not evidenced in the reviewed record, partially modeled, and fully modeled. Response gaps were calculated at the case level. Outcome severity was summarized by deaths directly caused by the aviation-relevant incident, by minimum direct economic loss in 2024 USD when available, and by passenger delay hours. Some losses are censored with greater-than signs, and the sample is small, which means that the ratios are only descriptive signals and not inferential estimates.

Efforts to ensure that case-by-case coding notes would be utilized, exclusion of unsupported primary interview claims, avoidance of post hoc reclassification by the coder, and trustworthiness of a set classification rubric. In this case, no third-party adapted figures are included, and the argument is advanced by use of original tables and text, thus avoiding reliance on third-party copyright in the artwork that can be included in the editable submission package.

4. Results

4.1. Case Profile and Modeling Coverage

Table 2 profiles the ten incidents. Hazard-specific planning was not evidenced in the reviewed record for five cases; two cases were partially modeled and three were fully modeled. This distribution shows that model-breaking conditions were not confined to one threat family. The five 'not evidenced' cases involved terrorism, radiation fallout, unexplained aircraft loss, pandemic onset, and cyber-logistics disruption. Partially modeled cases involved volcanic ash and a national NOTAM software outage. Fully modeled cases involved aircraft-accident response, mechanical-failure response, and extreme winter-weather operations. These labels describe available public evidence rather than the total contents of organizational records.

Table 2. Case profile, prior-modeling evidence, and severity indicators.

No.	Incident (year)	Hazard type	Prior-modeling evidence	Fatalities*	Economic loss†/delay hours‡
1	September 11 attacks (2001)	Terrorism	Not evidenced in reviewed record	2977	>USD 40.0B/2.60M h
2	Eyjafjallajökull ash disruption (2010)	Volcanic ash	Partially modeled	0	USD 4.70B/1.80M h
3	Fukushima fallout aviation disruption (2011)	Radiation/technological disaster	Not evidenced in reviewed record	0	USD 2.20B/0.30M h
4	Asiana Airlines Flight 214 response (2013)	Aircraft accident response	Fully modeled	3	USD 0.30B/0.18M h
5	Malaysia Airlines MH370 (2014)	Unexplained aircraft loss	Not evidenced in reviewed record	239	>USD 0.28B/0.42M h
6	Southwest Airlines Flight 1380 (2018)	Mechanical failure response	Fully modeled	1	USD 0.10B/0.07M h

Continued

7	COVID-19 onset phase (2020)	Pandemic/system shock	Not evidenced in reviewed record	Not calculated	USD 14.0B/2.00M h
8	Colonial Pipeline aviation fuel spillover (2021)	Cyber-logistics disruption	Not evidenced in reviewed record	0	USD 4.40B/0.25M h
9	Texas winter storm Uri aviation disruption (2021)	Extreme weather	Fully modeled	0	USD 1.70B/0.55M h
10	FAA NOTAM outage (2023)	Software/information failure	Partially modeled	0	USD 0.40B/0.19M h

Note: *Fatalities directly attributable to the aviation-relevant incident. †Lower-bound 2024 USD where estimates were reported as greater-than values. ‡Passenger-delay hours are retained from the structured dataset and should be read descriptively.

4.2. Descriptive Severity

Preparedness was not retained as a separate rating because it overlapped with prior-modeling evidence. Table 3 reports lower-bound mean losses and mean delay hours by prior-modeling group while explicitly noting censored values and outliers. Cases for which planning was not evidenced in the reviewed record include the September 11 and COVID-19 onset phases; their five-case lower-bound total is USD 60.88B and mean is USD 12.18B. Delay-hour patterns are not monotonic, and some cases were more consequential for safety or uncertainty without producing the largest measured delay burden. These are descriptive severity patterns, not preparedness comparisons.

However, the principal result is not an accurate loss multiplier. The defensible finding was that cases classified in the original dataset as unmodeled—reported here as "not evidenced in the reviewed record"—included the worst lower-bound tail results and revealed similar organizational deficiencies. This pattern is descriptive, not causal or inferential. The analysis encourages analytic generalization: model coverage can be useful but not enough, so adaptive capacity should be audited directly.

Table 3. Prior-modeling evidence and descriptive severity metrics.

Prior-modeling evidence	Cases (n)	Lower-bound mean loss (USD B)	Mean delay (M h)
Fully modeled	3	0.70	0.27
Partially modeled	2	2.55	1.00
Not evidenced in reviewed record	5	12.18*	1.11

Note: *Lower-bound mean uses USD 40B for September 11 and USD 0.28B for MH370, although the dataset marks both as greater-than values. Values are descriptive and not inferential.

4.3. Response-Gap Prevalence

Four themes for gaps in response were commonalities among all cases: lack of real-time situational awareness, fixed command structures, one-point logistical response, and slow interagency coordination. There was a situational-awareness gap in eight of 10 cases; command rigidity in seven; logistical dependency in six; and interagency friction in five. These gaps frequently occur together and align with the SIR focus on COP latency, authority migration, and mutual aid.

The gap profile also shows why scenario-independent readiness is not simply a technology problem. Action is not taken from a dashboard without having decision rights, resources cannot be mobilized from a mutual aid agreement lacking current contacts and exercises, and a trained leader cannot improvise the entire operation without a shared picture of the operating situation. Thus, the evidence suggests that readiness is a sociotechnical capability integrating people, organizations, information, and material resources. Table 4 summarizes the recurrent response gaps and their SIR interpretations.

Table 4. Recurrent response gaps and SIR interpretation.

Gap theme	Cases flagged	Operational meaning	SIR capability
Weak situational awareness	8 of 10	Decision makers lacked a fused, timely view of aircraft, infrastructure, staffing, weather, or external dependencies.	Common-operating-picture formation
Rigid command structures	7 of 10	Decision rights were slow to move to the team or agency closest to reliable information.	Authority migration
Single-point logistical dependencies	6 of 10	Fuel, software, ground support, or communications depended on fragile nodes or suppliers.	Mutual aid and redundancy
Slow interagency coordination	5 of 10	External agencies and operators had to negotiate roles during the event instead of activating rehearsed protocols.	Boundary-spanning coordination

4.4. Scenario-Independent Readiness Indicators

The cross-case synthesis generated three SIR indicators as capability targets for audit and future testing; it did not test whether anchor presence was associated with lower case-level impact. The first is authority-migration readiness, evidenced by semi-annual drills in which decision rights are explicitly transferred under ambiguous conditions and assessed through decision-latency and hand-off records. The second is COP spin-up capability, evidenced by a time-stamped dashboard or manual fusion process that can assemble minimum viable situational awareness within 60 minutes of incident onset. The third is mutual-aid activation, evidenced by pre-signed agreements that can move gates, staff, fuel, equipment, data, or public-agency support within two hours of request.

The indicators are intentionally audit-ready. They can be checked by reviewing drill logs, decision records, dashboard timestamps, exercise injects, mutual-aid memoranda, and after-action implementation evidence. They are not presented as universal thresholds validated for every airport or airline size. They are proposed as initial benchmarks for pilot audits and simulation-based refinement. Table 5 presents the audit-ready SIR checklist for SMS integration.

Table 5. Scenario-independent readiness checklist for SMS integration.

Incident phase	SIR capability	Benchmark	Audit evidence	Primary owner
Preparedness	Authority migration	Live or tabletop drill at least every 6 months	Drill plan, observer scores, decision-latency log, corrective-action register	Safety and operations leadership
Onset (0 - 60 min)	Common operating picture	Minimum viable COP within 60 minutes	Timestamped dashboard or manual fusion log; data-source checklist; failover evidence	Integrated operations center
Response (1 - 24 h)	Boundary-spanning mutual aid	Resource-sharing activation within 2 hours	Signed MOU, contact tree, exercise activation record, legal escalation path	Crisis manager and legal counsel
Recovery	Learning and update	Joint review within 7 days	After-action report, revised SOPs, owner/date for corrective actions	Joint airline-airport-ANSP task force

5. Discussion

5.1. What the Findings Add to Journal of Air Transport Management

The findings align with safety-science work that treats safety as an interaction among technical, organizational, and human systems rather than a property of isolated components. The results do not imply that scenario-specific planning should be reduced. Instead, they show why scenario-specific planning should be paired with scenario-independent capability testing. A model can identify known hazards, but it cannot guarantee readiness for unknown coupling, unfamiliar scale, or time pressure.

This contribution is distinct from a conventional aviation disruption catalogue. The unit of analysis is not the hazard type but the named organization's ability to adapt safely when the hazard type is not sufficient for decision-making. Appendix A distinguishes sector-wide shocks from airline-, airport-, and ANSP-specific responses. By using pre-event artifacts to classify prior-modeling evidence, the analysis avoids a common hindsight problem: treating post-event explanations as if they were available before the event. This improves conceptual clarity around not-evidenced, partially modeled, and fully modeled conditions.

The study also addresses the compliance-adaptation dichotomy, which can be seen in the recent studies of the capacity of aviation to react to various threats [5]. SIR does not demand improvisation on operators' part when it comes to safety governance. It seeks to have them seek regulations and controls for improvisation, to enact bounded authority migration, to time-stamp sense-making, and to pre-negotiate boundary crossing. This is what a structured flexibility actually translates to.

5.2. Implications for Airlines, Airports, and Air Navigation Service Providers

Changing SIR to auditable evidence is a priority for an airline or airport. Existing SOPs should be supplemented with exercises incorporating ambiguous injects that do not reward unsafe freelancing. The goal is to see if decision rights can flow quickly while maintaining transparency about who acts, what evidence supports the action, how alternatives are considered, and how safety risk is reduced.

Perhaps the most direct improvement for integrated operations centers is a minimum level of a COP. Operators can begin with a simple data-fusion checklist and then move on to purchase more advanced platforms. Aircraft and passenger positions, legality restrictions for the crew, fuel, gate, necessary NOTAMs, weather and infrastructure limitations, public-agency contacts, and a feed confidence rating should be included in the required first-hour view. A degraded COP should be available, as cyber/network disruption may compromise the systems that are supposed to assist the response. SIR provides an additional tool for air navigation service providers and regulators in conjunction with the current SMS audits. Auditors can ask if an emergency plan exists or when authority-migration was last exercised, how long COP formation took, whether or not mutual-aid was tested, and what corrective actions were closed after the last cross-organizational drill.

5.3. Implications for Cyber-Physical and Linked-Infrastructure Risk

Cyber-physical and/or linked-infrastructure disruption is becoming a major concern for the aviation industry. Aviation cybersecurity efforts also cite regulatory compliance, threat detection, user training, incident response planning, encryption, and protecting integrated aviation systems as some of the fundamental priorities [11] [12]. The utility failure incidents represented in this dataset highlight the need to consider cyber and software incidents as operational safety issues rather than merely information-security issues.

Other independent infrastructure research bears this out. Airports rely on external systems that might be one of the first to experience complications or issues before impacting an airport's operations center [13]. As a result, SIR includes mutual-aid arrangements and contact trees from external partners next to the internal dashboards. Without the ability to access timely information or resources from all partners involved in the COP, such as fuel, power, telecommunications, law enforcement, public health, and emergency management, a technically sophisticated COP is incomplete. A recent example of this is the 2024 global IT outage caused by a software failure, which reignited the urgency for planning for the unexpected in this area across vital infrastructures [17]. While this event is not included within the 2001-2024 case sample upon which this study was based, this event reinforces the relevance of a cross-infrastructure capability approach to scenario-independent readiness.

5.4. Limits of the Evidence

There are four limitations of the study. First, the 10-case sample is too small for analytic generalization to be used for estimating population-level probabilities or causal effects. Second, public records do not reveal all proprietary or internal planning evidence, and the retained audit trail lacks the double-coding details needed to assess or replicate the previously reported kappa. Third, consequence data in some cases vary, and greater-than values are censored. Fourth, there may be adaptations and workarounds that are informal and not documented in secondary sources. The strength of the study is in the transparency of the cross-case patterning and in an audit framework that can then be tested, rather than in accurate quantitative prediction.

Further research is needed to simulate, exercise, and independently audit scenario-independent readiness thresholds in airport settings. Agent-based and system-dynamics models could be used to vary common operating picture latency, the speed at which authority migrates during disruption, and the density of mutual-aid resources in order to identify nonlinear breakpoints in airport emergency response. Field studies could also examine how learning effects improve readiness while guarding against the unsafe normalization of deviation. Comparative studies across other safety-critical sectors, including maritime systems, rail systems, emergency medical services, and energy systems, could help assess whether the proposed thresholds are specific to aviation or broadly applicable across critical infrastructures. For air transport management scholarship and practice, the central contribution is the practical value of scenario-independent readiness as a management lens for airports, airlines, regulators, and emergency-planning stakeholders facing disruptions that fall outside existing scenario catalogues.

6. Conclusions

Zero-day aviation emergencies reveal the limitations of named hazards and scenario catalogues for safety. A recurring explanation for vulnerability across the 10 aviation-relevant disruptions was a lack of real-time sense-making, flexible decision authority, logistical redundancy, and rehearsed boundary-spanning coordination. These are capabilities that can still be applied no matter how familiar the hazard is or whether disruptions combine in new ways.

Using scenario-independent readiness, this insight is converted to an audit-ready complement to existing SMS practice. Operators gain concrete evidence to test and develop adaptive capacity with semi-annual authority-migration drills, two-hour mutual-aid activation, and seven-day joint learning reviews. The thresholds are only intended as an initial "readiness audit" for pilot implementation and not universal indicators of readiness. The larger implication is clear: aviation resilience depends not only on forecasting the next disruption, but on organizing people, technology, and institutions so that they can adapt safely when the forecast fails.

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Data Availability

Where appropriate, the structured secondary dataset and coding workbook will be submitted to an appropriate repository before final submission. Until deposited, they are available from the corresponding author on reasonable request. No primary interview data are used in this manuscript.

Declaration of Generative AI and AI-Assisted Technologies in the Manuscript Preparation Process

The author used AI tools in the development and editing of the article and reviewed the final content.

Author Contributions

I am the sole author of this manuscript and was responsible for the conceptualization, research, methodology, analysis, manuscript preparation, review, editing, and final approval of the submitted work. As this is a single-author manuscript, an additional authorship contribution statement is not applicable.

Conflicts of Interest

The author did not have any competing financial interests or personal relationships that could appear to have influenced this work.

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Appendix A. Case Selection and Organizational Unit of Analysis

The case was the adaptive response of the organizational unit named below during a disruption, rather than the hazard in the abstract. Cases entered the maximum-variation sample when they directly affected aviation operations and met at least one materiality screen: disruption of 12 hours or more, reported economic consequences above USD 100 million, or contemporaneous characterization as unprecedented or unusually disruptive. Economic values are the lower-bound figures retained in **Table 2**; they are used to document selection, not to infer population effects.

Repository protocol. The retained source record drew on publicly accessible official and sector repositories, including the 9/11 Commission, NTSB, FAA and U.S. Department of Transportation, EUROCONTROL, ICAO and ATSB, WHO and CDC, IAEA and Japanese government records, and CISA and FBI materials. Searches combined incident names and years with aviation, after-action, emergency plan, exercise, SOP, regulator, operator, disruption, and response. Proprietary, internal, paywalled, or otherwise inaccessible records were not interpreted as absent. When no public planning artifact was located, the case was classified as "not evidenced in the reviewed record". **Table A1** summarizes the case-selection evidence, assessed organizational units, shock levels, and prior-planning evidence.

Table A1. Case selection and organizational unit of analysis.

Case	Organizational unit assessed	Shock level	Selection evidence	Prior-planning evidence
September 11 attacks (2001)	U.S. civil aviation system, centered on FAA, airlines, and airports	Sector-wide	Direct national aviation disruption; lower-bound loss > USD 40.0B	Not evidenced in reviewed record
Eyjafjallajökull ash disruption (2010)	European airspace-management network, airlines, and airports	Sector-wide	Direct multi-day aviation disruption; loss USD 4.70B	Partially modeled
Fukushima fallout aviation disruption (2011)	Japanese aviation operators and public authorities managing route and airport exposure	Sector-wide	Direct aviation disruption; loss USD 2.20B	Not evidenced in reviewed record
Asiana Airlines Flight 214 response (2013)	Asiana flight operation and San Francisco airport emergency response	Airline- and airport-specific	Direct aircraft-accident response; loss USD 0.30B	Fully modeled
Malaysia Airlines MH370 (2014)	Malaysia Airlines and the multinational air-navigation/search coordination network	Airline- and ANSP-centered	Direct unexplained aircraft loss; lower-bound loss > USD 0.28B	Not evidenced in reviewed record
Southwest Airlines Flight 1380 (2018)	Southwest flight operation and associated regulator-led response	Airline-specific	Direct mechanical-failure response; rounded lower-bound consequence USD 0.10B with continuing inspection and remediation	Fully modeled
COVID-19 onset phase (2020)	Global civil aviation network of airlines, airports, and regulators	Sector-wide	Direct prolonged aviation system shock; loss USD 14.0B	Not evidenced in reviewed record
Colonial Pipeline aviation fuel spillover (2021)	U.S. East Coast airport-airline fuel logistics network	Sector-wide linked infrastructure	Direct aviation-fuel disruption; loss USD 4.40B	Not evidenced in reviewed record
Texas winter storm Uri aviation disruption (2021)	Texas regional airport, airline, and airspace operations	Sector-wide regional	Direct extreme-weather aviation disruption; loss USD 1.70B	Fully modeled
FAA NOTAM outage (2023)	FAA NOTAM service and dependent U.S. operators	ANSP-specific with sector-wide effect	Direct national aviation information outage; loss USD 0.40B	Partially modeled