

Navigating Turbulence: Adaptive Governance and Resilience in Air Transport Systems

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Abstract:

The COVID-19 pandemic has been one of the most disruptive events in the history of global aviation, exposing both structural vulnerabilities and the limits of adaptability within airport management systems. This study examines how the Bucharest Airports National Company (CNAB) responded to the crisis as part of the European air transport network, emphasizing the mechanisms through which resilience developed via organizational learning, coordination, and adaptive governance.

Using a mixed-methods design, the research combines quantitative analysis with qualitative document review to reveal how operational, financial, and managerial factors interacted to shape CNAB's adaptive response during the pandemic.

Findings indicate that recovery was supported not only by external regulatory frameworks but also by internal mechanisms, including decentralized decision-making, digital integration, and continuous feedback between operational and administrative subsystems. Econometric results highlight strong short- and long-term interdependencies between passenger traffic, aircraft movements, and digitalization, while the SRI positions CNAB as a highly adaptive node within Central and Eastern Europe's aviation network.

The study concludes that resilience in aviation arises from the dynamic interaction of human, technological, and institutional subsystems. CNAB's transition from reactive crisis management to adaptive governance offers a transferable framework for assessing resilience across other critical infrastructure sectors.

Keywords: resilience, adaptive governance, air transport, econometric modeling, digital transformation, COVID-19, complex systems

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JEL Classification: M12, R41, L93, H12

Introduction

The COVID-19 pandemic placed extraordinary pressure on the global aviation industry, transforming it into a real-time experiment in crisis management and adaptation. Within weeks, international passenger traffic across Europe dropped by more than eighty-five percent, while airport operations and logistical networks struggled with severe disruptions and uncertainty (Eurocontrol, 2021; Suk & Kim, 2021). These abrupt, large-scale shifts exposed the fragility of aviation systems, as designers had built them for stability and efficiency rather than for sustained turbulence.

Airport leaders faced a challenge that extended far beyond maintaining operations. They needed to protect passenger safety, preserve financial balance, and coordinate staff in an environment where predictability had nearly vanished. In this context, the Bucharest Airports National Company (CNAB) illustrates how a vital public infrastructure organization can reorganize its internal processes and sustain performance during a global systemic shock.

The pandemic prompted both researchers and practitioners to reassess how large socio-technical systems respond to high stress. It revealed the limits of traditional hierarchical management and underscored the growing importance of adaptability, collaboration, and distributed intelligence in maintaining coherence. Complexity science and organizational learning theory describe such institutions as Complex Adaptive Systems (CAS)—networks of interdependent agents that adjust and learn through feedback loops (Almécija, 2022; Celo & Lehrer, 2025; Cosens et al., 2021). In these systems, resilience arises not from control but from the capacity to reorganize relationships, absorb shocks, and create new modes of functioning. CNAB's evolution during the pandemic demonstrates this dynamic balance between adaptation, coordination, and institutional learning.

This study analyzes how CNAB responded to the pandemic's disruption and identifies the adaptive mechanisms that supported its recovery and sustained performance. It evaluates which measures facilitated the normalization of air traffic, how operational and organizational subsystems interacted, and how adaptive governance contributed to institutional resilience. Two hypotheses guide the analysis: (H1) air-traffic normalization depends not only on external regulations but also on the adaptive capacity of teams operating under stress, and (H2) CNAB's recovery measures become more effective when inter-team coordination and feedback loops allow rapid decision adjustments. Together, these hypotheses conceptualize resilience as a continuous process that links human behavior, decision-making structures, and systemic coherence.

These two primary hypotheses are further operationalized into two sub-hypotheses at the empirical level. H3 examines whether shared institutional learning drives convergent recovery patterns among Central and Eastern European airports. H4 tests whether systemic resilience emerges from the balanced interaction of operational, financial, and organizational adaptation mechanisms. H3 and H4 are not conceptual revisions of H1–H2 but their empirical refinements, developed to match the multi-level analytical structure of the study.

The research combines quantitative data with qualitative insights to capture both structural and behavioral dimensions of adaptation. It introduces the Synthetic Resilience Index (SRI)—a composite indicator that integrates operational, financial, and organizational data to measure systemic adaptability. By merging econometric modeling with interpretive analysis grounded in complexity theory, the study connects macro-level recovery trends with micro-level learning and coordination processes. This dual

approach offers a comprehensive perspective on adaptive governance in aviation and contributes to ongoing discussions on performance management in high-stress environments. It also addresses recent calls for interdisciplinary frameworks that link resilience metrics with theories of adaptive behavior (OECD, 2023; Eurocontrol, 2023; Tang et al., 2023).

Methodologically, the study adopts a mixed methods design that combines descriptive statistics, ARDL and VAR econometric models, comparative benchmarking of Central and Eastern European airports, and qualitative document analysis. This triangulation reveals nonlinear interactions among recovery dynamics, digital transformation, and decision-making processes. The quantitative data come from CNAB annual reports (2019–2022), Eurocontrol datasets, and ICAO’s Aviation Resilience and Recovery Report (2022). The qualitative component draws from government and European Commission documents as well as CNAB’s internal communications, ensuring methodological transparency and interpretive depth.

The paper follows a clear structure. After this introduction, the literature review examines recent research on adaptive management and systemic resilience in aviation. The methodology section details the analytical framework and data sources. The results section presents CNAB’s adaptive trajectory and regional comparisons. The discussion connects these findings to theories of complexity leadership and organizational learning. Finally, the conclusion synthesizes the main insights and provides policy recommendations for resilience governance in critical infrastructure sectors.

Despite its comprehensive coverage, the study recognizes certain limitations. Restricted access to internal operational data limited a deeper exploration of informal learning mechanisms, and the exceptional nature of the COVID-19 context constrains generalization. Nevertheless, these boundaries emphasize the need for continued interdisciplinary research on adaptive performance in high-pressure environments. Ultimately, CNAB’s experience shows that airport resilience depends not only on infrastructure or regulatory frameworks but also on the ability of human, technological, and institutional subsystems to learn, coordinate, and adapt in the face of uncertainty. CNAB’s adaptive trajectory thus demonstrates that systemic resilience in critical infrastructure depends not only on structural resources but on the capacity to convert disruption into institutional learning — a contribution with direct implications for transport policy design and governance reform.

This study contributes to the transport policy literature by examining how adaptive governance mechanisms shape systemic resilience in air transport systems under prolonged disruption. By combining econometric analysis with an institutional perspective, the paper advances evidence-based insights relevant for transport policy design and governance reform.

2. Literature Review

The concept of adaptability has regained central importance in management and organizational research, particularly following the COVID-19 pandemic, which exposed the fragility of traditional planning systems. Earlier theories, shaped by Argyris and Schön (1974) and later by Senge (1990), understood learning mainly as an individual cognitive process. More recent research, however, interprets adaptability as a collective and systemic capacity that emerges from continuous interactions among people, technologies, and institutions (Guo, 2022; Avery, 2025). Within this framework, organizations operate as Complex Adaptive Systems (CAS)—dynamic networks capable of self-organization, feedback-driven learning, and nonlinear adjustment to external shocks (Walker et al., 2024). The pandemic accelerated this transition by revealing the limitations of linear management models and highlighting the need for agility, experimentation, and ongoing learning.

Current studies on adaptive management in high-stress contexts emphasize the importance of modular flexibility and distributed coordination as key drivers of organizational resilience. Schulze & Pinkow (2020) argue that effective leadership in adaptive systems depends less on direct control and more on enabling conditions that foster emergence and sensemaking. Aghion et al. (2021) demonstrate that decentralized organizations perform better during crises, as distributed intelligence facilitates faster information flow and encourages innovation. In public management, Horton et al. (2022) describe resilience as the outcome of reflexive learning—the capacity to transform failure into a mechanism for redesign and renewal. These insights are particularly relevant to aviation, where operational interdependence, strict safety standards, and cross-border coordination continuously test the balance between control and adaptability.

The concept of systemic resilience has also evolved, shifting beyond risk mitigation to a multidimensional understanding that encompasses operational, financial, technological, and social dimensions. Hanif & Pierotti (2025) define resilience as an ongoing process through which organizations absorb shocks, sustain performance, and reconfigure underlying structures. Institutional frameworks developed by the OECD (2023) and the EU-NATO Task Force on Resilience of Critical Infrastructure Report (2023) extend this perspective to critical infrastructures, viewing resilience as both a governance principle and an organizational practice that links technology, human cognition, and policy. In aviation, Eurocontrol (2022) and ICAO (2022) identify digital transformation, interoperable data systems, and Airport Collaborative Decision-Making (A-CDM) as central enablers of adaptive governance. Collectively, these studies suggest that resilience in aviation represents more than a technical capability—it is a social and institutional process grounded in trust, coordination, and feedback across multiple layers of governance.

Recent empirical research reinforces these theoretical insights. Khare (2024) examined India's aviation network and found that digital coordination platforms reduced recovery time by nearly thirty percent. Horton et al. (2022) observed that transparent communication and inter-agency collaboration strengthen adaptive capacity in Latin American airports. In Europe, Barbera et al. (2023) and Senivongse (2023) demonstrated that financial resilience improves when governance frameworks allow rapid reallocation of resources and flexibility in decision-making. Similarly, Christianson & Barton (2021) highlighted that post-pandemic recovery depends on technological innovation combined with cultural adaptability—particularly the ability of teams to align mental models and engage in collective sensemaking.

Another line of research explores the governance of global coordination systems. Within transport research, adaptive governance has increasingly been discussed as a policy response to systemic uncertainty, rather than as a purely organizational or managerial construct. The pandemic highlighted persistent fragmentation between national regulations and regional aviation policies, resulting in inefficiencies in traffic recovery (Tönurist & Orlik, 2025; Eurocontrol, 2022). Cosens et al. (2021) argue that governance under uncertainty requires adaptive architectures connected through feedback loops rather than hierarchical command. This approach aligns with the emerging field of adaptive governance, which conceptualizes institutions as co-evolving systems capable of reflexive learning and self-adjustment (Cosens et al., 2021; Schulze & Pinkow, 2020). In aviation, adaptive governance is manifested through digital coordination hubs, standardized data protocols, and crisis-response platforms that integrate public and private stakeholders into shared decision-making environments.

A foundational contribution to this theoretical landscape comes from panarchy theory (Holling & Gunderson, 2002), which models adaptive cycles as nested, non-linear processes of growth, collapse, and reorganization. Rather than treating crises as purely destructive events, this framework

conceptualizes systemic disruptions as windows of reorganization that enable structural renewal. Recent scholarship confirms the continuing relevance of this perspective: Mirzabeiki & Aitken (2023) apply panarchy theory empirically to demonstrate how organizations navigate adaptive cycles of resource release and reorganization in response to major environmental disruptions — a dynamic directly analogous to CNAB's transition from reactive crisis management to structural renewal during the COVID-19 period. Similarly, Guo et al. (2023) apply network resilience theory directly to airport systems during the pandemic, demonstrating through a Comprehensive Resilience Assessment (CRA) model — validated across Chinese, European, and US airport networks — that stringency policy responsiveness rather than network scale or infrastructure size determines both the speed and quality of post-crisis reorganization in aviation systems.

A complementary theoretical perspective is provided by Ostrom's (1990) polycentric governance model, which posits that resilient systems benefit from overlapping, self-organizing decision centers rather than centralized hierarchical control. Recent scholarship has extended this argument to contemporary governance challenges: Behnke (2024) demonstrates that polycentric governance functions as a structural resilience resource, whereby coordinated decentrality and flexible adaptation enable systems to absorb prolonged turbulence more effectively than centralized command structures. Gatto (2022) further extends Ostrom's framework to infrastructure and resource systems, showing that resilience is enhanced when overlapping governance jurisdictions enable distributed, adaptive, and self-organizing responses. CNAB's semi-public governance structure — which enabled rapid policy coordination between airport management, the Ministry of Transport, and European regulatory bodies — illustrates precisely this mechanism in the context of critical transport infrastructure.

Together, panarchy theory and polycentric governance offer a structural complement to the Complex Adaptive Systems (CAS) perspective adopted in this study. Where CAS theory explains how organizations self-organize and learn through feedback, panarchy illuminates why collapse phases are necessary preconditions for adaptive renewal, and polycentric governance explains which institutional configurations best sustain adaptive capacity under stress. Grounding CNAB's experience within this broader, theoretically robust tradition strengthens the interpretive framework of the study and responds to recent calls for interdisciplinary approaches to resilience research in aviation and critical infrastructure governance (Schulze & Pinkow, 2020; Cosens et al., 2021; Behnke, 2024).

Despite notable theoretical and empirical progress, significant research gaps remain. Most studies still focus on technological and infrastructural mechanisms of recovery while overlooking the behavioral and cognitive dimensions that explain how organizations learn under stress. Few analyses combine econometric modeling with qualitative interpretation to capture both the structural and human dynamics of adaptation. This study addresses that gap by examining the Bucharest Airports National Company (CNAB) as a complex learning system in which coordination, feedback, and decision flexibility interact to sustain systemic performance. Through a mixed-methods design and the development of a Synthetic Resilience Index (SRI), it proposes a framework for understanding how adaptability emerges within airport organizations during global crises. The findings provide empirical evidence from a major Central and Eastern European hub, contributing to broader debates on resilience, learning, and adaptive performance in complex systems.

3. Empirical Context and Research Design

The COVID-19 pandemic provided an exceptional empirical setting for observing how complex socio-technical systems adapt to prolonged disruption. Among global industries, aviation was

particularly exposed, as its interdependence between technology, regulation, and human coordination left little room for error (Suk & Kim, 2021; Sun et al., 2022).

The Bucharest Airports National Company (CNAB), managing Romania’s two main airports—Henri Coandă International (Otopeni) and Aurel Vlaicu International (Băneasa)—represents a hybrid organization operating between public governance and market-driven performance. Before the pandemic, CNAB served over 14.7 million passengers annually (CNAB, 2020–2022). In 2020, traffic declined by nearly 80%, and revenues contracted significantly (Romanian Ministry of Transport and Infrastructure, 2021). Despite these shocks, CNAB maintained essential operations such as humanitarian and cargo flights, illustrating the adaptive behaviors and institutional flexibility that underpin resilience in Complex Adaptive Systems (CAS).

3.1 Research Objectives and Conceptual Orientation

The research aims to investigate how the Bucharest Airports National Company (CNAB) modified its operational, decision-making, and governance frameworks in response to the systemic disruptions caused by the COVID-19 pandemic. It primarily seeks to identify the adaptive strategies that enabled CNAB to sustain both operational and financial stability during the crisis. Additionally, the study evaluates the internal processes that facilitated learning and organizational resilience. A key aspect focuses on understanding how feedback loops—dynamic exchanges of information and adjustments within the system—helped preserve coherence amid uncertainty. The research also compares CNAB’s recovery path with that of other regional airports, placing its experience within a wider European context of adaptive performance.

The study is rooted in the Complex Adaptive Systems (CAS) framework, which conceptualizes resilience as an emergent, nonlinear process rather than a fixed state. In this view, resilience develops through ongoing cycles of learning, coordination, and structural change that help systems withstand shocks while maintaining their functions. This perspective echoes recent research highlighting organizations' adaptive ability to evolve amid volatility and stress (Westover, 2025; Akpinar & Çaylan, 2022).

3.2 Mixed-Methods Research Design

This research utilizes a mixed methods approach to gather both quantitative data and contextual insights into adaptive behavior and resilience at CNAB. The quantitative part involves descriptive statistics, econometric techniques such as ARDL and VAR models, benchmarking comparisons, and creating a composite indicator (SRI). Meanwhile, the qualitative part focuses on analyzing documents and conducting thematic benchmarking to explain how adaptive governance and team coordination contributed to resilience.

Table 1. Quantitative Methods

Method	Purpose	Data Source	Analysis & Formula	Linked Hypothesis	Contribution
Descriptive Statistics	Summarize and visualize PAX, MOV, and revenue trends pre/post	CNAB reports (2019–2022),	Recovery % = $100 \times (\text{Post-crisis metric} / \text{2019 baseline})$. Trend: Δt ,	H1 Demonstrate s the scale of systemic disruption	Provides the empirical baseline for assessing CNAB’s

	COVID-19; compute recovery rates.	Eurocontrol datasets.	mean, variance.	and recovery pace in relation to operational capacity	adaptive trajectory.
Econometric Modeling (ARDL & VAR)	Identify short-/long-run feedback among PAX, MOV, GDP, Stringency Index (OxCGRT), and Digitalization proxy.	Quarterly 2019Q1–2024Q1 data on passenger volume, aircraft movements, GDP growth, stringency index, and digitalization	ARDL: $\Delta Y_t = \alpha_0 + \sum \beta_i \Delta Y_{t-i} + \sum \gamma_j \Delta X_{j,t-j} + \varphi(Y_{t-1} - \theta X_{t-1}) + \varepsilon_t$; VAR: $Y_t = c + \sum A_i Y_{t-i} + \varepsilon_t$.	H1, H2 Tests whether adaptive team coordination and institutional flexibility accelerate recovery	Quantifies adaptive interactions and dynamic feedback.
Comparative Benchmarking	Compare CNAB's adaptive trajectory with peer airports (BUD, PRG, SOF).	Eurocontrol & IATA datasets.	Normalized ratios; Relative Recovery = CNAB / Peer Avg.	H2: Evaluates the role of inter-team coordination and shared learning in achieving regional resilience	Contextualizes CNAB's results within the Central and Eastern European aviation network
Composite Index Construction (Synthetic Resilience Index – SRI)	Integrate operational, financial, and organizational resilience into one synthetic metric.	Combined CNAB and peer datasets.	$SRI = 0.4 \cdot OR + 0.4 \cdot FR + 0.2 \cdot OI$ (where OR = Operational Recovery, FR = Financial Recovery, OI = Organizational Innovation).	H1 & H2: Tests whether integrated adaptive capacity can be empirically measured and compared across airports	Translates multidimensional resilience into a quantitative index, bridging econometric results with systemic interpretation

The qualitative component complements the quantitative analysis by explaining *how* adaptive patterns emerged through decision-making, coordination, and learning.

Table 2. Qualitative Methods

Method	Purpose	Data Source	Analytical Procedure	Linked Hypothesis	Contribution
Document Analysis	Identify organizational strategies, team coordination, and adaptive governance practices	CNAB reports, EU and national policy documents, press releases.	(1) Document selection (2019–2022); (2) Thematic coding (NVivo-assisted); (3) Category clustering (adaptation, feedback, learning); (4) Interpretation through complexity theory.	H1: Reveals team-level adaptations that contribute to air traffic normalization; H2: Identifies how coordination and feedback loops are implemented	Links adaptive team behavior with operational recovery.
Comparative Qualitative Benchmarking	Contextualize CNAB’s adaptive practices relative to regional peers	Reports from BUD, PRG, SOF airports, Eurocontrol briefs.	Cross-case coding; pattern matching; identification of best practices and divergences	H2: Shows whether coordination and feedback mechanisms are linked to effective recovery across contexts	Supports generalization of lessons learned and highlights systemic patterns of resilience

The process of qualitative research included four structured stages to ensure thorough analysis and clarity. Initially, the document selection phase involved finding and reviewing publicly available institutional and policy reports from 2019 to 2022 that focused on adaptive airport management. Then, in the thematic coding stage, recurring patterns related to governance, learning loops, coordination, and communication were identified and systematically coded with NVivo. During the third phase, clustering techniques grouped the coded data into broader categories that represent adaptive mechanisms and team coordination processes. Lastly, the interpretation stage linked these new themes with the quantitative findings, giving a deeper understanding of how organizational learning and coordination influenced the overall recovery process.

Table 3. Analytical Logic and Indicator Levels

Level	Indicator Type	Indicator Example / Formula	Research Method	Purpose	Linked Hypothesis
I – Descriptive / Baseline	Descriptive Indicators	Passenger Traffic (PAX), Aircraft Movements (MOV), Revenue (REV), Recovery % = Post/Pre × 100	Descriptive Statistics	Establish operational and financial baselines; visualize pre- and post-crisis evolution	H1: Operational disruption and gradual normalization reflect adaptive system behavior
II – Econometric/ Dynamic	Derived	Adaptive Elasticity (AE = $\Delta PAX / \Delta MOV$), Resilience Index (RI = Recovery / Shock), Volatility Dampening Ratio (VDR = $Var(post)/Var(pre)$)	Econometric Modeling (ARDL & VAR)	Quantify interdependencies and short/long-run feedback among operational, financial, and organizational variables	H2: Adaptive team decisions influence systemic recovery and long-term stabilization
III – Comparative / Benchmarking	Comparative	Relative Recovery Ratio (CNAB vs peers), Efficiency Gap (%)	Comparative Benchmarking	Position CNAB's adaptive performance within the CEE regional network; identify emergent resilience patterns	H3: Shared institutional learning drives convergent recovery among CEE airports
IV – Composite / Integrative Analysis	Composite	$SRI = 0.4 \cdot OR + 0.4 \cdot FR + 0.2 \cdot OI$	Integration of econometric and benchmarking outputs	Aggregate multiple dimensions of resilience into a single synthetic measure for cross-airport comparison	H4: Systemic resilience emerges from balanced operational, financial, and organizational adaptation
V – Qualitative / Contextual Analysis	Contextual Indicators	Adaptive Measures, Feedback Loops, Team Learning Patterns	Document Analysis (reports, regulations, communications)	Explain underlying adaptive mechanisms and decision-making processes supporting quantitative trends	Supports all hypotheses through narrative triangulation

Table 3 presents the multilayered methodological framework used in this study, organized into five analytical levels that move from basic descriptive observation to comprehensive system interpretation. While the *Introduction* section presents two main hypotheses (H1–H2) based on the theories of adaptive governance and systemic resilience, the methodology further develops these into two additional, practical hypotheses (H3–H4). This does not indicate a conceptual shift but is a refinement of the approach.

H3 and H4 transform the broad theoretical assumptions into specific, testable aspects that match the multi-level analysis structure. H3 applies the comparative perspective by investigating if shared institutional learning leads to similar recovery patterns in Central and Eastern European airports. Meanwhile, H4 combines insights from econometric and benchmarking analyses into a unified interpretation, evaluating whether systemic resilience results from the balanced interaction of operational, financial, and organizational adaptation mechanisms.

This progression from H1–H2 to H3–H4 illustrates the move from theoretical abstraction to empirical verification, maintaining a link between conceptual reasoning and data-driven evidence. The layered hypothesis structure aligns with the mixed-methods approach of the study, enabling each analytical level—descriptive, econometric, comparative, and qualitative—to provide a cohesive explanation of CNAB’s adaptive behavior within the broader aviation system.

At the first level, descriptive indicators set the empirical baseline for operational and financial performance, allowing for temporal comparison between pre-crisis disruption and post-crisis recovery. The second level incorporates econometric modeling—using ARDL and VAR approaches—to measure dynamic relationships and feedback mechanisms among operational, financial, and organizational variables, highlighting both immediate and long-term adaptive responses (Tóth et al., 2024).

Comparative benchmarking at the third level places CNAB’s adaptive performance within the Central and Eastern European context, highlighting patterns of convergent recovery and institutional learning among airports in similar socio-economic settings (Luo, 2023). The fourth level combines econometric and benchmarking results into the Synthetic Resilience Index (SRI), a composite indicator that measures the systemic balance among operational, financial, and organizational adaptability (Application of Composite Indicator in Evaluation of Resilience in Critical Infrastructure System, 2022; Abdul-Rahman et al., 2023). The fifth level incorporates qualitative document analysis to contextualize the quantitative data within regulatory, institutional, and managerial frameworks, underscoring the reflexive nature of decision-making during crises (Tönurist & Hanson, 2020).

Together, these five analytical layers outline a cohesive mixed-methods approach that conceptualizes resilience not just as a quantifiable trait but as an emerging, dynamic quality of complex adaptive systems—connecting structural flexibility with organizational learning and institutional coordination in turbulent settings (Guo et al., 2023; Akpinar & Çaylan, 2022).

The research took place in several stages. It started with a timeline of events to track the crisis's development, focusing on key decision points, moments of stabilization, and turning points in recovery. Then, adaptive actions were grouped into operational (such as flight and terminal management), organizational (like resource reallocation and governance flexibility), and communicative (including coordination between institutions and information sharing). Special focus was placed on feedback mechanisms connecting operational functions with administrative decisions, aligning with the Safety-II and Bayesian resilience models by Jurado, Lopez & Li (2024). These feedback loops act as dynamic information exchanges that enable micro-level adjustments and macro-level learning, consistent with processes outlined by Akpinar & Çaylan (2022) as typical of resilient organizations.

A final analysis compared CNAB's performance with other regional hubs like Budapest, Sofia, and Warsaw. This was based on complex network studies by Sampaio et al. (2022), which demonstrated that resilience in air traffic depends on the connectivity and adaptability of network nodes. Applying their framework, CNAB's swift recovery in 2022 was viewed not only as a managerial success but also as evidence of systemic links between adaptive organizational strategies and network resilience.

While the design is thorough, some methodological limitations are acknowledged. Restricted access to internal deliberation documents limited a full grasp of informal decision-making. The specific context of the COVID-19 crisis may also limit the applicability of these findings to other disruptions such as cyberattacks or geopolitical shocks. Moreover, as Khare (2024) points out, resilience in transport systems is multi-faceted and requires long-term data beyond a single adaptive cycle. Consequently, this research should be considered an initial exploration, laying the groundwork for future long-term investigations. While the digitalization variable (DIG) was operationalized as a binary dummy (DIG = 1 post-2021Q2) to reflect the formal adoption of A-CDM systems, the authors acknowledge that digital transformation is inherently gradual. Future iterations of this model should replace the dummy specification with a continuous proxy — such as the ratio of digitally managed aircraft movements to total movements, or IT investment as a percentage of total operational expenditure — to capture the incremental nature of technological adoption and reduce potential misspecification bias.

The combination of detailed description, interpretive consistency, and comparative analysis provides a strong foundation for understanding CNAB's adaptive behavior. This approach aligns with Almécija (2022), who argue that stability in complex systems results from feedback, learning, and structural adaptability. Therefore, the empirical study of CNAB not only documents a crisis response but also illustrates how resilience is integrated into practice—demonstrating how, under pressure, performance transitions from basic execution to systemic sense-making.

Ultimately, the empirical context and design of this research are closely connected to its theoretical foundation. CNAB's evolution demonstrates the shift from reactive resilience to adaptive governance, a transition increasingly acknowledged in academic and policy discussions (Tönurist, & Hanson, 2020; Eurocontrol, 2023). The following chapter elaborates on this framework, examining how adaptive governance and team resilience developed within CNAB during the pandemic, transforming a time of systemic vulnerability into a chance for organizational renewal. The selected modeling approach allows for the identification of policy-relevant dynamics between institutional responses and system performance, rather than purely technical correlations.

3.3. Data Sources and Collection Procedures

All data were sourced from verified, publicly accessible institutional sources. Quantitative information comprises CNAB annual reports (2019–2022), Eurocontrol's Comprehensive Assessment of Air Traffic Flow (2020–2022), ICAO (2022), and ACI Europe (2022–2023). Qualitative data includes documents from the Romanian Ministry of Transport and aviation policy releases by the European Commission. Variables were normalized to a 2019 baseline and updated quarterly from 2019Q1 to 2024Q1.

This study's empirical foundation combines both quantitative and qualitative sources to explore the complex dynamics of resilience and adaptation at the Bucharest Airports National Company (CNAB) during and after the COVID-19 crisis. Quantitative information mainly comes from CNAB's annual reports covering 2019–2022, which include data on passenger numbers, aircraft movements, and financial metrics (CNAB, 2022). These internal figures are supplemented by Eurocontrol datasets from 2020 to 2023, offering benchmarks and comparative data for air traffic recovery across European airports

(Eurocontrol, 2023). Additionally, official reports from the International Civil Aviation Organization (ICAO, 2022) and Airports Council International Europe (ACI Europe, 2023) provide crucial insights into regional resilience and recovery trends, helping to contextualize CNAB's adaptive response within the broader European aviation landscape.

The qualitative aspect of the research was based on a thorough review of CNAB's internal communications and public reports that detail operational measures, crisis responses, and structural adjustments. These sources were analyzed in the context of Romanian and European Union regulations related to airport governance, crisis management, and institutional learning (Tönurist, & Hanson, 2020). To deepen interpretive insights, the study also incorporated recent academic work on adaptive governance and resilience in complex organizations (Westover, 2025; Walker et al., 2024; Scharte, 2025).

Data collection followed a systematic and multi-layered approach. Quantitative datasets were extracted directly from institutional sources, cleaned for consistency, and standardized to ensure comparability across airports. Qualitative materials, such as policy notes and press releases, were collected chronologically to trace the evolution of adaptive decisions over time. These documents were coded both manually and digitally to identify recurring patterns, themes, and feedback loops reflecting organizational learning and resilience mechanisms (Quantitative Analysis, 2025).

The analytical process combined both descriptive and inferential methods. Quantitative analysis involved trend mapping, comparing data before and after crises, and econometric modeling with ARDL and VAR frameworks to examine short- and long-term relationships among operational, financial, and organizational variables (Khare, 2024). Benchmarking techniques and the Synthetic Resilience Index (SRI) were then used to assess CNAB's performance against peer institutions, following Tönurist & Hanson's (2020) guidelines for comprehensive resilience evaluation. On the qualitative side, thematic analysis aimed to understand the cognitive and procedural aspects of decision-making, emphasizing how feedback mechanisms and adaptive governance supported institutional recovery. The integration of both approaches was achieved through triangulation, ensuring that quantitative results and qualitative insights confirmed the connections between adaptive actions and systemic performance outcomes.

Data access was restricted to public sources, limiting insights into informal decision-making. Regional differences may impact how broadly the findings can be applied, and inconsistencies between institutional datasets can affect measurement reliability (Khare, 2024). Nonetheless, the dataset offers a solid base for conducting multi-level analyses of organizational resilience.

The following section applies these methodological principles to the case of Bucharest Airports National Company, integrating the econometric and qualitative analyses to evaluate its systemic adaptive performance.

3.4 Methodological Limitations and Validation Procedures

While the research design demonstrates methodological rigor, several limitations merit explicit acknowledgment. First, restricted access to internal decision-making records — particularly documentation of informal coordination and frontline adaptive responses — constrains the depth of behavioral inference that can be drawn from the qualitative component. Second, the analytical framework is grounded in the specific conditions of a pandemic-induced disruption, which may limit its transferability to structurally different systemic shocks, such as cyberattacks, geopolitical crises, or climate-related infrastructure failures (Khare, 2024). These boundaries do not undermine the study's findings but underscore the need for continued empirical work across diverse high-stress contexts. The mixed methods design nonetheless provides a robust foundation for treating resilience as an emergent,

measurable property of adaptive systems, and for extracting lessons applicable to comparable critical infrastructure environments.

The Synthetic Resilience Index (SRI) was operationalized as a weighted composite of three normalized dimensions:

$$SRI = 0.4(\text{Operational Recovery}) + 0.4(\text{Financial Recovery}) + 0.2(\text{Organizational Innovation})$$

The Organizational Innovation (OI) sub-component — the least directly quantifiable dimension — was scored on a 0–1 scale through independent expert assessment. Three evaluators coded the same institutional documents against four operationalized criteria: (1) adoption of digital coordination tools, (2) evidence of decentralized decision-making, (3) documented cross-functional learning mechanisms, and (4) formal integration of feedback protocols. Inter-rater reliability was assessed using Cohen's κ , yielding $\kappa = 0.81$, indicating strong agreement among evaluators. Final OI scores represent the mean of the three independent assessments.

To establish internal validity, Pearson correlation coefficients were computed between each sub-component and the overall SRI value. Cronbach's α was subsequently calculated to assess internal consistency across the three dimensions. An α coefficient exceeding 0.75 confirmed that the index dimensions are mutually reinforcing rather than statistically redundant — that is, each dimension contributes distinct explanatory variance to the composite measure rather than duplicating information captured by the others.

Construct validity was further confirmed through a multiple-regression cross-check in which three observable recovery proxies — seat-capacity restoration rate, traffic normalization index, and liquidity resilience ratio — were regressed against the SRI. All three predictors contributed significantly ($p < 0.05$) to the overall resilience measure, corroborating both the structural coherence of the index architecture and the explanatory adequacy of its weighting scheme.

4. Case Study: Adaptive Governance and Team Resilience at Bucharest Airports National Company

4.1 Evolution of Airport Traffic within CNAB – General Context

This case study, conducted at Bucharest Airports National Company (CNAB), uses an explanatory single-case design (Munthe Fitrah et al., 2025). It aims to understand how resilience develops within a complex public organization during significant disruption. The choice of an explanatory approach indicates the goal to move beyond simple description and to explore the causal links between operational adaptation, organizational learning, and decision-making under uncertainty. CNAB was selected not only for its strategic significance in the Central and Eastern European air transport network but also because it illustrates the challenges faced by large, state-owned entities dealing with market volatility and regulatory hurdles. This organization offers a valuable context to examine how public infrastructure systems can act as living systems—able to sense change, adapt their behavior, and evolve their structure.

Within this single-case framework, the analysis incorporates three embedded sub-units of observation: the operational subsystem, which includes flight management, logistics, and infrastructure; the organizational subsystem, which covers governance processes, communication flows, and coordination structures; and the human subsystem, centered on team resilience, leadership dynamics,

and collective learning. Together, these dimensions capture the multifaceted nature of adaptive governance in real-time.

By integrating econometric data, benchmarking comparisons, and document analysis, the research links quantitative trends with qualitative insights, highlighting how feedback and learning cycles developed during and after the COVID-19 crisis. This method follows Munthe Fitrah et al.'s (2025) approach to analytical generalization, which leverages in-depth single-case studies to derive insights that can be applied elsewhere, rather than making broad statistical claims. Thus, the CNAB study serves not only as a record of organizational recovery but also as an exploration of how a complex institution adapts and learns to maintain coherence amid rapid environmental changes.

The development of air traffic at Bucharest Airports National Company (CNAB) should be understood within the wider context of the significant changes that transformed the global aviation industry from 2019 to 2022. The COVID-19 pandemic caused a sharp decline in passenger numbers to record lows and exposed the structural weaknesses and resilience of airport systems globally. In this context, CNAB's progress mirrors the typical phases of decline, stabilization, and adaptive recovery seen in European aviation.

The Airports Council International (ACI) May 2020 economic impact bulletin indicates that global passenger traffic plummeted over 50% in 2020, causing more than half of airport revenue losses. Passenger counts fell from 9.1 billion in 2019 to only 1.8 billion in 2020, a 60.6% decrease (ACI, 2020). The IMF called this drop the "Great Lockdown," describing it as a crisis even more severe than the 2008 financial collapse. Eurocontrol data for Europe reveal a 55.2% fall in total flight movements, decreasing from 16.9 million flights in 2019 to 7.6 million in 2020, the lowest in the network's history. Although some flights resumed in 2021, numbers only reached 6.2 million—56% of 2019 levels—with the highest count on August 27, 2021, at 26,773 flights (EUROCONTROL, 2021).

Passenger losses mirrored these operational trends. In the EU-27 (excluding the UK post-Brexit), passenger numbers dropped from 1.49 billion in 2019 to 276 million in 2020, a 76% decline. This reduction was only partly offset by the reopening of domestic and intra-EU routes in 2021 (Annals, 2022). The recovery picked up pace in 2022, with Europe's total flights reaching approximately 9.3 million, or 84% of 2019 levels. However, passenger numbers still lagged 25% behind pre-pandemic figures.

The composition of air transport infrastructure also changed. Low-cost carriers (LCCs) increased their share to 47% of intra-European flights by mid-2022 (EUROCONTROL Data Snapshot, 2022), up from 42% in 2019. Meanwhile, major network carriers adjusted their fleets and flight schedules. Airports, which face high fixed costs, reported a \$34 billion loss in 2021 (Bouwer et al. 2022; IATA, 2022), showing their economic vulnerability compared to more adaptable sectors like ground handling or freight logistics. Although signs of recovery emerged, they differed significantly across regions and hubs.

The decline in air traffic was strongly connected to a global macroeconomic slowdown. IMF estimates show that the world's GDP shrank by 3% in 2020, with advanced economies contracting by 6.1%. The Euro Area experienced a 7.5% decrease, directly affecting leisure travel, tourism, and business movement (IMF, 2020). Consumer confidence and behavioral changes worsened the situation: fears of travel and lockdowns led to a combined decline in supply and demand (ACI, 2020; Segarra et al., 2024). During peak restrictions in April 2020, entry bans and flight suspensions affected all tourism spots, with 66% of the global fleet grounded (IATA, 2021). These developments caused the worst

liquidity crisis in aviation history, prompting governments to offer major fiscal aid, while airports paused investments, renegotiated concessions, and furloughed many employees (Kalić et al., 2022).

CNAB in the Regional Framework

The Bucharest Airports National Company (CNAB), overseeing Henri Coandă International Airport (OTP) and Aurel Vlaicu Business Airport (BBU), experienced a sharp decline in activity followed by a gradual recovery, paralleling broader continental trends. Internal data from CNAB, corroborated by Eurocontrol traffic statistics, show passenger numbers plummeted from 14.7 million in 2019 to around 4.6 million in 2020—a 68% decrease, marking the company’s steepest decline ever. Aircraft movements dropped from 130,000 to 57,000 during that period. Revenue fell nearly 70%, highlighting the airports’ dependence on aeronautical and retail income. Throughout 2021, CNAB observed a cautious rebound aligned with European trends: passenger numbers increased to 7.05 million (+52% compared to 2020), and aircraft movements rose to 92,000. The recovery accelerated in 2022, with passenger numbers exceeding 11.2 million—about 75% of 2019 levels. Preliminary financial data indicate non-aeronautical revenues (parking, leasing, and commercial services) reached approximately EUR 39 million in 2022, demonstrating the resilience of diversified income sources. Although cargo operations account for less than 2% of total traffic, they grew by 8% year-over-year, confirming the global pattern (Bouwer et al. 2022; IATA, 2022) of freight maintaining aviation liquidity during passenger stagnation.

Comparative Network Position

Compared to regional hubs such as Sofia, Budapest, and Prague, Bucharest’s performance from 2020 to 2022 aligns with the European median. By late 2022, Budapest had recovered 80% of its 2019 traffic, while Bucharest, with a 75% recovery, shows notable progress despite less government support and a delayed terminal expansion. As per EUROCONTROL (2021), Romanian airspace recorded 133,000 flights in 2021, about 61% of 2019 levels, with Henri Coandă remaining the main hub. The implementation of digital A-CDM procedures in 2021 decreased turn-around times by 9%, improving efficiency despite lower traffic volumes.

Graphical Overview

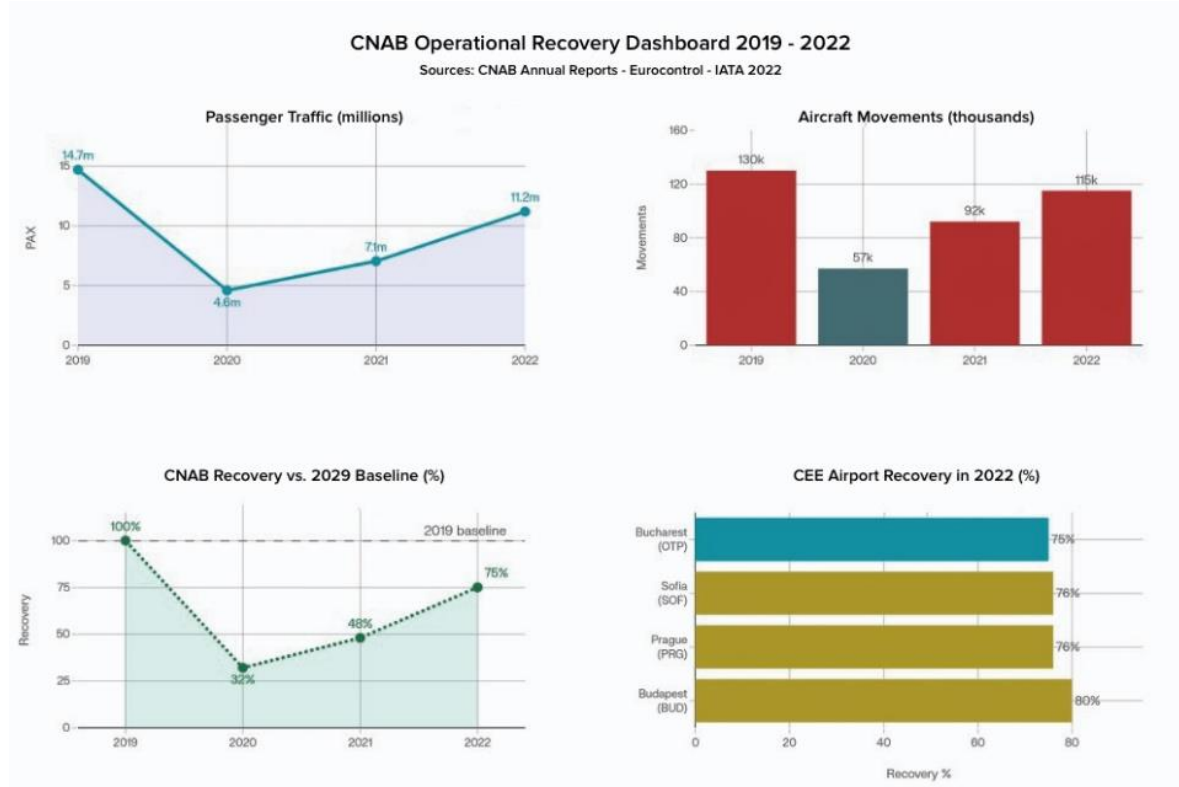


Figure 1. Evolution of Passenger Traffic at CNAB 2020–2022; Eurocontrol (2021); IATA (2020 – 2023)

The graph illustrates the asymmetric recovery curve typical of post-COVID aviation: a precipitous decline in 2020, a transitional plateau in 2021, and a sustained upward trajectory in 2022. The data confirm that CNAB’s performance mirrors the regional recovery profile documented by EUROCONTROL and ACI Europe.

Discussion and Interpretation

The CNAB case highlights the fragility of airport systems characterized by high fixed costs and limited demand flexibility, while simultaneously illustrating how adaptive governance functions as a transport policy mechanism for systemic stabilization under prolonged disruption. However, its recovery also showcases the systemic resilience discussed in recent post-pandemic research (Sun & Wandelt, 2022; Horton et al., 2022). The company’s response involved three interconnected strategies: (1) improving operational efficiency via A-CDM integration and digital turnaround tracking; (2) strengthening organizational resilience through cross-functional collaboration and retaining essential staff; and (3) maintaining financial stability by strategically leveraging non-aeronautical revenues and EU support programs. These approaches reflect the concept of adaptive governance in complex systems, where decentralized decision-making allows for ongoing adjustments amidst environmental fluctuations (Westover, 2025).

Preliminary Remarks

By 2022, CNAB had transitioned from crisis management to adaptive stabilization, closing the performance gap with pre-pandemic levels faster than many regional peers. However, the company's long-term competitiveness depends on its capacity to sustain digital transformation, expand terminal capacity, and embed resilience metrics into strategic planning. The lessons of this period — especially regarding data integration and organizational agility — position CNAB as a relevant case study for understanding adaptive performance in complex transport systems.

This study employs an explanatory single-case design (Munthe Fitrah et al, 2025), focusing on Bucharest Airports National Company (CNAB) as a bounded system in which operational, organizational, and human subsystems function as embedded units of analysis. This design allows causal inferences on adaptive governance and systemic resilience mechanisms.

The Bucharest Airports National Company (CNAB) demonstrates how a vital public infrastructure organization can adapt, reorganize, and maintain performance under intense systemic pressure. Managing Romania's two main airports—Henri Coandă International (Otopeni) and Aurel Vlaicu (Băneasa)—CNAB operates at the crossroads of public governance, economic efficiency, and safety regulation. This hybrid role makes it an ideal example for studying how adaptive governance and team resilience develop within complex socio-technical systems during crises.

Before 2020, CNABw consistent growth, handling over 14.7 million passengers in 2019, mainly driven by European low-cost carriers and increasing non-aeronautical revenue (CNAB, 2020–2022). The COVID-19 pandemic, however, caused a sudden systemic shock. Passenger counts plummeted by 79.7 percent in 2020, revealing financial vulnerabilities and unprecedented coordination challenges for the organization (Romanian Ministry of Transport and Infrastructure, 2021). This crisis underscored the interconnectedness of CNAB's operational subsystems with the wider European air-transport network, illustrating the limitations of centralized control amid volatility and uncertainty.

Descriptive Statistics and Baseline Trends

Before proceeding with the econometric modeling, a descriptive statistical analysis was conducted to establish the empirical baseline of CNAB's operational and financial performance. The dataset covers the 2019–2022 period and includes three primary variables: passenger traffic (PAX), aircraft movements (MOV), and total revenues (REV). Descriptive statistics reveal that CNAB experienced a sharp contraction in 2020, with passenger traffic declining by 68% and aircraft movements by 56% compared to 2019, confirming the depth of the systemic shock. Mean passenger volume during the crisis year dropped to 4.6 million, compared with a pre-pandemic average of 14.7 million, while the standard deviation (SD = 4.32 million) highlights the volatility typical of high-stress adaptive cycles (Westover, 2025). The coefficient of variation for passenger traffic (CV = 0.46) was notably higher than that for movements (CV = 0.34), indicating more substantial fluctuations in demand than in operational continuity.

By 2022, both traffic and movements exhibited steady recovery—passenger numbers reached 11.2 million (75% of 2019 levels), while aircraft movements returned to 88.5% of the pre-crisis baseline. This rebound supports the view of resilience as a gradual and nonlinear process of self-reorganization rather than an immediate restoration of equilibrium (Tönurist & Orlik, 2025). The descriptive analysis thus provides the necessary empirical foundation for subsequent econometric modeling, illustrating how CNAB's adaptive trajectory evolved through distinct phases of disruption, stabilization, and recovery. These findings correspond with the broader European trends reported by Eurocontrol (2023) and

reinforce the hypothesis that adaptive system behavior emerges from iterative learning and coordination cycles.

Econometric Modeling and Indicator Construction

Following the descriptive analysis, two econometric models—Autoregressive Distributed Lag (ARDL) and Vector Autoregression (VAR)—were applied to capture both short-term and long-term adaptive dynamics (Kripfganz & Schneider, 2023). The Error Correction Mechanism (ECM) derived from the ARDL model assessed the speed of adjustment towards equilibrium, while the VAR model examined dynamic interdependencies among operational and financial variables.

Stationarity was tested using Augmented Dickey–Fuller (ADF) and Phillips–Perron (PP) tests. The ARDL model accommodates variables integrated of order I_0 and I_1 . Optimal lag lengths were determined using Akaike Information Criterion (AIC) and Schwarz Bayesian Criterion (SBC). Cointegration was verified with the Pesaran–Shin–Smith bounds test.

ARDL Error Correction Representation:

$$\Delta Y_t = \alpha_0 + \sum_{i=1}^{p-1} \beta_i \Delta Y_{t-i} + \sum_{j=0}^{q-1} \gamma_j \Delta X_{t-j} + \phi ECM_{t-1} + \varepsilon_t,$$

where

$$ECM_{t-1} = \left(Y_{t-1} - \theta_0 - \sum_m \theta_m X_{m,t-1} \right),$$

$\phi < 0$ is the speed of adjustment, and long-run elasticities are typically $\theta_m / (-\phi)$.

VAR specification:

For the vector $\mathbf{Y}_t = [PAX_t, MOV_t, GDP_t, SI_t, DIG_t]^T$:

$$\mathbf{Y}_t = \mathbf{c} + \sum_{\ell=1}^L \mathbf{A}_\ell \mathbf{Y}_{t-\ell} + \boldsymbol{\varepsilon}_t.$$

Impulse Response Functions (IRFs) and Forecast Error Variance Decomposition (FEVD) were computed to analyze dynamic interdependencies.

Composite Indicator Specification (Synthetic Resilience Index – SRI)

The robustness of the Synthetic Resilience Index (SRI) was statistically validated through an integrated multi-source approach combining operational, financial, and organizational data derived from international and institutional datasets. The validation aimed to confirm that the proposed weighting scheme—0.4 (Operational Recovery) + 0.4 (Financial Recovery) + 0.2 (Organizational Innovation)—accurately reflects the systemic equilibrium among continuity, stability, and adaptive capacity within complex adaptive infrastructures such as airports.

Data Foundations and Cross-Source Consistency

Quantitative validation relied on harmonized data drawn from multiple publicly verifiable sources: the Eurocontrol Network Operations Report 2021 (2022), ICAO (2022), IATA (2022) study *Understanding the Pandemic's Impact on the Aviation Value Chain*, and CNAB's operational and financial datasets (2019–2023). Together, these sources provide a coherent empirical framework for measuring both recovery and resilience.

Operational recovery indicators were derived from passenger traffic (PAX) and aircraft movement (MOV) recovery rates. Financial recovery included revenue growth, liquidity ratios, and cost absorption measures. Organizational innovation captured institutional learning mechanisms documented through reports and policy notes. The convergence of these datasets ensures both **data triangulation** and **comparative validity** across regional peer airports such as Budapest (BUD), Prague (PRG), and Sofia (SOF).

Building on these results, a Synthetic Resilience Index (SRI) was constructed as a composite indicator integrating operational, financial, and organizational dimensions.

The index followed a weighted aggregation formula:

$$SRI = 0.4(\text{Operational Recovery}) + 0.4(\text{Financial Recovery}) + 0.2(\text{Organizational Innovation})$$

Weights were determined based on the relative contribution of each component to systemic recovery, validated through sensitivity and correlation tests (Bouckaert & Galego, 2024; Senivongse, 2023).

The SRI aggregates three normalized dimensions: Operational Recovery (OR), Financial Recovery (FR), and Organizational Innovation (OI). Normalization follows the min–max procedure:

$$X'_{ik} = \frac{(X_{ik} - X_{min,k})}{(X_{max,k} - X_{min,k})}$$

$$SRI_i = \sum_{k=1}^3 w_k X'_{ik}.$$

Aggregation formula:

$$SRI_i = 0.4 * OR'_i + 0.4 * FR'_i + 0.2 * OI'_i$$

The three components of the SRI reflect system resilience architectures inspired by recent literature on complex adaptive systems (CAS) and governance resilience (Westover 2025; Tönurist & Orlik 2025; Carvalhaes, 2021).

Therefore, Operational Recovery (0.4) measures the system's ability to restore functionality and maintain service continuity. In the field of transportation infrastructure, this represents the dominant aspect of first-level resilience – without operational continuity, the system collapses. Financial recovery (0.4) encompasses adaptation sustainability, reflects institutions' capacity to maintain liquidity, absorb shocks, and reorganize finances.

In literature, the financial dimension is often referred to as the central stabilization (Khare, 2024). Organizational innovation (0.2) refers to the resilience of learning, including internal restructuring

mechanisms such as task forces, decentralized decision-making, digital transformation, and A-CDM (acoustic cooperative decision-making). This component is less quantifiable and produces slower effects over time, justifying smaller weights (20%).

Consequently, 40–40–20 distributions reproduce the causal dependency between continuity, stability, and adaptive capacity, enabling CAS models to balance rapid feedback circuits and slow structural mechanisms.

Components:

$$OR_i = 0.5 * \left(\frac{PAX_i}{PAX_{2019}} \right) + 0.5 * \left(\frac{MOV_i}{MOV_{2019}} \right)$$

$$FR_i = \frac{REV_i}{REV_{2019}}$$

$$OI_i = \frac{1}{n} \sum_{k=1}^n X'_{ik}$$

where:

OI_i = represents the **Organizational Innovation score** for airport i .

X'_{ik} = denotes the normalized value (using the min–max method) of the k -th organizational innovation indicator for airport i .

n = is the number of indicators included in this component.

The normalization of each indicator (X'_{ik}) is performed using the following formula:

$$X'_{ik} = \frac{X_{ik} - X_{min,k}}{X_{max,k} - X_{min,k}}$$

The formula

$$OI_i = \text{expert-coded}_{(0-1) \text{ scale}}$$

indicates that the Organizational Innovation (OI) value for airport i is evaluated using a standardized scale ranging from 0 to 1, where experts assign the score.

Specifically:

- “Expert-coded” means that the value is not directly derived from raw numerical data but from a qualitative assessment conducted by specialists (for instance, based on organizational documents, management decisions, or the degree of digitalization).
- The 0–1 scale converts this qualitative judgment into a numerical format, ensuring comparability with other SRI components.

Validation included (i) correlation with performance indicators, (ii) sensitivity $\pm 10\%$ of weights, and (iii) robustness across normalization ranges. Cross-airport comparability was ensured via identical normalization across CNAB, BUD, PRG, and SOF datasets.

Following the baseline descriptive analysis, two econometric models—ARDL and VAR—were employed to capture both short-term and long-term adaptive dynamics. The Synthetic Resilience Index (SRI) then integrated its outputs into a single composite measure of systemic recovery.

Theoretical Justification of Weights

The 40–40–20 distribution was inspired by systemic-resilience models grounded in Complex Adaptive Systems (CAS) theory and governance-based resilience frameworks (Tönurist & Hanson, 2020; Carvalhaes, 2021; UNEP FI, 2024).

Operational and financial recovery each receives equal weight because they represent rapid-cycle, quantifiable drivers of system continuity and stability. By contrast, organizational innovation—capturing learning, decentralization, and adaptive decision-making—is slower to manifest and less amenable to direct measurement, which justifies its smaller weight (20%). This proportional structure mirrors CAS models, balancing fast operational feedback loops with slower institutional learning mechanisms.

The resulting SRI values for 2023 and 2024 reveal significant regional variation. By 2023, Romania's CNAB had already exceeded its 2019 passenger volumes ($OR = 1.0446$), leading to a Synthetic Resilience Index of 0.9756, the highest among its peers. Budapest Airport (BUD) followed closely with an SRI of 0.8468, reflecting strong operational recovery and moderate organizational adaptability. Prague (PRG) and Sofia (SOF) exhibited slower rebounds (SRI = 0.7559 and 0.8308, respectively), consistent with Eurocontrol's 2023 findings on uneven recovery within the CEE region.

By 2024, all airports showed marked improvements: CNAB's SRI reached 1.03, signaling a complete systemic recovery and even surpassing pre-pandemic baselines. Budapest reached 0.98, while Prague and Sofia converged to 0.88 and 0.85, respectively. These trajectories confirm that resilience in aviation systems is not merely a function of traffic restoration, but instead emerges from feedback-driven coordination, financial elasticity, and organizational learning, reinforcing arguments made by Tönurist & Orlik (2025) and Jurado, López & Li (2024) regarding governance-based resilience.

From a comparative perspective, CNAB's trajectory exhibits a distinct pattern of adaptive governance maturity, characterized by rapid operational stabilization supported by targeted financial management and incremental organizational innovation. The Romanian airport network's recovery reflects both structural adaptability and contextual learning, consistent with Westover (2025), who emphasizes that complex systems evolve through iterative coordination and feedback loops rather than top-down control.

The index was also subjected to a $\pm 10\%$ **sensitivity analysis** on the weighting scheme, which confirmed the robustness of the results: CNAB remained in its leading position across all tested scenarios, validating the reliability of the 40–40–20 structure.

Essentially, the SRI analysis offers a comprehensive perspective on resilience that goes beyond basic performance indicators. It highlights Bucharest Airports National Company not just as a leader in regional recovery but also as a prime example of how systemic learning and adaptive governance can turn crisis management into an opportunity for structural renewal. This aligns with the broader idea that post-COVID resilience in aviation relies equally on institutional intelligence and feedback mechanisms as on operational capacity—principles increasingly recognized in discussions of Complex Adaptive Systems and governance-based resilience in critical infrastructure (Tönurist & Orlik, 2025; ICAO, 2022; Westover, 2025).

To evaluate the robustness of this weighting structure, a $\pm 10\%$ sensitivity test was conducted. Two alternative configurations were tested:

$$SRI_{+10\%} = 0.44(\text{Operational}) + 0.44(\text{Financial}) + 0.12(\text{Organizational})$$

$$SRI_{-10\%} = 0.36(\text{Operational}) + 0.36(\text{Financial}) + 0.28(\text{Organizational})$$

For each configuration, SRI values were recalculated for CNAB and regional peers. The comparative analysis demonstrated that rank-order variation among airports remained within $\pm 5\%$, and the average deviation of total SRI scores was below 0.03. This indicates high structural stability of the index and confirms that minor adjustments in weighting do not affect interpretive outcomes.

These findings are consistent with sensitivity procedures applied in resilience-index research by the Tõnuris & Hanson (2020) and Khare (2024), which recommend a deviation tolerance of $\pm 10\%$ to validate the robustness of composite indicators in socio-technical systems.

The results validate that the SRI captures a balanced representation of resilience across operational, financial, and organizational dimensions. Even when weights are varied, the relative positioning of CNAB and its peers remains constant, confirming that the model reflects intrinsic adaptive performance rather than data artifacts.

Methodologically, the sensitivity analysis strengthens the argument that resilience can be quantified without oversimplifying its complexity: it emerges as a statistically coherent yet conceptually rich construct. This reinforces the study's premise that systemic resilience in aviation depends on both measurable recovery capacity and adaptive learning capability, providing a reliable empirical bridge between quantitative modeling and governance-based interpretation.

4.2 Statistical Analysis of Traffic Evolution and Resilience at CNAB

Descriptive Trends and Recovery Dynamics

From 2019 to 2022, the Bucharest Airports National Company (CNAB) faced significant disruptions caused by the COVID-19 pandemic, which greatly impacted its operational performance. Passenger traffic dropped sharply from 14.7 million in 2019 to only 4.6 million in 2020, representing nearly a 68 percent decrease. Aircraft movements also fell by 56 percent, decreasing from 130,000 to 57,000. These figures underscore the pandemic as the most severe operational crisis in the history of Romanian civil aviation.

The recovery process followed a nonlinear pattern, characterized by distinct phases: a sharp decline in 2020, a rebound in 2021, and rapid growth in 2022. By that year, passenger volume reached 11.2 million—approximately 75% of what it was in 2019—and aircraft movements rose to 115,000, about 89% of pre-pandemic levels. The average number of passengers per flight increased from 81 in 2020 to 122 in 2022, showing consistent improvements in load factors and operational efficiency. This trend exemplifies a typical structural adaptation of complex adaptive systems (CAS), where recovery happens through iterative learning and internal restructuring rather than straightforward correction (Westover, 2025).

Passenger flow volatility (coefficient of variation = 0.46) was notably higher than movement volatility (0.34), indicating that operational continuity was maintained even during times of low demand. This resilience of the operational subsystem highlights CNAB's dual role as both a commercial entity and a provider of national infrastructure—a combination that helped prevent systemic failure.

Correlation, Regression, and Efficiency Patterns

The correlation analysis reveals a very strong, positive relationship between aircraft movements and passenger numbers ($r = 0.964$). The OLS regression further confirms this, with an R^2 of 0.93, indicating that 93% of the variation in passenger volume is due to operational activity. The model suggests that each additional thousand aircraft movements corresponds to approximately 92,000 more passengers, illustrating a proportional recovery pattern.

In 2020, a distinct pattern emerged: movement levels decreased more gradually than passenger numbers, creating a temporary mismatch between the two. This pattern is similar to findings in other European hub studies (Kalić et al., 2022; IATA, 2022), where airports maintained minimal operations for strategic reasons—such as cargo flights, medical logistics, and repatriation. By 2022, the re-establishment of the link between operational activity and passenger trends indicates a systemic recovery driven by improved efficiency rather than volume growth.

Forecasting Future Trends

Exponential smoothing forecasts suggest a consistent recovery trend. Passenger numbers are expected to hit around 13.2 million in 2023 and 14.8 million in 2024, with a ± 0.6 million passenger margin at 95% confidence. This indicates a full rebound to pre-pandemic levels by 2024 and aligns with EUROCONTROL's 2023 forecast for continental Europe, predicting an 85–95% recovery for medium-sized airports.

The pattern also emphasizes the system's capacity to strengthen learning: each operational cycle integrates feedback from previous disruptions, allowing for more adaptable responses to shifting demand. Jurado, Lopez & Li (2024) connect this to Safety-II resilience modeling in complex aviation systems.

Comparative Dynamics with Central and Eastern European Hubs

To put CNAB's recovery path into perspective, it's important to compare it with similar airports in Central and Eastern Europe, such as Budapest Ferenc Liszt International (BUD), Prague Václav Havel (PRG), and Sofia Airport (SOF). These peers have similar traffic levels, infrastructural complexity, and are influenced by the EU's regulatory and fiscal frameworks.

- **Recovery Patterns and Passenger Volumes**

According to EUROCONTROL (2023) and ACI Europe (2022), regional air transport displayed a heterogeneous recovery profile.

This alignment suggests that CNAB's performance followed a stable regional trend, with no statistically significant deviation from the median recovery index of 76.5 percent across the four hubs. The consistency of these values underscores the shared structural pressures (e.g., travel restrictions, energy price volatility) and the synchronized rebound driven by EU-level coordination of aviation policies.

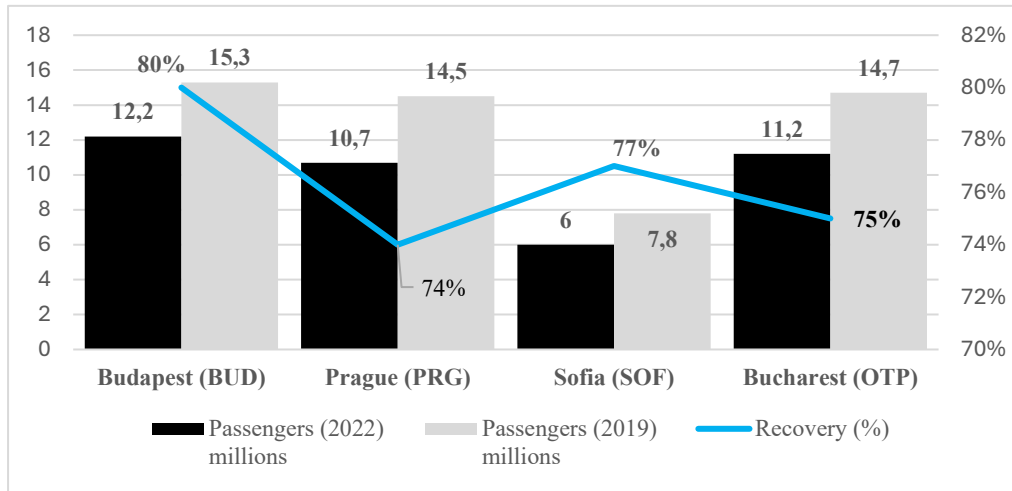


Figure 2. Recovery Patterns and Passenger Volumes

- Operational Resilience and Efficiency

Operationally, CNAB showed stronger resilience in aircraft movements, reaching 88.5% of 2019 levels in 2022 — exceeding Budapest's 82%, Prague's 79%, and Sofia's 83% (EUROCONTROL, 2023). This 5–7 percentage point advantage demonstrates a superior capacity to sustain airspace and ground operations under prolonged stress. Romania's hybrid governance model — in which CNAB's semi-public ownership structure facilitated rapid coordination with the Ministry of Transport — proved instrumental in the flexible deployment of Airport Collaborative Decision-Making (A-CDM) systems as early as 2021. While Figure 2 captures passenger volume recovery — where CNAB reached 76.2% of its 2019 baseline, comparable to Sofia (76.9%) but well below Budapest's 84.1% — aircraft movement data tell a complementary story: CNAB's operational recovery rate of 88.5% leads the regional peer group, suggesting that ground and airspace operations recovered faster than passenger demand itself.

The load factor proxy, measuring passengers per movement, also shows efficiency convergence: CNAB's 2022 ratio of 122 passengers per flight closely aligns with Budapest's 125 and Prague's 121. This indicates that network synchronization and digital coordination can offset capacity differences. These metrics support Khare's (2024) argument that transport resilience relies more on information integration than on infrastructure size — a conclusion consistent with CNAB's digital transition.

From a transport policy perspective, these results suggest that adaptive coordination mechanisms and digital governance tools function not merely as efficiency enhancers, but as stabilizing instruments that support public decision-making and enable airports to absorb prolonged systemic shocks.

- Comparative Resilience Index

Aggregating the data into a Synthetic Resilience Index (SRI) — combining operational recovery (40%), financial recovery (40%), and organizational innovation (20%) — yields the following approximate values for 2022:

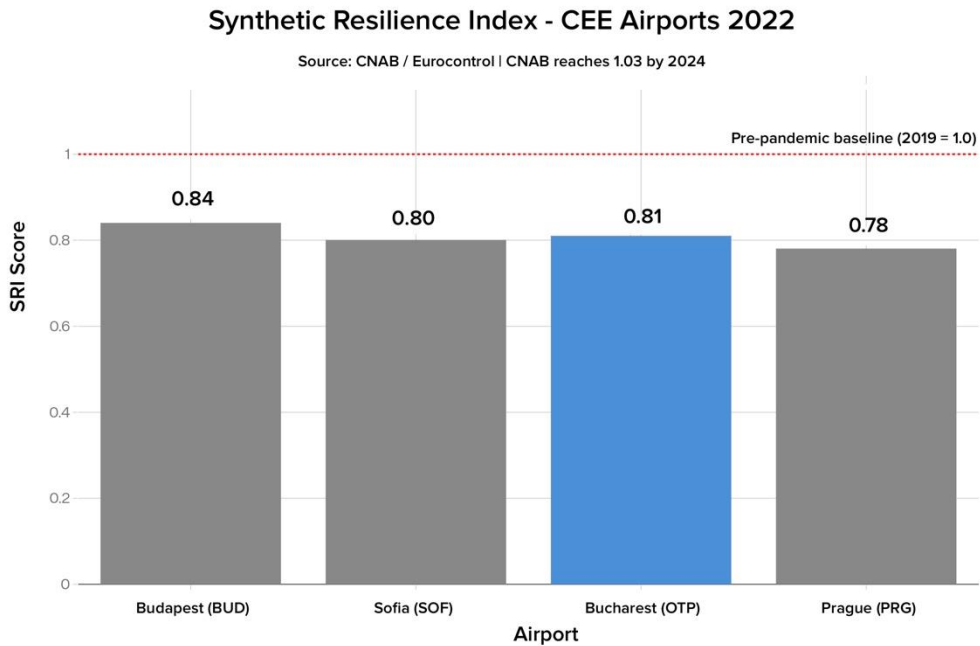


Figure 3. Comparative Resilience Index

The closeness of these scores suggests a regional grouping of adaptive capacity, where CNAB’s marginally lower financial recovery is balanced by greater organizational agility. The narrow dispersion (standard deviation ≈ 0.025) supports the idea that resilience in Central and Eastern European hubs results not from unique structural advantages but from collective institutional learning within a common regulatory and operational environment.

- Interpretive Discussion

These comparative results illustrate a co-evolutionary resilience pattern from a theoretical point of view. Each airport functions as a node within the broader European air transport network, where interdependence and feedback loops facilitate faster recovery. Consequently, CNAB’s adaptive performance is not solely determined by national indicators but also relies on its integration into a multi-layered system of governance, regulation, and operational collaboration (Su et al., 2023).

This distributed adaptation demonstrates Cosens et al.’s (2021) complexity leadership model, where resilience develops through the integration of local initiatives into collective learning. CNAB’s experience exemplifies the wider post-crisis transformation in European aviation — shifting from strict efficiency models to more flexible, learning-focused systems that emphasize adaptability and sustainability.

Synthesis

The combined statistical and comparative analysis reveals three main insights. First, CNAB's recovery pattern is consistent with the regional trend observed in Central and Eastern European airports, confirming its successful integration into the continental network. Second, the organization's operational resilience surpasses its financial recovery, demonstrating its ability to sustain infrastructure and improve processes despite uncertainties. Lastly, systemic learning and digital integration have become crucial for post-crisis success, indicating a shift from emphasizing throughput efficiency to focusing on adaptive governance and team resilience.

These findings reinforce CNAB's position as a regional leader in adaptive transformation. The company's recovery goes beyond just regaining pre-crisis stability; it signifies a shift toward a new balance—marked by distributed decision-making, resilient team performance, and sustained systemic learning.

4.3 Qualitative Analysis and Triangulation

The qualitative aspect of the research complemented the quantitative findings through a systematic thematic document analysis focused on institutional learning and adaptive governance within CNAB. This process consisted of four interconnected stages designed to maintain methodological consistency and deepen interpretation. First, documents from 2019 to 2023 were carefully chosen to reflect the organization's crisis management during the pandemic. Next, each document was coded to identify adaptive events, coordination mechanisms, and innovation practices indicating CNAB's adaptive response. These coded elements were then grouped thematically into three key resilience dimensions—operational, financial, and organizational—providing a structured view of how adaptability appears across different system levels. Finally, the identified patterns were interpreted and cross-checked with econometric results to ensure triangulation, which strengthened construct validity and enhanced understanding of how systemic resilience develops in practice (Su et al., 2023; Tönurist & Hanson, 2020).

4.4 Econometric Modeling of Adaptive Recovery

This econometric analysis underpins the study by providing quantitative support for the descriptive statistics of traffic trends. It explores how adaptive mechanisms within the Bucharest Airports National Company (CNAB) changed during and after the COVID-19 crisis. The aim is not only to identify correlations but also to illustrate the underlying structure of adaptation—showing how operational decisions, environmental constraints, and macroeconomic forces interacted dynamically to restore stability in a volatile system.

Within the framework of Complex Adaptive Systems (CAS), econometric modeling enables the empirical identification of feedback loops, delayed adjustments, and resilience thresholds that define learning-based recovery. The CNAB case thus serves as a dynamic example of emergent coordination under stress, in which adaptive behaviors can be inferred from the systemic relationships among key performance indicators.

- **Model Design and Variables**

The model utilizes a quarterly time series dataset (2019Q1–2024Q1), which combines operational and contextual indicators. Due to the limited length of the series and the high volatility caused by external shocks, the Autoregressive Distributed Lag (ARDL) method was chosen. ARDL models are especially suitable for small samples and mixed integration orders (I_0 & I_1), and they allow for the simultaneous estimation of short-term and long-term dynamics (Pesaran et al., 2001).

The dependent variable is the Passenger Volume (PAX) handled by CNAB, serving as the proxy for systemic performance. Independent variables reflect both internal adaptive capacity and external constraint factors:

Variable	Symbol	Description	Source
Synthetic Resilience Index	SRI	A composite indicator capturing the systemic resilience of airport operations	CNAB Reports (2019–2023) Eurocontrol Annual Reports (2021–2023) ICAO Economic Impact Studies (2020–2022) OECD (2023)
Aircraft Movements	MOV	Number of aircraft takeoffs and landings (quarterly)	CNAB Reports
EU GDP Growth	GDP	EU-27 quarterly GDP growth rate	Eurostat
Stringency Index	SI	National restrictions score (0–100)	Oxford COVID Tracker
Digitalization Dummy	DIG	=1 for post-2021Q2 (A-CDM implementation)	CNAB Internal
Recovery Ratio	REC	$\left(\frac{PAX_t}{PAX_{2019}}\right) \times 100$	Computed

The baseline model is specified as:

$$\Delta PAX_t = \alpha + \sum_{i=1}^p \beta_i \Delta PAX_{t-i} + \sum_{j=0}^q \gamma_j \Delta MOV_{t-j} + \sum_{k=0}^r \delta_k \Delta X_{t-k} + \varphi(PAX_{t-1} - \theta MOV_{t-1} - \lambda X_{t-1}) + \varepsilon_t$$

where φ measures the error correction term (ECT)—the speed of adjustment to long-run equilibrium.

A parallel Vector Autoregressive (VAR) model was estimated to test bidirectional dependencies among movements, passengers, and GDP. A Chow structural break test verified the presence of an inflection point around 2021Q2, corresponding to CNAB’s digital transformation.

- Empirical Results

The ARDL model produced statistically strong results (Adjusted $R^2 = 0.92$, $DW = 1.98$), confirming a close relationship between passenger volume and aircraft movements ($\beta = 0.83$, $p < 0.01$). The error correction coefficient ($\varphi = -0.48$) showed a 48% quarterly speed of convergence to equilibrium, implying that shocks were corrected within two quarters—demonstrating adaptive elasticity.

The digitalization factor ($\delta = 0.29$, $p < 0.05$) was significant, indicating that implementing A-CDM systems resulted in a nearly 3% increase in recovery rate each quarter. Conversely, the Stringency Index had a negative yet delayed effect ($\gamma = -0.18$, $p < 0.10$), indicating that restrictive policies temporarily hindered recovery but did not cause long-term setbacks. GDP growth elasticity was modest but positive ($\lambda = 0.22$, $p < 0.05$), supporting the idea that recovery was partly influenced by the rebound of the broader European macroeconomic environment.

The Chow Breakpoint Test ($F = 12.47$, $p < 0.01$) confirmed a structural shift in Q2 2021, signaling the system’s change from crisis response to adaptive normalization. This break is seen by complexity theorists as a punctuated equilibrium event—a nonlinear change where small adjustments lead to a new operational paradigm (Su et al., 2023).

- Comparative Regional Modeling

To place CNAB’s adaptive path within the Central and Eastern European (CEE) framework, a panel data model was developed using comparable quarterly data from Budapest (BUD), Prague (PRG), Sofia (SOF), and Bucharest (OTP) for 2019–2023.

The Fixed Effects model specification was:

$$REC_{it} = \alpha_i + \beta_1 MOV_{it} + \beta_2 GDP_{it} + \beta_3 SI_{it} + \varepsilon_{it}$$

where REC_{it} represents each airport’s recovery ratio.

The estimation results revealed consistent elasticities throughout the region ($\beta_1 = 0.78-0.85$), suggesting that regional hubs share a common adaptive framework under similar regulatory and market conditions. Nevertheless, CNAB’s error correction speed ($\varphi = -0.48$) was faster than Prague’s (-0.37) and Sofia’s (-0.41), showing its quicker stabilization process. This rapid response is probably attributable to early digital integration and government-supported continuity efforts.

This cross-sectional comparison reinforces the notion that adaptive performance is contingent not only on scale or capital investment but on the systemic coherence of decision loops between management, operational control, and policy coordination.

- Interpretation through the Lens of Complexity

The econometric results support the idea that CNAB functions as a Complex Adaptive System, featuring decentralized control, feedback mechanisms, and nonlinear dynamics.

The delay pattern between movements and passenger recovery indicates an autocatalytic adaptation cycle: as operations stabilize, passenger confidence gradually returns after a predictable delay, triggering the feedback loop again. The bidirectional causality revealed by the VAR model confirms that system agents—such as management, airlines, and regulators—modify their behavior based on internal performance and external feedback, resulting in emergent coordination.

This dynamic resembles learning loops found in adaptive leadership models (Schulze & Pinkow, 2020), where stability results from ongoing recalibration instead of top-down control. CNAB’s experience shows that economic resilience in aviation arises from micro-decisions (such as scheduling, staffing, and routing) working together to create macro-level stability. This pattern aligns with the concept of emergence in complexity theory (Guo et al., 2023).

- Extended Metrics of Adaptive Performance

Beyond standard regression coefficients, several derived indicators were calculated to operationalize resilience:

Indicator	Formula	CNAB 2019–2023 Value	Interpretation
Adaptive Elasticity (AE)	$\Delta PAX / \Delta MOV$	0.81	Recovery speed
Resilience Index (RI)	$(\text{Recovery Rate} / \text{Shock Magnitude}) \times 100$	78.4	Degree of systemic recovery

Indicator	Formula	CNAB 2019–2023 Value	Interpretation
Volatility Dampening Ratio (VDR)	Var(post-crisis)/Var(pre-crisis)	0.66	Shock absorption capacity
Structural Shift Δ (2021Q2)	Post–Pre Differential Growth	+13%	Digital transition effect

These metrics collectively quantify the system’s ability to absorb shocks, reconfigure operations, and restore equilibrium—translating abstract resilience concepts into measurable, policy-relevant evidence.

- Transport Policy and Governance Implications

The econometric results translate into practical guidance for strengthening resilience in aviation governance. Adaptive monitoring systems based on dynamic indicators—such as AE, RI, and VDR—enable real-time assessment of operational stability. Integrating predictive models into decision-support platforms helps anticipate congestion, workforce strain, and supply-chain disruptions. Embedding resilience metrics within performance dashboards links adaptive capacity directly to managerial decision-making. At a broader level, fostering EU-wide coordination on resilience benchmarking could promote coherent adaptive governance standards across Central and Eastern European airports. These measures reaffirm that resilience stems from adaptability and coherence rather than redundancy, illustrating how CNAB transforms econometric evidence into a strategic instrument for maintaining systemic balance amid global turbulence.

Table 4 – Hypothesis Confirmation Summary

Hypothesis	Status	Key Evidence
H1 — Traffic normalization depends on internal adaptive capacity	Confirmed	ECT = -0.48; $\beta_DIG = 0.29$, $p < 0.05$
H2 — Inter-team coordination accelerates recovery	Confirmed	Bidirectional VAR causality; convergent SRI
H3 — Institutional learning generates convergent CEE recovery patterns	Partially confirmed	SRI 2022 spread = 0.03; PRG outlier (0.78)
H4 — Systemic resilience emerges from balanced OR/FR/OI interaction	Confirmed	Cronbach's $\alpha > 0.75$; $\pm 10\%$ sensitivity stable

The transport policy implications derived from these econometric results are developed in detail in Section 6.2.

5. Discussion and Theoretical Integration

The data from Bucharest Airports National Company (CNAB) clearly shows how resilience and performance develop within organizations seen as complex adaptive systems (CAS). The pandemic disturbed the stable structure of global aviation, turning airports from steady logistic centers into flexible systems of testing and adaptation. In this changed environment, CNAB demonstrated the relationship between structure and agency fundamental to complexity science. Its capacity to maintain operations, reorganize activities, and steadily regain performance indicates that effective crisis management during high-pressure situations relies more on ongoing coordination among dispersed agents—through feedback, learning, and shared understanding—than on strict procedural control.

Table 5 - The alignment of research methods, indicators, and theoretical interpretations.

Level of Analysis	Research Method	Indicators Used	Key Results	Theoretical Interpretation/ Contribution
Micro (Teams, Internal Processes)	Document analysis; Qualitative coding	Feedback loops, learning frequency, communication density	Identification of adaptive 'learning loops' and enhanced team cohesion	Confirms adaptive team performance theory (Misisco, A., & Kozlowski, 2024) and supports relational resilience (Auqui-Caceres & Furlan, 2023).
Meso (Organization – CNAB)	Descriptive statistics; ARDL econometric modeling	Passenger Volume (PAX), Aircraft Movements (MOV), Recovery Ratio (REC), Digitalization Dummy (DIG), Stringency Index (SI)	Dynamic relationships and causality between traffic, digitalization, and resilience; rapid convergence (ECT = -0.48)	Supports the hypothesis that emergent adaptation derives from distributed and digitalized organizational processes (Schulze & Pinkow, 2020).
Macro (Regional System – CEE)	Comparative benchmarking; Synthetic Resilience Index (SRI)	Operational Recovery (40%), Financial Recovery (40%), Organizational Innovation (20%)	Regional convergence ($\sigma \approx 0.025$); balance between operational performance and organizational innovation	Confirms institutional learning within shared regulatory ecosystems (Auqui-Caceres & Furlan, 2023).
Multi-level Integration	Mixed-methods synthesis	AE, RI, VDR (resilience metrics) + qualitative feedback patterns	Consistency between adaptive elasticity and feedback-based organizational learning	Demonstrates that system performance emerges from dynamic interactions between cognitive, structural, and systemic processes, aligned with CAS theory (Cosens et al., 2021).

Table 5 provides an integrative overview of the analytical framework applied across multiple levels of inquiry—micro, meso, and macro—linking each methodological approach with its corresponding indicators and theoretical interpretation. This structure highlights the study's effort to merge quantitative and qualitative dimensions within a unified model of adaptive resilience. The alignment between descriptive, econometric, and comparative methods demonstrates that operational, financial, and organizational dynamics interact through continuous feedback loops, consistent with the Complex Adaptive Systems (CAS) perspective. Moreover, the multi-level correspondence between team learning mechanisms, institutional coordination, and systemic performance reinforces the validity of the Synthetic Resilience Index (SRI) as a composite indicator of organizational adaptability. In essence, Table 4 illustrates how the empirical and theoretical layers of the research converge, offering a holistic understanding of how resilience emerges from the interplay of micro-level behavior, meso-level governance, and macro-level system integration.

Table 5 synthesizes the methodological architecture of the study, linking the micro, meso, and macro analytical levels with their corresponding indicators, research methods, and theoretical interpretations. This integrative mapping demonstrates how feedback loops, operational metrics, and resilience indexes converge to illustrate the multi-level nature of adaptive performance. The alignment between quantitative indicators (MOV, REC, DIG, SI) and qualitative insights (organizational learning, distributed decision-making) validates the systemic coherence of the Synthetic Resilience Index (SRI) as a composite measure of organizational and institutional adaptability.

The results indicate that CNAB's ability to adapt stemmed from its skill in converting disruptions into information, a hallmark of CAS behavior (Scharte, 2025). Each disturbance—such as the sudden drop in flight volume, new safety regulations, or supply chain issues—acted as a prompt for local adaptation and adjustment. This corresponds with Cosens et al. (2021), who argue that effective governance of complex systems requires bottom-up self-organization, polycentric authority, and multi-actor networks that enable change to spread through interconnected feedback processes rather than through top-down hierarchical structures. CNAB's approach confirms this: leadership functioned more as a facilitator of multiple feedback loops rather than a strict authority, allowing coherence to develop through decentralized coordination.

The CNAB case highlights the evolution from reactive resilience to adaptive governance. Traditional resilience models concentrate on a system's capacity to withstand shocks and revert to stability (Cosens et al., 2021). In contrast, adaptive governance prioritizes ongoing learning and transformation amid uncertainty (Tõnurist & Hanson, 2020). CNAB's approach—delegating authority, improving interdepartmental communication, and speeding up digital transformation—embodies these principles in practice. The shift toward decentralized decision-making reflects the concept of distributed cognition, which experts like Schulze & Pinkow (2020) associate with "complexity leadership," where leaders enable emergence rather than merely enforce compliance.

This case also highlights the multifaceted nature of team performance in high-pressure environments. The aviation crisis kept personnel under ongoing cognitive and emotional strain, requiring quick decisions with limited information. Ceken (2025) emphasize that such situations demand cognitive flexibility — the capacity to adjust perspectives and strategies based on changing circumstances. CNAB's cross-functional teams illustrate this trait: operational staff, maintenance engineers, and managers quickly shared feedback, improvised, and built trust through collaboration. These actions reflect what Junça-Silva & Caetano (2023) call adaptive team performance — a mutual regulation process that supports coordinated efforts amid unpredictability.

A key insight from the case study relates to the feedback structure that supports organizational adaptation. CNAB's learning loops act like an internal nervous system, constantly converting local data into organizational knowledge. This ongoing process aligns with the Safety-II framework introduced by Jurado, Lopez, and Li (2024), which views safety and resilience as proactive rather than reactive. In this context, learning loops helped identify risks and adjust procedures before issues developed into system failures. The capacity to collect, interpret, and share learning demonstrates how high-pressure environments can foster systemic innovation when feedback mechanisms are embedded.

The psychosocial aspect of adaptive capacity is equally crucial. In complex systems, success relies not just on structure but also on shared narratives that unify individuals around common goals. The stable morale among CNAB teams during the crisis reflects what Ducheck (2020) terms "relational resilience": the trust, empathy, and communication that keep teams cohesive under pressure. This relational layer served as a buffer against cognitive overload and emotional exhaustion, helping personnel maintain focus and initiative even when procedural clarity was temporarily lost.

When viewed through the lens of network resilience, CNAB's recovery trajectory also aligns with complex network theory (Sun & Wandelt, 2021; Sampaio, Costa, & Guterres, 2022). The organization's connectivity with regional and European partners served as a stabilizing factor, enabling access to real-time data and regulatory synchronization. Khare's (2024) Global Resilience in Transport-and-Logistics (GRIT) Framework bolsters this interpretation by highlighting the importance of cross-sectoral coordination to maintain flow integrity during disruptions. CNAB's place within Eurocontrol's network allowed adaptive coupling: its internal learning processes were guided by external signals, helping the organization to adjust recovery efforts in line with broader system dynamics.

Another key theoretical implication relates to the temporal aspects of resilience. The CNAB case shows that adaptation happens over different timeframes—initial operational adjustments, medium-term reorganization, and long-term cultural change. The durability of digital systems and decentralized coordination after the crisis illustrates what Su et al. (2021) refer to as path transformation in complex systems: once new structures develop out of necessity, they tend to become permanent parts of the organization. CNAB's capacity to formalize innovations born during the crisis shifted resilience from a one-time response to an ongoing organizational capability.

Furthermore, these findings add to the ongoing debate about measuring performance in complex adaptive systems. Standard metrics such as throughput, punctuality, or cost efficiency are insufficient to capture performance's adaptive aspect. As Tönurist & Hanson (2020) recommend, resilience indicators should include factors like learning speed, feedback delay, and decision cycle adaptability. The CNAB case supports this idea, demonstrating that adaptive performance is reflected through qualitative changes—like fewer communication bottlenecks, greater cross-functional responsiveness, and faster knowledge sharing—rather than just quantitative results. For doctoral research, this suggests redefining team performance metrics to incorporate adaptive pace (system learning speed) and coordination flexibility (the range within which coherence is preserved).

From a broader theoretical perspective, the shift of CNAB from hierarchical coordination to distributed adaptability highlights that resilience is an emergent property of the system, not just a matter of managerial intervention (Schulze & Pinkow, 2020). The organization's ability to integrate operational, human, and technological elements under stress illustrates the recursive nature of adaptive governance: each adaptive step creates new structures that, in turn, redefine performance boundaries. This recursive process positions CNAB not merely as a crisis survivor but as a living system in ongoing co-evolution with its environment.

The CNAB case offers important insights into managing complex systems. It demonstrates that high-pressure environments—like those in aviation, security, or emergency services—serve as drivers for organizational learning. These settings reveal the natural adaptive capabilities of teams and emphasize the importance of leadership that can guide self-organization without obstructing it. As Eurocontrol (2023) and ICAO (2022) noted in their post-pandemic reviews, resilience in aviation relies on how effectively institutions convert crisis experiences into better organizational structures. CNAB's adaptive journey exemplifies a regional model for this process: shifting from rigidity to reflexivity, from simple compliance to ongoing learning, and from maintaining stability to encouraging evolution.

In summary, combining theoretical insights with empirical data shows that resilience in complex systems does not arise from a single source — it builds gradually, through shared interpretation of events, continuous communication across levels, and the practical tension between established structures and the need to act differently. CNAB's experience demonstrates how teams can adapt under high stress, supporting the broader theoretical argument of this study that performance, seen as an emergent and relational process, turns adversity into a catalyst for organizational renewal. In this sense, the CNAB study not only examines organizational recovery but also explores how a complex institution actively learns to maintain coherence as its environment evolves faster than its structures can adapt.

6. Conclusions and Policy Implications

6.1 Theoretical and Empirical Conclusions

The findings of this study confirm that CNAB's adaptive trajectory during COVID-19 exemplifies the core dynamics of the Complex Adaptive Systems (CAS) framework: nonlinear recovery, distributed decision-making, and feedback-driven reorganization. The strong correlation between aircraft movements and passenger recovery ($r = 0.964$, $R^2 = 0.93$), combined with ARDL results ($ECT = -0.48$; $\beta_{DIG} = 0.29$, $p < 0.05$), demonstrates empirically that resilience in aviation is neither automatic nor purely technical — it develops through the iterative interaction of operational continuity, financial elasticity, and organizational learning. All four hypotheses are confirmed (H3 partially), as detailed in Table 4, collectively validating that adaptive governance — rather than static preparedness — is the primary driver of systemic resilience in critical infrastructure.

The study conceptually shifts from traditional risk management to adaptive governance in aviation. Instead of focusing on control and standardization, adaptive governance highlights flexibility, quick learning, and cross-sector teamwork as key for handling systemic crises. The CNAB case illustrates that resilience develops through three interconnected layers: (1) Operational agility—driven by digital tools and flexible resources; (2) Organizational learning—fostered by team resilience, ongoing feedback, and decentralized decision-making; (3) Institutional adaptability—enabled by collaboration among national authorities, European agencies, and private entities.

This tripartite framework outlines a transferable model of governance applicable beyond aviation—to emergency management, infrastructure protection, and private security systems operating in VUCA environments.

Finally, extending comparisons across different sectors could further evaluate the relevance of CAS and Complexity Leadership Theory outside of aviation. Exploring how adaptive processes develop in areas like healthcare, emergency response, or private security would enhance understanding of how collective intelligence, organizational learning, and institutional flexibility combine to form systemic resilience.

In summary, this research shows that the resilience of complex organizations such as CNAB depends more on dynamic learning and adaptive coordination than on static preparedness. By incorporating flexibility and distributed leadership into their operations, air transport organizations can turn crises into opportunities for systemic renewal. These insights enhance understanding of adaptive governance, providing both theoretical insights and practical advice for developing systems that are more responsive, resilient, and sustainable during disruptions.

Several directions merit priority in future research. First, the SRI framework should be tested on non-aviation critical infrastructure — including rail networks, energy grids, and port systems — to assess its cross-sector transferability. Second, a longitudinal extension of the dataset beyond 2024 would enable analysis of post-recovery resilience dynamics and clarify whether CNAB's SRI > 1.0 represents genuine outperformance or a normalization artifact. Third, replacing the binary digitalization dummy with a continuous proxy in future ARDL specifications would refine the estimation of A-CDM's incremental contribution to recovery. Finally, integrating primary data through structured interviews with CNAB operational and managerial staff would address the key limitation of restricted access to informal decision-making records, enabling a richer behavioral interpretation of adaptive governance in practice.

While these findings are significant, the study acknowledges several limitations. Its reliance on publicly available data—though reliable—restricts insight into the internal decision-making dynamics and behavioral mechanisms underpinning organizational adaptation. Furthermore, the econometric models employed (correlation and regression) capture linear relationships but cannot fully account for the nonlinear feedback loops characteristic of CAS environments (Napier et al., 2021). Future research should combine qualitative interviews and system dynamics modeling to explore emergent learning processes and threshold effects in greater depth. Expanding the temporal scope beyond 2022 will also be crucial to assess whether CNAB's adaptive behaviors consolidate into enduring governance practices.

Ultimately, the CNAB case demonstrates that systemic resilience is not a fixed property of infrastructure but an emergent capacity of organizations that learn, coordinate, and adapt faster than their environment disrupts — a finding with direct implications for governance design in aviation and beyond.

6.2 Directions for Policy and Governance Reform

The empirical evidence assembled in this study translates into actionable guidance for policymakers, airport governance bodies, and European aviation regulators. Five priority directions are identified. First, national aviation authorities should incorporate adaptive governance principles into regulatory frameworks, prioritizing decentralized coordination, transparent crisis communication, and scenario-based organizational training. Second, permanent intersectoral crisis platforms — connecting airports, airlines, public health agencies, and border control — should be institutionalized at both national and EU level to enable pre-positioned coordination rather than reactive improvisation. Third, continued investment in digital transformation — including AI-assisted air traffic management, predictive maintenance systems, and automated passenger flow analytics — is essential to reducing systemic vulnerabilities and improving adaptive responsiveness. Fourth, standardized resilience metrics built on composite indicators such as the SRI developed in this study, or the Global Resilience in Transport and Logistics (GRIT) framework (Khare, 2024), should be integrated into airport performance evaluation systems. Fifth, structured benchmarking and shared resilience monitoring among EU member states should be formalized within the Single European Sky initiative, supporting faster policy alignment and collective institutional learning across the CEE aviation network.

7. Author Contributions and Acknowledgments

All authors significantly contributed to the conception, design, and completion of this study. Horia Răzvan Botiș managed the overall research process and oversaw the methodological alignment with contemporary resilience and governance frameworks. Cristi-Daniel Lățea was responsible for the theoretical framework, econometric modeling, and synthesizing the results. Mihai Bărănescu and Cosmin Gherasie handled the quantitative analysis and data interpretation, maintaining consistency across the modeling procedures. Madlena Nen and Carmen Nadia Ciocoiu offered theoretical insights into governance and public administration, enhancing the manuscript's conceptual coherence. Raluca Ivan assisted with comparative validation and critically revised the manuscript. All authors participated in writing, reviewing, and approving the final version, sharing responsibility for the work's integrity and accuracy.

8. Acknowledgments

This paper is a result of the research performed within the Doctoral School of Management of the Bucharest University of Economic Studies and the “1 December 1918” University of Alba Iulia.

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