

FROM VUCA TO BANI: A PARADIGM SHIFT IN CRITICAL INFRASTRUCTURE RESILIENCE – A COMPREHENSIVE CASE STUDY OF THE BUCHAREST CENTRALIZED HEATING SYSTEM

Olga BUCOVETȚCHI***, Mihaela Beatrice ISTUDOR**

***“Nicolae Bălcescu” Land Forces Academy, Sibiu, Romania

**National University of Science and Technology Politehnica Bucharest, Romania

olga.bucovetchi@upb.ro, mihaela.istudor@stud.faima.upb.ro

Abstract: *The global landscape of critical infrastructure management is undergoing a fundamental transformation. For decades, the VUCA (Volatility, Uncertainty, Complexity, Ambiguity) framework provided the primary lens for risk assessment. However, the contemporary era—marked by climate instability, rapid technological disruptions, and systemic fragility—demands a more nuanced approach. This paper explores the transition to the BANI (Brittle, Anxious, Nonlinear, Incomprehensible) paradigm, focusing on its implications for the Bucharest centralized heating system (CMTEB). By combining resilience theory with empirical data from a specialized questionnaire involving 62 technical experts and managers, the study evaluates systemic vulnerabilities and the role of emerging technologies. The findings indicate that while traditional robustness is declining, the integration of Digital Twins, AI-driven predictive maintenance, and IoT-based monitoring offers a strategic pathway to transition from structural brittleness to systemic resilience.*

Keywords: BANI, VUCA, centralized heating system, resilience

1. Introduction

For over thirty years, the strategic landscape was dominated by the “VUCA” acronym, a concept popularized by the United States Army War College to describe the multilateral world following the end of the Cold War. In this framework, managers focused on mitigating Volatility through agility, addressing Uncertainty with information, managing Complexity by restructuring, and resolving Ambiguity through experimentation. However, as noted Trump & Linkov, the interconnectedness of modern global systems has created risks that VUCA no longer adequately captures [1]. The crises of the early 2020s—ranging from the logistical collapses during the pandemic to the energy shocks caused by regional conflicts—suggested that our systems are not just complex, but fundamentally fragile and unpredictable.

In response to these limitations, Cascio proposed the BANI framework, providing a more relevant vocabulary for understanding the dynamics of today’s chaotic environment [2]. While VUCA described the symptoms of a changing world, BANI describes the state of the systems themselves.

- Brittle - this dimension refers to systems that are susceptible to sudden, catastrophic failure despite appearing robust on the surface. In the context of critical infrastructure, brittleness is often the result of an over-optimization for efficiency at the expense of redundancy [1]. For instance, the Texas power grid failure of 2021 serves as a classic example of a brittle system that collapsed under a nonlinear weather event.
- Anxious - unlike uncertainty, which is an informational gap, anxiety is a psychological state induced by the constant

threat of disaster. In critical infrastructure management, this manifests as a fear that any minor technical glitch could escalate into a social crisis, leading to what Hanson, D. et al. describe as strategic paralysis [3].

- **Nonlinear** - these challenges the traditional cause-and-effect models of engineering. In a nonlinear environment, small perturbations (such as a 1% pressure drop in a thermal pipeline) can trigger disproportionate consequences (a district-wide blackout), making traditional risk matrices obsolete [4].

- **Incomprehensible** - represents the “data-information paradox”. We possess more telemetry than ever, yet we understand less about the systemic root causes of failure. The complexity has evolved into a state where human cognition alone cannot parse the interdependencies without the aid of machine learning [5].

The Bucharest centralized heating system (CMTEB) represents a good example of a BANI system. As the second-largest centralized heating network in the world, serving over 1.2 million citizens through nearly 4,000 km of pipes, its operation is vital for the social and economic stability of the Romanian capital. The primary transport network consists of 954 km of pipelines, while the secondary distribution network includes 2,963 km of pipelines. However, the system is currently trapped in a “brittleness trap”. Decades of underinvestment have resulted in a network where over 70% of the primary transport pipes have exceeded their technical lifespan [6].

Within the BANI paradigm, the CMTEB's failure is not merely a technical event but a multi-dimensional crisis. The system generates profound social anxiety every winter, as citizens and decision-makers alike face the incomprehensibility of a network that loses thousands of tons of hot water per hour without precise localization. The failures are notoriously nonlinear; a rupture in one main pipeline can alter the hydraulic balance of the entire city, causing secondary

breaks in seemingly unrelated sectors. This study highlights that the resilience of such a system can no longer be maintained through traditional “break-fix” maintenance but requires a radical shift toward technological “comprehensibility.”

This study seeks to bridge the gap between high-level BANI theory and the practical realities of urban infrastructure management. By focusing on CMTEB, the study pursues three main objectives. First, it seeks to correlate the four BANI dimensions with the specific technical and organizational stressors currently impacting the Bucharest district heating network. Second, it uses empirical evidence gathered through the designed questionnaire to assess the system’s “Brittleness” and “Nonlinearity” as perceived by those most familiar with its vulnerabilities. Finally, the paper outlines a technological roadmap—centred on the integration of IoT, AI, and Big Data—aimed at restoring systemic comprehensibility and establishing a new foundation for urban resilience.

2. Research methodology

The research methodology is based on a convergent mixed-methods design, enabling the triangulation of qualitative theoretical insights with quantitative empirical data. The study employs the “Resilience Matrix” framework as its main analytical instrument, focusing on four key stages of systemic resilience: the capacity to plan and prepare for disruptions, the ability to absorb shocks, the efficiency of recovery processes, and the long-term capability to adapt [1]. This holistic approach ensures that resilience is not viewed as a static state of “robustness” but as a dynamic process of institutional learning.

To capture the lived reality of the system's operation, the research design incorporates a survey-based approach. This method was chosen because technical logs and maintenance reports often fail to capture the “organizational anxiety” or the perceived “incomprehensibility” of failures that are

central to the BANI framework. By gathering insights directly from the technical and managerial staff, the study gains a more nuanced understanding of the systemic thresholds and the informal strategies used to manage the network's brittleness.

The primary data collection instrument was a structured "Resilience perception questionnaire", specifically developed to translate abstract BANI concepts into measurable technical and operational indicators. The questionnaire comprised 25 items, meticulously curated to reflect four thematic chapters.

- Structural integrity, sought to quantify "Brittleness" by evaluating asset age, the frequency of unplanned outages, and the perceived proximity of a systemic tipping point.
- Response capability investigated "Nonlinearity" by measuring the time-lag between failure detection and restoration, as well as the predictability of the system's hydraulic behaviour under stress.
- The third part addressed Organizational psychology, focusing on the "Anxiety" dimension. It explored the clarity of internal communication channels, the stress levels of the operational staff during the winter peak, and the degree of confidence in current contingency plans.
- Technological readiness assessed the penetration of "Industry 4.0" tools, such as SCADA systems, GIS mapping, and automated sensors, providing a baseline for the proposed technological roadmap.

To enhance the validity and reliability of the findings, a targeted sampling strategy was adopted, involving 62 respondents with substantial expertise in the Bucharest thermal energy system. The sample was deliberately stratified to capture a broad range of organizational perspectives. Senior managers and key decision-makers

accounted for 25% of participants, contributing insights into strategic priorities as well as political and economic constraints. Field engineers with more than ten years of experience formed the largest group (45%), providing a practical perspective on the infrastructure's physical deterioration. The remaining 30% comprised operational personnel and control room technicians, who offered valuable information on the day-to-day challenges and complexity of managing the network. This balanced representation ensures that the findings reflect both the strategic and tactical challenges of the BANI environment. The quantitative data derived from the questionnaire were processed using descriptive statistics to identify central tendencies and correlation analysis to explore the relationships between variables — such as the link between aging assets and operational anxiety. Simultaneously, qualitative comments and open-ended responses were coded using thematic analysis. This dual approach was particularly effective in identifying recurring patterns of "systemic frustration", which serves as a qualitative approach for the "Incomprehensible" dimension of the BANI framework. The results were further validated against historical maintenance reports and internal audit data from the 2022-2023 and 2023-2024 heating season, ensuring that the perceptions recorded in the survey align with the empirical reality of the system's performance.

3. Analysis results

To provide a structured overview of the empirical findings, Table 1 synthesizes the correlation between the BANI framework dimensions and the specific technical and operational indicators assessed through the expert survey, highlighting the predominant trends identified in the 62 responses.

Table 1: Integrated Framework of Research Results (Expert Survey Synthesis, n=62)

Questionnaire Section	BANI Dimension	Key Indicators / Research Focus	Main Findings and Statistical Insights
I. Structural Integrity	Brittle	Asset age, frequency of unplanned outages, proximity to systemic tipping point.	78% of experts categorize the network as "critically brittle". Over 60% of primary pipelines have exceeded their 25-year service life.
II. Response Capability	Nonlinear	Failure detection-to-restoration lag, predictability of hydraulic behavior under stress.	A 20% increase in maintenance effort did not lead to a proportional decrease in fluid losses, confirming a nonlinear feedback loop.
III. Organizational Psychology	Anxious	Internal communication clarity, operational staff stress levels, confidence in contingency plans.	65% of staff experience chronic stress. 40% of operational personnel exhibit decision-making paralysis due to fear of catastrophic errors.
IV. Technological Readiness	Incomprehensible	Penetration of Industry 4.0 tools (SCADA, GIS, IoT-based monitoring).	82% of respondents feel they are "flying blind" during technical incidents. Less than 15% of the secondary network is equipped with IoT sensors.

3.1. Empirical evaluation of systemic brittleness

The synthesis of data from the Structural integrity part reveals a profound alignment between the BANI concept of “Brittleness” and the current state of the CMTEB infrastructure. A staggering 78% of the sampled experts categorized the primary transport network as “critically brittle”, a term that suggests a system maintaining an appearance of functionality while concealing a total lack of internal resilience. The aging of assets emerged as the primary driver of this fragility; our analysis confirms that over 60% of the primary pipelines have exceeded their 25-year service life, creating a “brittleness trap” where the structural integrity of the network is compromised by decades of corrosive degradation and material fatigue. This brittleness is further

quantified by the perceived probability of cascading failures. Approximately 45% of the respondents, primarily those from the field engineering cohort, believe that the system has reached a critical tipping point. In their view, the network no longer possesses the structural redundancy required to absorb localized shocks, meaning that a single rupture in a main pipeline is increasingly likely to trigger a total systemic collapse. This perception of “impending breakage” is a typical for BANI era, where systems fail not through gradual decline, but through sudden, catastrophic transitions from a state of "working" to “broken”.

3.2. Mapping nonlinear dynamics in failure restoration

The research findings regarding “Nonlinearity” challenge the traditional, linear models of infrastructure maintenance.

Analysis of the response capability part indicates a significant disconnection between maintenance effort and systemic stability. Despite a reported 20% increase in localized interventions during the 2022-2023 and 2023-2024 seasons, the data shows that thermal fluid losses did not decrease proportionally; in several critical sectors, the losses actually accelerated. This illustrates a classic nonlinear feedback loop: the process of repairing one weakened segment often involves hydraulic pressure shifts that inadvertently trigger new ruptures in adjacent, equally brittle sections [7]. This nonlinearity is also evident in the temporal dimension of restoration. The time required for system recovery after an outage was found to be increasingly unpredictable. Respondents noted that what used to be a standard 12-hour repair can now escalate into a multi-day crisis due to “secondary complications” that defy traditional engineering expectations. For the CMTEB, nonlinearity means that small, seemingly insignificant operational adjustments can have vast, disproportionate consequences for the entire urban heat supply, rendering traditional cause-and-effect planning insufficient for modern winter peak demands.

3.3. Organizational anxiety and the decision-making crisis

The third dimension of the BANI framework, “Anxiety” was reflected in the data concerning human resources and internal communication. The survey reveals that 65% of the operational and field staff experience chronic stress levels during the heating season, a state that goes beyond professional concern into a deeper form of “systemic anxiety”. This anxiety is rooted in the constant threat of unpredictable failures and the high social stakes of an outage in a city of nearly two million people [4]. A critical consequence of this organizational anxiety is decision-making paralysis. Our results show that 40% of junior and operational staff frequently delay making critical adjustments to flow or pressure until

they receive explicit authorization from senior management. This fear of causing a nonlinear catastrophe through a minor operational error creates a rigid, hierarchical response structure that is the opposite of the agility required for resilience. The “Anxious” organization at CMTEB is thus trapped in a reactive loop, where the fear of failure hinders the very proactive measures needed to prevent it [3].

3.4. The information paradox: From complexity to incomprehensibility

Finally, the study investigated the “Incomprehensible” dimension by evaluating the gap between data availability and operational clarity. The findings suggest that CMTEB is suffering from an acute information paradox. While the system generates vast amounts of telemetry, 82% of the respondents feel they are “flying blind” during large-scale technical incidents. The lack of an integrated, real-time data dashboard means that information remains siloed within disparate departments, making the overall state of the 4,000-kilometer network incomprehensible to those responsible for its management.

This incomprehensibility is enhanced by the low penetration of modern monitoring technologies. With less than 15% of the secondary network equipped with IoT sensors, the detection of leaks remains a manual, almost archaeological process of physical inspection. The expert consensus indicates that the current complexity of the network's degradation has surpassed the limits of human intuition and manual monitoring [6]. Without the aid of advanced digital tools to synthesize and visualize the data, the system's behaviour remains a “black box”, where failures occur without clear warning and restoration efforts are guided more by tradition than by real-time insight.

4. Discussions

4.1. The strategic imperative: moving beyond the VUCA mentality.

The transition from a VUCA to a BANI

environment necessitates a profound reassessment of management strategies for the Bucharest heating system. As argued by Cascio, the shift is not merely an academic nuance but a fundamental change in the ontology of risk [2]. In the previous VUCA paradigm, the primary goal of CMTEB was to reduce uncertainty through better forecasting and to manage complexity through organizational decentralization. However, in the BANI era, the goal must shift toward building capacity for the incomprehensible. This requires a move away from the “illusion of control” that traditional maintenance logs provide. Management must acknowledge that the system is inherently brittle and that failures are not anomalies but expected systemic behavior. According to Trump & Linkov, resilience in such environments is defined by the ability to undergo “graceful degradation” rather than catastrophic collapse [1], a concept that is currently absent from the strategic planning of the Bucharest energy sector.

4.2. Technological interventions as the antidote to BANI stressors

To effectively counter the specific stressors identified in our results, a targeted technological roadmap is essential. Each dimension of the BANI framework can be addressed through a corresponding pillar of Industry 4.0. To mitigate “Brittleness”, the implementation of Digital Twins is paramount. By creating a high-fidelity virtual replica of the physical network that incorporates real-time corrosion data and historical stress patterns, CMTEB can perform predictive simulations that identify “breaking points” before they manifest physically. This aligns with the findings of [7], who emphasize that “smarter” grids tend to exhibit greater resilience, as they are capable of proactively isolating vulnerable node.

Furthermore, to combat the “Incomprehensibility” and “Anxiety” dimensions, the deployment of an integrated IoT-based sensory network is no longer an

option but a survival requirement. The current “information void” identified in our survey can only be filled by real-time telemetry that flows into centralized, AI-driven dashboards. These systems can utilize machine learning to parse nonlinear data patterns—such as subtle pressure fluctuations that precede major ruptures—thereby restoring a level of comprehensibility to the network’s operations. As noted by Bucovetchi, O et al, business optimization in complex environments relies on the ability to transform raw data into actionable insight [5], a process that current CMTEB workflows lack. Providing field teams with access to these real-time dashboards can significantly reduce operational anxiety by replacing guesswork with data-driven confidence [4].

4.3. Cultivating a resilience-oriented organizational culture

The research highlights that technological solutions must be accompanied by an evolution in organizational culture. The “Anxiety” dimension and the resulting decision-making paralysis suggest that CMTEB currently operates under a “culture of compliance” rather than a “culture of resilience”. In a BANI world, the person closest to the point of failure must have the tools and the authority to act. This decentralized approach, recommended by [3], requires a shift toward “organizational resourcefulness”, where staff are trained to be agile and adaptive. Building this culture involves a radical transparency in communication; the current siloed information structure must be dismantled to ensure that every level of the organization understands the systemic interdependencies. Ultimately, the thermal resilience of Bucharest is as much a human and psychological challenge as it is a technical one, requiring leadership that can lead through incomprehensibility.

5. Conclusions

The Bucharest heating system stands at a

crossroads between a 20th-century mechanical past and a 21st-century BANI future. The “brittleness” uncovered by our research is a physical reality that cannot be ignored, but it is the “incomprehensibility” of the system that poses the greatest risk to long-term resilience.

Through our analysis of the 62 expert responses, we conclude that:

- Systemic resilience is currently at a “critical low”: The infrastructure is exceptionally brittle, lacking both the robustness to absorb operational shocks and the redundancy required to bypass failures.
- Digitalization is not an “option” but a “survival strategy”: Integrating advanced technologies like IoT, AI, and Digital Twins

is vital to prevent chronic instability and nonlinear collapse, providing the data clarity essential for modern management.

- A paradigm shift in management is required: Decision-makers must embrace the BANI framework to develop strategies that prioritize “graceful degradation” and “rapid recovery” over the impossible goal of “zero failure” in an aged network.

Ultimately, the thermal resilience of Bucharest depends on our ability to make the incomprehensible, comprehensible. By leveraging technology to map and monitor the system's brittleness, we can transform a fragile infrastructure into a robust pillar of urban life once again.

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