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Unveiling the Intersection of Crisis Management and Resilience in Tackling Real-world Uncertainty in Infrastructure's Emergency Events

Ali Nouri Qarahasanlou

Department of Technology and Safety, UiT the Arctic University of Norway, Tromsø, Norway. E-mail: Ali.Nouri@uit.no

Javad Barabady

Department of Technology and Safety, UiT the Arctic University of Norway, Tromsø, Norway. E-mail: Javad.Barabady@uit.no

Abbas Barabady

Department of Technology and Safety, UiT the Arctic University of Norway, Tromsø, Norway. E-mail: Abbas.b.abadi@uit.no

Mohsen Vahabbi

Department of Technology and Safety, UiT the Arctic University of Norway, Tromsø, Norway. E-mail: Mohsen.Vahabi@uit.no

Managing uncertainty in critical infrastructure during emergency events presents a significant challenge. This paper explores the synergy between crisis management and resilience strategies as complementary approaches to addressing uncertainties in emergency event management. While crisis management focuses on immediate response and recovery, resilience encompasses both short-term reactive measures and long-term adaptability to ensure system robustness. Both approaches play a crucial role in managing complex emergency events, such as infrastructure failures caused by extreme weather events, by ensuring operational continuity and minimizing damage. The study categorizes uncertainties into aleatoric (inherent variability), epistemic (knowledge gaps), stochastic (event-driven risks), and ontological (black swan events), highlighting their impact on decision-making in emergency management. A comprehensive framework is proposed, integrating crisis management with resilience strategies to enhance anticipation, resistance, and recovery from disruptions. The focus of this paper is on Atmospheric Icing Accretion Emergency Events (AIAEEs) in power distribution systems, exploring the integration of predictive maintenance, smart grids, redundancy, and other advanced strategies to improve infrastructure resilience. Additionally, the Onion Model is introduced, offering a layered approach to resilience at personal, organizational, and technical levels. By combining these approaches, stakeholders can enhance infrastructure robustness, mitigate the impact of future emergencies, and address the growing risks posed by climate change. This study provides actionable insights for developing adaptive, robust, and resilient systems in critical infrastructure management.

Keywords: Crisis Management, Resilience Strategies, Uncertainty Management, Emergency Events, Critical Infrastructure

1. Why Linking Crisis Management and Resilience is Matter

When discussing uncertainty from a risk management perspective for “random and dynamic events”, four key categories emerge: “Known Probability-Known Consequences”, “Unknown Probability-Known Consequences”, “known Probability-Unknown Consequences”, and “Unknown Probability-Unknown Consequences,”. Each corresponds to a distinct type of uncertainty: aleatoric (inherent variability), epistemic (knowledge gaps), stochastic (event-driven risks), and ontological (rare, unpredictable events or black swans). Aleatoric uncertainty, such as atmospheric changes affecting ice accumulation on power lines, is irreducible and assessed via quantitative risk analysis. Epistemic uncertainty arises from incomplete knowledge, like the effects of icing, and can be managed through improved understanding. Stochastic uncertainties, like cascading failures during icing events, require systematic investigation and scenario planning. Ontological uncertainty, the most challenging, relates to unpredictable, rare occurrences that necessitate comprehensive risk management -

strategies, including contingency planning for unforeseen black swan events, in which most parts of the emergency events, crises, and disasters take place in this type (Thekdi and Aven 2024; Christer 2017; Vahhabi et al. 2023; Aven 2015). The relationship between these uncertainties is depicted in Figure 1, where the objective is to move from unknowns to knowns using appropriate strategies (progressing from the bottom-left to the top-right).

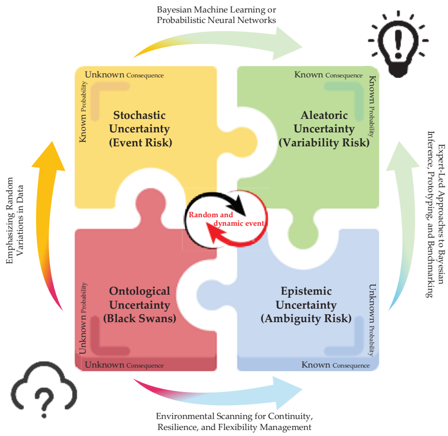

Figure 1: Uncertainties type in emergency event management (Adapted from (Christer 2017; Thekdi and Aven 2024))

In power distribution systems under cold climate conditions, EEs like atmospheric icing accretion (referred to as Atmospheric Icing Accretion Emergency Events (AIAEEs)) involve various types of uncertainties, including aleatoric, epistemic, stochastic, and ontological. To address these challenges, methods such as predictive maintenance, microgrids, redundancy, smart grids, advanced grid analytics, energy storage, community engagement, and weather forecasting are implemented. For example, predictive maintenance utilizes real-time sensor data and advanced analytics to detect and mitigate potential failures proactively, thereby minimizing downtime and enhancing system reliability during icing events (Mahmoud et al. 2021). Microgrids and distributed generation systems provide localized power generation that operates independently of the main grid, ensuring continuous power supply to critical facilities during crises (Kostenko and Zaporozhets 2023). Redundancy entails duplicating critical components in the power distribution network, utilizing backup systems like standby generators and uninterruptible power supplies to eliminate single points of failure. (Hordeski 2020). Smart grids enable efficient electricity distribution and rapid service restoration through two-way communication between utilities and customers (Bollen 2011). Advanced analytics, including machine learning and AI, enhance grid performance and support crisis decision-making (Linardos et al. 2022). Energy storage systems like batteries ensure continuous power supply during outages, while community engagement promotes effective responses and energy-saving practices (Dufty 2020). Advanced weather forecasting aids in preparing for extreme weather, and infrastructure adaptations support long-term resilience (Gkika et al. 2023).

As demonstrated in most of the mentioned approaches, defining at least one risk pillar is considered essential for effective EE management. Without one, the likelihood of the EE becoming a crisis (which could escalate into a disaster) increases. Figure 2 presents a bar chart with a fitted normal distribution curve for different types of EE.

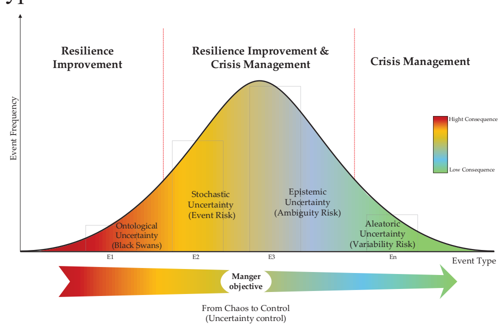

Figure 2: Navigating Uncertainties by Resilience and Crisis Management in Complex Systems

It illustrates a framework for dealing with different types of uncertainties encountered in resilience improvement and emergency event management, categorized by their event frequency and associated approach in complex systems. In complex systems, unlike in simple systems, information gathering is often more challenging, and sometimes, the required information is either inaccessible or undefined as observable data (Zaki et al. 2021). While in simple systems, such issues can be resolved using similar system data, expert judgment (Mottahedi, Sereshki, Ataei, Qarahasanlou, et al. 2021), or data generation (Singh et al. 2021), these solutions are not easily applicable to complex systems. As a result, most events in complex systems involve both event risk and ambiguity risk. As shown in the figure, the middle part of the curve carries the most weight, reflecting the prominence of these risks. The left tail represents black swan events, which are rare in complex systems and are influenced by various risk barriers. Similarly, the right tail contains events that occur with near-complete information, which are also rare in complex systems due to the presence of variable internal and external risk factors. Consequently, the control of uncertainties in complex systems is often beyond full control, making the development of resilient systems essential. Here, resilience refers to the ability of a system to withstand, adapt to, and recover from disruptions while maintaining essential functions (Sarwar et al. 2018). It extends beyond preventing events, focusing instead on effective recovery and adaptability to mitigate impacts. In general, resilience is a multifaceted concept encompassing personal, organizational, and technical layers. These dimensions interact to enhance overall system robustness (De Marchi et al. 2023; Folke et al. 2010).

For achieving a resilient infrastructure in EE management, as shown in Figure 2 (at the top of the curve), three main requirements are highlighted: Resilience Improvement, a combination of Resilience Improvement and Crisis Management, and Crisis Management. On the left, low-frequency events involve ontological uncertainty, which are unpredictable, rare events requiring resilience-building strategies. Moving towards the middle, Stochastic Uncertainty is addressed by both resilience improvement and emergency management, as these events have a more predictable frequency but still involve significant variability. The central section deals with epistemic uncertainty, characterized by gaps in knowledge or information, and demands a combination of resilience strategies and risk management to reduce ambiguity. Finally, as event probability increases on the right, aleatoric uncertainty becomes dominant, where traditional emergency event management approaches are required to handle risks based on inherent variability.

Thus, A combined approach of crisis management and resilience strategies provides an effective solution for power distribution challenges. Crisis management ensures immediate response and recovery, minimizing damage and maintaining critical services (Mitroff, Shrivastava, and Udwadia 1987). Resilience focuses on adaptability and long-term robustness, enabling systems to withstand and evolve through recurring threats (Bie et al. 2017). Together, these approaches provide a robust framework for addressing the complexities of power distribution system management. This paper provides a comprehensive analysis of the interplay between crisis management and resilience strategies in power distribution networks, offering a deeper understanding of their applications and benefits. By examining these concepts retrospectively, the study highlights their complementary roles in addressing AIAEEs. The insights gained aim to equip stakeholders with actionable strategies to enhance both immediate response capabilities and long-term system resilience, ultimately improving the robustness and adaptability of critical infrastructure.

The paper is structured as follows: Section 2 explores the linkage between crisis management and resilience in AIAEE management, highlighting methods like predictive maintenance and smart grids to address uncertainties. Section 3 presents the Onion Model framework, detailing its layered approach to enhancing resilience at personal, organizational, and technical levels. The conclusion emphasizes the importance of integrating these strategies for improved response and long-term system resilience.

2. What is the Linkage Between Crisis Management and Resilience in AIAEE Management

The linkage between crisis management and resilience in AIAEE management is crucial for effectively addressing the multifaceted challenges posed by ice-related emergencies. This connection ensures that immediate actions to mitigate risks are supported by long-term strategies to enhance system robustness and adaptability. Ice management, as a key component, plays a vital role in minimizing the impact of ice features on critical operations. Ice management refers to a set of activities aimed at reducing or avoiding actions from any kind of ice feature (sea ice or glacial ice) that could pose a threat to a particular operation. This includes ice surveillance through detection, tracking, and forecasting; identification and evaluation of physical threats; maintaining a working ice alert system; employing physical ice management by support vessels; ensuring safe avoidance of hazardous ice; complying with hazard/ice alerting systems; and establishing safe shut-down procedures for floating or bottom structures. The ice management system encompasses detection, monitoring, forecasting, decision-making, hazard analysis, physical ice management, alerting, recording, and performance analysis ("ISO 35104:2018" 2018).

This management, in critical shape, is classified as crisis and disaster management, which needs a comprehensive approach. A comprehensive approach to AIAEE management needs to encompass two broad views: crisis management and resilience. These strategies must address the multifaceted challenges posed by AIAEEs to ensure both the structural integrity of power systems and the operational readiness of organizations. Emphasizing the importance of a holistic view, crisis management should include advanced engineering solutions, while resilience should focus on preparedness, response, and recovery plans.

Effective crisis management needs to identify potential crises, assess risks, and develop robust strategies to mitigate their impacts. Key elements of crisis management include preparedness, response, recovery, and learning from past experiences to enhance future resilience. The historical development of crisis management strategies, from the "International Decade for Natural Disaster Reduction to modern frameworks like the Sendai Framework" (Coppola 2006), highlights the evolving understanding of disaster risk reduction and the integration of resilience principles. The incorporation of big data and advanced technologies plays a significant role in improving crisis management practices by enabling better risk assessment, early warning systems, and coordinated response efforts. Moreover, the emphasis on collaboration among stakeholders, including government agencies, emergency responders, and the public, underscores the need for a unified approach to managing crises. By continuously refining crisis management strategies and integrating lessons learned from past events, organizations can enhance their ability to withstand, adapt to, and recover from crises. This proactive and adaptive approach not only minimizes the immediate impacts of crises but also contributes to long-term organizational resilience and sustainability. As a summary shown in Figure 3, crises have three main phases: pre-AIAEEs, during AIAEEs, and post-AIAEEs.

Each phase can be further divided into specific components that contribute to comprehensive crisis management (Pursiainen 2017; Vahhabi et al. 2023):

- Pre-AIAEEs (Blue part in Figure 3) Include prevention, preparedness, and uncertainty-risk analysis to avoid or mitigate impacts, establish readiness through protocols and training, and develop adaptable strategies by evaluating risks and uncertainties.
- During the AIAEEs (Yellow part in Figure 3), Focuses on immediate response through crisis team activation, emergency plan implementation, and stakeholder coordination to manage impacts and maintain essential functions.
- Post-AIAEEs (Orange part in Figure 3) Involves recovery to restore operations, learning from the event to improve future responses, and ongoing uncertainty-risk analysis to integrate insights into preparedness and recovery.

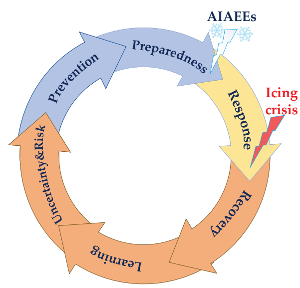

Figure 3: AIAEE management through a crisis management lens (Pursiainen 2017; Vahhabi et al. 2023)

It must be mentioned that risk evaluation is a critical component that spans both the pre-AIAEE and post-AIAEE phases. It ensures that potential threats are continually monitored, and strategies are adapted to address emerging risks effectively.

On the other side, the *technical resilience* assessment framework encompasses multiple phases, including pre-disaster, mid-disaster, and post-disaster evaluations. Pre-disruption (Blue part in Figure 3) assessments focus on resilience, involving reducing vulnerability and enhancing robustness to potential threats. This includes proactive measures such as risk assessments, strengthening infrastructure, and developing comprehensive emergency plans. The goal is to minimize the impact of possible disruptions through careful planning and preparation. During the disruption phase (Yellow part in Figure 3), flexibility becomes paramount. Resilience here means the ability to adapt and respond dynamically to changing conditions. It involves the effective deployment of resources, real-time decision-making, and maintaining operational continuity under stress. Flexibility ensures that the system can cope with immediate challenges and mitigate the adverse effects of the disruption. Post-disruption (Orange part in Figure 3) Resilience focuses on recoverability, maintainability, and rapidity. Recoverability refers to the ability to restore normal operations efficiently. Maintainability involves sustaining recovery efforts and ensuring that systems remain functional during the rebuilding process. Rapidity highlights the importance of swift recovery to reduce downtime and long-term impacts. This phase emphasizes learning from the event to improve future preparedness and response capabilities. Comprehensive resilience assessment involves quantifying various metrics, such as resistance capability, adaptability, and recovery rate, to provide a holistic view of the system's performance under stress. These metrics are weighted based on their relative importance to ensure a balanced evaluation. By integrating resilience assessment into the planning and operational strategies, power systems can enhance their robustness against ice-related disasters, minimize the impact of such events, and improve overall reliability.

Figure 4 shows various metrics and three critical phases in resilience for disaster or crisis management that refer to the capacity of systems, communities, or organizations to withstand, adapt to, and recover from disruptions (Mottahedi, Sereshki, Ataei, Nouri Qarahasanlou, et al. 2021)).

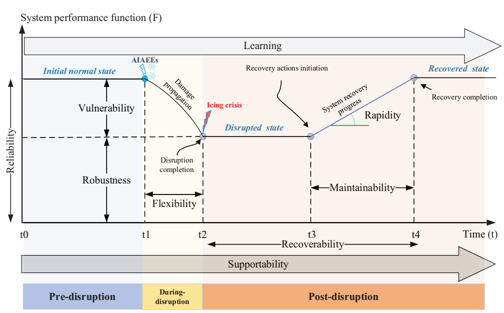

Figure 4: Technical resilience definition in relation to AIAEEs (adapted from (Mottahedi, Sereshki, Ataei, Nouri Qarahasanlou, et al. 2021))

While overlapping in certain areas, crisis management and resilience assessment offer distinct strategies that together enhance AIAEE management. Crisis management focuses on pre-event preparedness (risk reduction and planning), immediate response (resource allocation and communication), and post-event recovery (restoration, learning, and risk reassessment). Resilience assessment emphasizes long-term system resistance evaluation, real-time performance monitoring during events, and post-event recovery analysis with continuous improvement. Crisis management addresses immediate impacts and operational continuity, resilience assessment builds long-term robustness and adaptability. Together, these approaches provide a comprehensive framework for managing and mitigating AIAEE risks and uncertainties.

3. How Can Crisis Management and Resilience Be Linked in AIAEE Management?

In contrast, resilience assessment takes a broader view, evaluating the system's long-term capacity to absorb, adapt, and recover from disruptions. It involves assessing the system's robustness before an event, its performance during the event, and its recovery after the event. This continuous process of monitoring, data analysis, and strategy adjustment aims to build a system that cannot only withstand disruptions but also emerge stronger and more adaptable.

Both approaches share common goals, such as risk assessment and resource allocation, but they operate on different timescales and focus on different aspects of system management. Crisis management is more immediate and tactical, dealing with an event's direct impacts, while resilience assessment is strategic, focusing on long-term system improvement and sustainability.

The integration of crisis management and resilience assessment is crucial for handling AIAEEs effectively. Crisis management provides the necessary immediate response mechanisms to handle the direct impacts of ice events, ensuring operational continuity and minimizing immediate disruptions. On the other hand, resilience assessment focuses on building long-term system capabilities to withstand and recover from future events, thereby reducing vulnerability and enhancing overall system robustness. As shown in Figure 5, crisis management and resilience assessment are complementary approaches that, when integrated, provide more barriers to controlling AIEEs.

Crisis management addresses the immediate needs of response and recovery, while resilience assessment ensures long-term system robustness and adaptability. Resilience implementation, as discussed, unfolds in three key stages during an emergency event (EE). In the blue section of Figure 5, resilience is proactively built before the event, focusing on preparedness and mitigation. During the event, as shown in the yellow section, resilience is applied to respond effectively. Lastly, in the orange section, resilience focuses on restoration and recovery after the EE, ensuring continuity and improvement. This is a cycle of continuous enhancement.

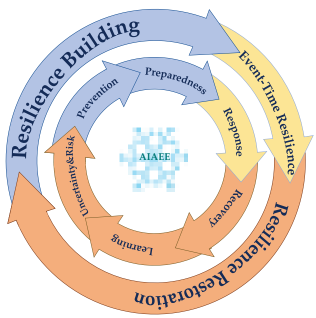

Figure 5: Crisis management and resilience assessment concepts in AIAEE management

In Figure 6, the onion model for AIAEE Management is proposed. The term "Onion Model" is used because assessing and managing a system based on two concepts, including emergency events management and resilience, requires multiple layers of defence or strategies. Each layer addresses different aspects of uncertainties.

Like peeling an onion, the first layer is EE management, which was discussed in the previous section. Then, resilience building involves progressing through various layers, including personal, organizational, and technical. Each layer represents a distinct dimension or type of risk that must be considered and mitigated.

At the personal level of resilience, various human emotions and psychological characteristics play a crucial role. Ethics, for instance, is fundamental in fostering human resilience during crisis management. Implementing ethical resilience can follow a six-step approach: conducting ethical assessments, balancing principles through stakeholder involvement, raising ethical awareness through training, establishing monitoring mechanisms, continuous improvement by evaluation, and reviewing ethical challenges post-event (Vahhabi et al. 2023). This ensures that decisions and actions are ethically sound, enhancing the overall resilience of individuals and communities during crises.

Organizational resilience implementation, as depicted in the figure, involves several structured steps. First, ethical assessments are conducted to ensure all decisions align with organizational values and stakeholder interests. Preparedness strategies are then developed to allocate resources and define roles for emergency events. During disruptions, effective response mechanisms are balanced with decision-making frameworks. Field approaches and technical solutions are deployed to address real-time challenges, ensuring operational continuity. Finally, continuous learning and adaptation are emphasized to improve future resilience through lessons learned and ongoing evaluations.

The third layer of resilience, and the primary focus of this research, is technical resilience, which is outlined in detail within the comprehensive framework presented in Figure 6. The proposed onion model framework integrates crisis management and technical resilience assessment to ensure robust infrastructure and operational continuity.

In the pre-AIAEE phase, as blue arrows in the outset layer, which includes risk assessment, prevention, and preparedness, the framework starts with system identification and boundary detection to understand critical components and vulnerabilities. This is followed by defining suitable response and mitigation strategies and categorizing/clustering appropriate techniques using advanced methodologies like Machine Learning and Monte Carlo simulations.

During AIAEEs (as yellow arrows in the outset layer) and sometimes after that, these techniques are implemented in both real-world scenarios and virtual platforms, such as agent-based model simulations. This allows for the collection of new data and updated information on the infrastructure's resilience during AIAEEs. Post-

AIAEEs, as orange arrows in the outset layer, outcomes are evaluated, and cause-and-effect relationships are identified, providing valuable insights into the system's resilience.

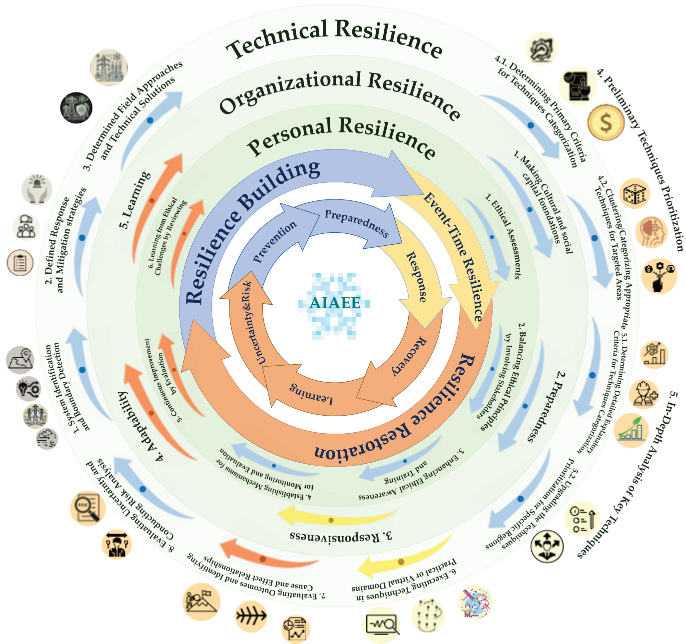

Figure 6- Onion Model for AIAEE Management: Merging Crisis Management and Three Tiers of Resilience Assessment Approaches

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Based on this knowledge, the entire management process is upgraded through risk evaluation, and new planning strategies are set to enhance the infrastructure's long-term resilience. This continuous cycle of assessment, implementation, and improvement ensures that the system remains adaptable and robust against future AIAEEs.

4. Conclusion

This study explores the integration of crisis management and resilience strategies to address the challenges posed by AIAEEs in power distribution networks. Crisis management provides immediate response mechanisms to minimize disruptions and ensure operational continuity, while resilience strategies focus on long-term system adaptability, robustness, and recovery. By combining these approaches, stakeholders can effectively manage uncertainties, ranging from aleatoric and epistemic to stochastic and ontological, ensuring a more robust framework for emergency event management.

The proposed framework, including the Onion Model, offers a layered approach to addressing uncertainties, incorporating pre-event preparedness, real-time response, and post-event recovery. The integration of predictive tools such as advanced analytics, microgrids, and smart grids with resilience metrics ensures that power systems are not only prepared for immediate impacts but also capable of evolving to meet future challenges. This dual approach underscores the importance of combining crisis response with resilience building to enhance infrastructure reliability and adaptability. Implementing the outlined strategies enables power distribution systems to improve reliability, minimize downtime, and better withstand future AIAEEs amid global risks like climate change.

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