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Toward Adaptive Governance for Critical Infrastructure Resilience: A DAO-Enabled Framework for Collaborative Crisis Management

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Critical Infrastructure (CI) systems are increasingly characterized by complex interdependencies, cross-sectoral coupling, and vulnerability to systemic disruptions that can propagate across national borders. Traditional governance frameworks (hierarchical, centralized and compliance-oriented) struggle to coordinate multiple actors under conditions of high uncertainty, time-pressure and information asymmetry. This paper examines how adaptive governance mechanisms, and specifically Decentralized Autonomous Organizations (DAOs) principles, can enhance decision-making, coordination and accountability in CI resilience management. We develop a DAO-enabled adaptive governance layer integrated into an existing CI resilience platform and evaluate it through a scenario-based comparative analysis. A cross-border snowfall disruption affecting the Italy–Switzerland A2–A9 corridor is used to compare a conventional hierarchical coordination workflow with a DAO-enhanced governance configuration. The proposed model combines programmable decision rules, role-based and weighted voting, dynamic escalation and emergency override mechanisms within a DAO architecture. Results indicate that DAO-enabled governance can reduce decision latency, improve traceability and accountability, and enhance shared situational awareness, while remaining compatible with European regulatory frameworks such as the CER Directive and NIS2. The paper concludes by positioning DAOs as adaptive governance overlays that can support hybrid human-machine coordination in safety-critical CI systems and outlines future governance and regulatory research.

Keywords: Critical Infrastructure Resilience; Adaptive governance; Collaborative crisis management; Decentralized Autonomous Organization (DAO); Coordinated decision-making;

1. Introduction

Critical Infrastructure (CI) operate as tightly coupled, cross-sector and cross-border systems. Disruptions propagate not only through physical assets, but through organizational and governance layers, where coordination, authority and information sharing are often fragmented. In such contexts, resilience depends as much on governance structures as on technical robustness. The EU CER Directive (EC, 2022) emphasizes coordinated resilience across public authorities, private operators and civil protection actors.

Most CI crisis management arrangements rely on hierarchical escalation and centralized validation. While these models provide legal clarity, they struggle under time pressure, particularly in cross-border settings characterized by multiple authorities, partial trust and asymmetric information. Decision latency, coordination bottlenecks and weak traceability are the main challenges, especially during compound and fast-evolving events.

Recent advances in digital coordination technologies, including Distributed Ledger Technologies and Decentralized Autonomous Organizations (DAOs), offer potential mechanisms to address some of these governance limitations (Petrenj and Trucco, 2023). However, DAO models cannot be directly applied to safety-critical CI contexts due to legal constraints, accountability requirements and the need for human oversight. This paper argues that DAO mechanisms (when carefully adapted) can serve as adaptive governance layers that enhance coordination and accountability without undermining institutional authority or human judgment. The contributions of the paper are:

(i) it identifies key governance limitations in cross-border CIR;
(ii) it proposes a DAO-enabled adaptive governance model tailored to safety-critical environments; and
(iii) it evaluates the model through a realistic cross-border disruption scenario.

2. Background

2.1 Operational interdependencies and governance limitations in CI

Interdependencies between CI make disruptions propagate through both physical and organizational layers. Despite recognition of interdependencies in risk analysis, operational responsibility remains fragmented across organizations and jurisdictions. Actors operate under distinct mandates, escalation logics and performance objectives. During fast-evolving events, this fragmentation hampers shared situational awareness and coordinated response.

Most CI crisis management arrangements rely on hierarchical governance models which provide legal clarity and defined responsibility, but hey struggle under time pressure. Centralized validation creates coordination bottlenecks, sequential communication increases decision latency, and authority does not always align with situational expertise. In cross-border contexts, mismatched escalation thresholds and informal coordination further exacerbate these limitations. This highlights a mismatch between the dynamics of interdependent CI and the governance mechanisms used to manage them.

2.2 Decentralized governance and digital coordination technologies

Distributed digital technologies enable new coordination mechanisms based on shared state, cryptographic assurance, and immutable records (Hassan and De Filippi, 2021). DAOs offer programmable decision rules, transparent validation processes and auditable governance actions. However, DAOs developed for digital ecosystems cannot be directly transferred to safety-critical contexts. CI governance operates under strict legal mandates, accountability requirements and confidentiality constraints. Full automation and unrestricted transparency are therefore neither feasible nor desirable. The relevance of DAOs for CI lies in their potential to support structured coordination and *robust governance* (Ansell et al., 2024) under uncertainty turbulence, institutional fragmentation and incomplete information.

2.3 Governance trade-offs and the need for adaptive models

Governance in CIR involves trade-offs between competing objectives, summarized in Table 1. Purely hierarchical models prioritize control and legal clarity but sacrifice adaptability (Nolte & Lindenmeier, 2024). Fully decentralized models emphasize participation and transparency but struggle with authority and accountability. Neither approach alone adequately supports resilience in complex, cross-border CI systems so competing objectives must be balanced and authority adjusted dynamically under uncertainty. (Kleczewski, 2025). These trade-offs motivate the adaptive governance model developed in this paper, which uses DAO mechanisms to balance decentralization and control through programmable, role-based coordination.

3. Methodology

The study adopts a qualitative, multi-stage research approach combining diagnostic analysis, conceptual modelling, and scenario-based evaluation. This methodology is appropriate for examining governance mechanisms that are difficult to assess through empirical experimentation but can be systematically evaluated through structured comparison under realistic conditions. The methodology consists of three stages.

Table 1: Trade-offs in CIR governance approaches

Trade-Off	Description	Implications
Decentralization/ Efficiency	More actors increase coordination load	Hybrid models needed
Transparency/ Privacy	Auditability vs. sensitive CI data	Permissioned ledgers with selective disclosure
Automation/ Oversight	Smart contracts vs. contextual judgment	Human-in-the-loop governance essential
Inclusivity/ Competence	Participation vs. expertise	Role-based and weighted decision rights

3.1 Stage 1: Analysis of governance challenges

The first stage involved a structured review of academic and institutional literature on CIR, crisis management, and multi-actor coordination. The review identified recurring governance challenges, including fragmented authority, slow validation and escalation, limited traceability of decisions and reluctance to share information across organizational and jurisdictional boundaries. These findings provided the baseline for the design of an alternative governance model.

3.2 Stage 2: Conceptual modelling of a DAO-enabled governance layer

In the second stage, a DAO-enabled governance layer was conceptually modelled as an extension to the existing CIR platform. The objective was to augment it with programmable coordination and decision-making mechanisms.

Design choices were guided by three constraints: compatibility with existing institutional mandates, preservation of human oversight in safety-critical decisions, and alignment with regulatory requirements such as CER and NIS2. The resulting model is permissioned, role-based and non-financial, with governance logic encoded in smart contracts and sensitive operational data managed off-chain.

3.3 Stage 3: Scenario-based evaluation

The third stage evaluated the proposed governance model through a realistic cross-border disruption scenario involving a severe snowfall event affecting the Italy–Switzerland corridor (Section 5). Two governance configurations were compared: a baseline hierarchical workflow and a DAO-enhanced governance configuration. The scenario enabled structured comparison of coordination dynamics, decision latency and governance behavior across different phases of the disruption.

3.4 Evaluation Dimensions and Metrics

The comparison focused on four evaluation dimensions:

- *Governance performance,* including role clarity, decentralization of validation and traceability of decisions;
- *Coordination effectiveness,* including decision latency and inclusiveness;
- *System qualities,* including robustness under load and shared situational awareness;
- *Resilience impact* across preparedness, mitigation, response and recovery.

These dimensions provide a consistent basis for assessing whether DAO-enabled governance mechanisms address the governance challenges identified in the diagnostic stage.

4. A DAO-Based Adaptive Governance Model for Critical Infrastructure

4.1 Design Principles

The proposed DAO-based governance model is designed as an adaptive governance layer integrated into an existing *CIR Platform – PIC* (Petrenj et al., 2023). The purpose is not to replace authority or operational control systems, but to improve coordination, traceability and responsiveness in multi-actor crisis management. The DAO governance layer was designed according to three guiding principles.

Complementarity. The DAO layer complements existing command-and-control structures rather than substituting them. Statutory authorities retain their legal mandates, including the power to make unilateral decisions when required. The DAO provides a structured mechanism for shared validation, coordination, and accountability around those decisions.

Programmability. Governance rules are encoded into smart contracts to automate predictable coordination tasks, such as alert validation, quorum formation, escalation triggering and audit logging. Automation is limited to well-defined procedures; discretionary judgment remains human-led.

Permissioned decentralization. Participation is restricted to verified institutional actors (such as infrastructure operators, civil protection authorities, emergency services and coordination centers) using role-based digital credentials. This ensures inclusiveness without sacrificing competence, authority clarity or security.

Together, these principles ensure that decentralization enhances adaptability while remaining compatible with safety-critical and regulated environments.

4.2 Governance Architecture

The governance layer can be implemented on a permissioned distributed ledger that supports selective transparency and auditable coordination. The architecture consists of five core components:

1) *Role-based identity and credentials.* Each participating organization is represented through a digital identity bound to its institutional role. Voting rights and decision privileges are derived from roles, not economic tokens.
2) *Multi-level decision logic.* Governance is structured into distinct decision layers corresponding to operational and strategic actions. Each layer has its own quorum rules, voting weights and escalation thresholds.
3) *Programmable escalation mechanisms.* Smart contracts automatically trigger escalation when predefined conditions are met, such as severity thresholds, failed consensus or timeouts.
4) *Emergency override with accountability.* Authorities with legal jurisdiction can override collective processes when immediate action is required. Overrides must be justified and are immutably recorded.
5) *Immutable audit trail.* All governance actions (votes, timestamps, identities, rationales, and outcomes) are logged on-chain. Operational data remain off-chain, with cryptographic hashes ensuring integrity and traceability.

This hybrid on-chain/off-chain architecture balances transparency with confidentiality, aligning with regulatory requirements while enabling post-incident learning.

4.3 Multi-level decision-making logic

To reflect the varying urgency and impact of decisions in CI crisis management, the governance model distinguishes between two decision levels and possible emergency override as a fail-safe mechanism (Figure 1).

Level 1: Operational Activation

Level 1 voting governs immediate, time-sensitive operational actions, such as validating alerts, activating snow removal resources, issuing traffic warnings or adjusting traffic flow. At this level each participating stakeholder holds one vote (7 in total) – National Road Operators (IT + CH), Police, IT Emergency Medical Services, IT Fire Service, IT Rail Operator and the PIC Duty Operator Decisions are triggered automatically upon detection of predefined conditions. Actions require a simple majority of four out of seven votes (4/7).

The objective is rapid parallel validation. Instead of relying on a single duty operator, multiple actors verify conditions simultaneously. Once quorum is reached, predefined operational actions are executed automatically or recommended to operational systems. This mechanism directly addresses decision latency and single-point-of-failure risks identified in hierarchical governance models.

Level 2: Strategic and Escalation Decisions

Escalation to Level 2 governance is triggered to addresses strategic decisions with significant safety, legal or cross-border implications, such as tunnel closures, large-scale rerouting or coordinated resource reallocation. Voting rights are weighted to reflect statutory responsibility (asymmetric) and cross-border symmetry.

In the evaluated scenario, 9 institutional actors participate, with a total of 13 votes. Civil Protection Authorities in Italy and Switzerland get involved and hold two votes each, reflecting their legal mandate for emergency coordination. National Road Operators in Italy and Switzerland also hold two votes each, reflecting their direct operational responsibility for the infrastructure. The remaining stakeholders hold one vote each.

Strategic decisions require a qualified majority of nine out of thirteen (9/13) votes, ensuring broad institutional consensus across jurisdictions while maintaining responsiveness under time pressure.

Emergency override and accountability

Crisis situations may evolve faster than any consensus mechanism. Because of this, the governance model preserves emergency override powers for legally mandated authorities, such as civil protection or prefectures. An override:

- immediately authorizes action without quorum,
- requires explicit justification,
- is immutably logged for post-event review

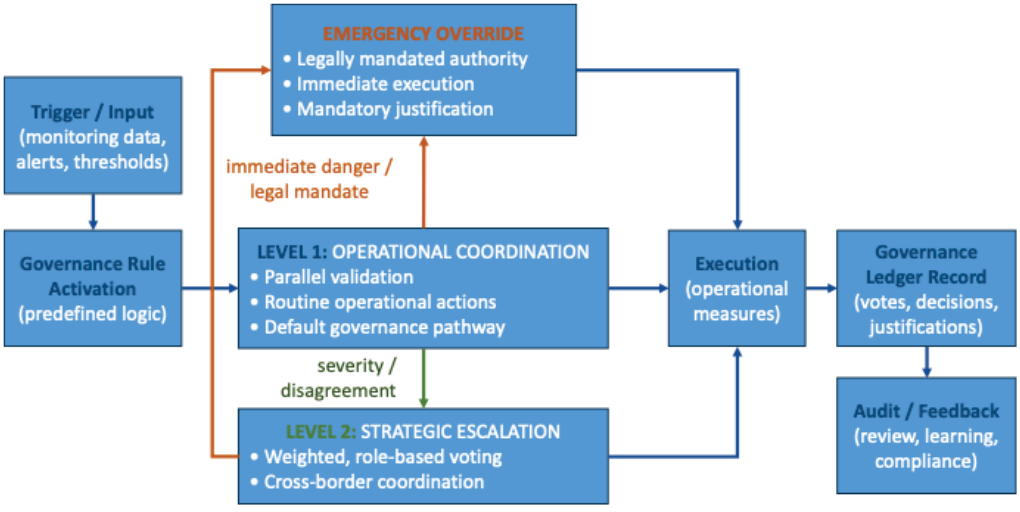

Figure 1: DAO-enabled adaptive governance model with operational coordination, strategic escalation and emergency override

This mechanism reconciles adaptability with legality. It prevents governance deadlock while strengthening accountability, as exceptional decisions are transparently documented rather than informally negotiated.

4.4 Adaptive features and learning mechanisms

Adaptivity in the proposed model arises from the interaction of programmable rules, contextual triggers and human judgment. Adaptive features include:

- severity-based escalation thresholds,
- dynamic delegation of decision rights under predefined conditions,
- integration of real-time monitoring data,
- persistent governance logs supporting post-incident analysis.

Over time, governance parameters (e.g. quorum thresholds or escalation conditions) can be refined based on observed performance and lessons learned. In this way, the DAO layer supports also institutional learning and continual improvement.

5. Scenario: Cross-Border Snowfall Disruption

5.1 Scenario context

The evaluation scenario involves a severe snowfall event affecting the transalpine A2–A9 corridor between Italy and Switzerland, a cross-border CI supporting freight transport, commuter mobility, tourism and emergency response. In the scenario, the disruption initially affects the Italian side of the corridor, with cross-border impacts emerging progressively as congestion and safety risks propagate toward Switzerland.

Snowfall events in this region are particularly challenging because operational responsibilities are distributed across national road operators, civil protection authorities, police forces and emergency medical services, operating under different legal and organizational frameworks. Decisions such as tunnel closures, traffic rerouting and resource deployment have significant safety and economic implications and require rapid cross-border coordination.

The scenario was designed to reflect realistic meteorological evolution, operational constraints, and institutional interactions, while remaining sufficiently structured to enable systematic comparison of governance configurations.

5.2 Event progression and decision points

The scenario unfolds in several stages:

1) Early detection: Meteorological services identify a severe weather front.

2) Initial disruption: Visibility decreases and minor collisions occur.
3) Escalation: Major congestion develops; tunnel access becomes unsafe.
4) Cross-border tension: Swiss operators consider closing key segments while Italian authorities hesitate due to economic implications.
5) Crisis response: Emergency services coordinate detours and resource reallocation.
6) Recovery: Efforts focus on clearing snow, restoring traffic and documenting actions.

5.3 Baseline governance workflow

In the baseline configuration, coordination follows a hierarchical workflow centered on a platform duty operator. Alerts are manually validated, information is shared sequentially and escalation depends on bilateral communication and hierarchical approval.

This configuration exhibits several vulnerabilities:

- decision latency due to sequential validation;
- coordination depends heavily on individual operators under high workload;
- decision rationales are weakly documented;
- cross-border alignment relies on informal negotiation.

These characteristics reflect common limitations of centralized crisis coordination under time pressure.

5.4 DAO-Enhanced governance configuration

In the DAO-enhanced configuration, the same operational platform is augmented by the governance mechanisms described in Section 4.

- *Level 1 governance* enables parallel validation of alerts by multiple actors and supports rapid activation of predefined operational measures.
- *Level 2 governance* supports weighted, role-based decision-making for strategic and cross-border actions.
- *Emergency override* allows legally mandated authorities to act unilaterally when required, with explicit justification and audit logging.

All governance actions are recorded immutably, providing a shared governance-level operational picture and enabling post-incident review.

5.5 Cross-border coordination dynamics

The scenario highlights how structured, programmable governance reduces coordination friction in cross-border settings. Rather than relying on ad-hoc negotiations, the DAO-enabled configuration provides a shared decision space in which positions, disagreements, and resolutions are explicit, time-bound and auditable.

This structured visibility improves mutual awareness across jurisdictions and reduces ambiguity regarding responsibility and authority, without bypassing legal mandates or confidentiality constraints.

6. Results

6.1 Governance performance

The DAO-enhanced system shows clear improvements in governance performance compared to the baseline workflow. Distributed validation mechanisms reduce reliance on a single coordinating actor, while role-based participation clarifies authority and responsibility across organizations.

Governance processes become explicit and structured: decision thresholds, escalation conditions and override rules are predefined and consistently applied. As a result, coordination behavior is more predictable under stress, and deviations from standard procedures are transparently documented rather than informally negotiated.

From a regulatory perspective, these features directly support CER and NIS2 requirements concerning traceability, role clarity and accountability in crisis management processes. In contrast, the baseline configuration relies heavily on individual discretion and informal coordination, resulting in fragmented documentation and limited auditability.

6.2 Reduction in decision latency

The most tangible improvement is the reduction in activation and escalation time.

Under the baseline configuration:

- operational activation typically requires sequential validation, leading to delays of approximately 10–20 minutes;
- strategic escalation, particularly in cross-border contexts, frequently exceeds 20 minutes.

Under the DAO-enhanced configuration:

- *Level 1 operational activations* are validated through parallel voting, typically within 3–7 minutes;
- *Level 2 escalation decisions* are reached more rapidly due to predefined voting structures and escalation thresholds.

Latency reduction is achieved through parallelization of validation, elimination of redundant communications and automated execution once quorum is reached. Importantly, the process still includes a human verification window, confirming that automation accelerates coordination without eliminating oversight.

6.3 Coordination effectiveness and situational awareness

The DAO-enhanced governance model improves coordination effectiveness by enabling shared, time-synchronized situational awareness across all participating actors. All stakeholders observe the same evolving state of alerts, votes and decisions, reducing ambiguity about whether actions have been validated, escalated or overridden.

In the baseline configuration, situational awareness depends on manual information dissemination and bilateral communication, increasing the risk of desynchronization, particularly in cross-border settings.

On the other hand, the DAO layer provides a common governance-level operational picture. Divergent positions between actors are explicitly recorded and resolution pathways are visible to all participants. This transparency strengthens mutual trust and reduces coordination friction without requiring full data disclosure.

6.4 Transparency and accountability

Transparency and accountability are significantly enhanced under the DAO-enhanced governance model. Each governance action is immutably logged with associated identities, timestamps and decision rationales. This creates a reliable audit trail that supports post-incident analysis, regulatory reporting, and organizational learning.

Emergency overrides become formally documented events rather than informal exceptions. This strengthens accountability without constraining legitimate authority.

6.5 Resilience performance across phases

The DAO-enhanced governance model demonstrates improvements across all four resilience phases (Table 2):

- Preparedness: Clear role definition and predefined governance rules improve readiness and coordination expectations.
- Mitigation: Parallel alert validation and automated escalation enable earlier intervention.
- Response: Reduced decision latency and improved situational awareness enhance agility during peak disruption.
- Recovery: Immutable decision records facilitate reporting, review and compensation processes.

These improvements are primarily governance-driven rather than technical, highlighting the central role of coordination mechanisms in resilience outcomes.

7. Discussion

7.1 Implications for CI governance

The results indicate that many observed resilience gains come not from new sensing or analytics capabilities, but from improved governance structures. By redistributing validation and formalizing escalation logic, the DAO-enabled model reduces coordination friction that typically emerges under stress. This supports the view that resilience failures in complex CI systems are often governance failures rather than technical ones.

Table 2. Qualitative impact of DAO-enabled governance across resilience phases

Phase	Baseline	DAO-Enhanced	Improvement Mechanisms
Preparedness	Moderate	High	Role codification, verified readiness
Mitigation	Moderate	High-Very High	Automated alerts, parallel decisions
Response	Low-Moderate	High	Faster activation, transparent coordination
Recovery	Low-Moderate	High	Immutable logs and reporting

The proposed model operationalizes adaptive governance by enabling authority to shift with context and severity while remaining institutionally grounded. Distributed validation accelerates routine decisions, whereas weighted voting and override preserve legitimacy for high-impact actions. This adaptive balance is difficult to achieve within purely hierarchical or purely decentralized governance models.

7.2 Theoretical contributions

From a resilience engineering perspective, this work demonstrates how governance mechanisms can be made adaptive through programmable rules without displacing human judgment. Resilience principles (anticipation, flexibility, and learning) are embedded directly into coordination processes.

The study also contributes to coordination theory by illustrating how hybrid human–machine governance systems can reduce authority–expertise mismatches. The DAO-enabled model supports parallel sense-making while preserving accountability. This reframes decentralization as structured coordination rather than loss of control.

Importantly, the results suggest that governance should be viewed as a continuum, dynamically adjusting coordination structures to operational needs.

7.3 Human, legal, and institutional considerations

Despite the benefits of automation, human-in-the-loop oversight remains essential in safety-critical contexts. The emergency override mechanism shows how automated governance can coexist with discretionary authority while improving accountability through explicit justification and traceability.

While aligned with EU CER and NIS2 directives for traceability, role clarity and accountability, formal certification of smart-contract-based – governance processes remain an open challenge. Privacy and confidentiality constraints further require careful design of selective disclosure mechanisms.

Institutional readiness and effective adoption depend on training, trust in the governance process and clear understanding of roles.

8. Conclusion

This paper examined how adaptive governance mechanisms can strengthen CIR in complex, multi-actor and cross-border contexts. The study showed that programmable, role-based governance mechanisms can reduce decision latency, improve transparency and enhance cross-border coordination while preserving legal authority and human oversight. A central contribution is the reframing of DAOs as *adaptive and dynamic governance continuum* responsive to operational context and severity. This approach avoids the pitfalls of both rigid centralization and unstructured decentralization.

The limitation is conceptual evaluation (scenario-based), not validation in live operational environments. The results demonstrate *potential* improvements and define clear directions for further research. Future work should also cover regulatory research to formalize the legal status of programmable governance mechanisms. As CI become increasingly interconnected, governance innovation will be as important as technical robustness in achieving resilience.

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