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Integrating Systems Thinking into Resilient Infrastructure Design: A Case Study on the Shahid Rajaee Port Explosion

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ABSTRACT

Robust critical infrastructure resilience is imperative for sustaining economic stability, national security, and societal well-being amid escalating multi-hazard threats. This study analyzes the process of designing resilient critical infrastructure through a comprehensive hybrid methodology, employing the logical framework of observation-assertion-argument. Meaningful integration of systemic thinking with core resilience indicators is achieved via synthesis of prior research and the developed hybrid approach. Empirical observation of the 2025 Shahid Rajaee Port explosion (70 fatalities, $198M losses) exposed systemic vulnerabilities within Iran's International North-South Transport Corridor (INSTC), demonstrating that conventional redundancy measures failed to prevent service disruption during cascading failures. Shahid Beheshti Port's role as Rajaee's backup—sustaining INSTC operations—confirms that critical infrastructure resilience requires proportional capacity distribution across port networks and hazard-diversified risk management. We assert that true resilience necessitates intelligent redundancy harmonizing three pillars: inherent capacity (applying ecological adaptability principles to infrastructure), correlation-centric component design (mapping dynamic interdependencies), and stakeholder-driven self-organization. This is evidenced by the Rajaee incident, where centralized control exacerbated fire propagation, and further validated by seismic exposure analysis: despite Chabahar's limited throughput, strategic enhancement of this sustainably developed port can mitigate future operational collapse at Rajaee. We argue that operationalizing resilience requires: (1) converting strategic policies into technical metrics (e.g., chaos-theoretic container handling capacity dispersion and multi-hazard contingency planning), (2) embedding modular metabolic flexibility to absorb localized shocks, and (3) institutionalizing learning loops through distributed adaptive control nuclei to complete critical infrastructure self-organization cycles. This study confirms that only integrated correlation-aware redundancy—not isolated backups—aligns socio-economic-environmental performance with sustainability across hazard cycles.

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1. Introduction

The contemporary world is developing with an ever-increasing number of complex systems. International cooperation has expanded social and economic systems, while growing technological dependency underscores the need for a comprehensive understanding of modern and sequential systems' behavior. It is also crucial to account for unpredictable events in complex systems' operations. This need becomes particularly evident when an event disrupts these systems' acceptable performance levels. To understand system behavior, a systemic approach must be adopted—one that extends beyond engineering and demands an interdisciplinary perspective. This necessity can be summarized by arguing that all stakeholders in systems-related fields must embrace systems thinking as decision-makers.

1.1. Resilience Concept

In the early 2000s, a paradigm shift emerged in disaster management, moving from "fighting against" risks to "living with" them—a perspective encapsulated in the UNISDR's 2002 report "Living with Risk" [1]. Recognizing the inevitability of disasters, policymakers emphasized preparedness over eradication, marking a conceptual transition from vulnerability to resilience. This evolution was institutionalized through global frameworks like the Hyogo Framework [2] and the Sendai Framework [3], which prioritized societal resilience as a cornerstone of disaster risk reduction. Resilience is a concept with numerous definitions, commonly encompassing capacities such as planning and preparation for adverse events (planification), mitigating impacts (absorption/resistance), minimizing recovery time (recovery), and evolving through adaptive processes (adaptability) [4-12]. Holling (1973) further categorized resilience into engineering resilience (resistance and rapid return to equilibrium) and ecological resilience (adaptability) [13]. Additional terms like restoration—combining recovery and adaptability—have emerged [14].

From technical, organizational, social, and economic perspectives, systems impacted by disruptions (natural, human, or hybrid) can reduce impacts, recover, and return to an "acceptable" state, which may be degraded, equivalent, or improved compared to pre-disruption levels. For example, post-disaster road infrastructure may face reduced service (e.g., closures), restoration, or enhancement (e.g., widened lanes improving safety and flow). Recovery dynamics are assessed through metrics such as the minimum performance boundary (lowest acceptable functionality), latency limit (maximum tolerable recovery delay), and rapidity (recovery rate) [14, 15].

Resilience engineering emerged to develop methods enhancing organizational robustness and flexibility, proactive risk monitoring, and resource management amid disruptions [16]. Conceptual advances include Alexander's historical analysis of resilience in crisis management and Klein et al.'s exploration of its interdisciplinary evolution [17, 18]. While institutional/organizational resilience is a newer focus [19], critiques highlight a persistent gap: most definitions lack quantitative, operational measures [20], rendering resilience challenging to quantify and apply practically despite its conceptual richness.

In this study, one of the main dimensions of resilience, known as the systemic approach, is examined, and efforts have been made to explain the foundations of implementing this approach. Given that resilience refers to the ability to maintain and restore system functionality during a hazard, the target community and the hazard will be addressed subsequently. In the present article, critical infrastructure systems include railway and road networks, airways, port networks, and related structural facilities. Additionally, hazards encompass a wide range of disruptions affecting environmental, social, and economic performance levels of essential service infrastructures, including earthquakes, floods, tsunamis, and terrorist attacks.

1.2. Background

The quality of life in modern communities heavily depends on the capacity of infrastructure networks to withstand hazards when they occur, absorbing the impact of disasters and quickly restoring pre-event conditions—or even improving upon them. Designing lifelines and infrastructure components to meet modern safety standards, along with implementing effective management policies, is crucial to addressing the essential needs of communities—not only during normal operations but also in emergency situations [21–24].

Critical Infrastructure Systems (CIS) serve as the backbone of modern society, underpinning economic prosperity, social welfare, and public security. Over the past decade, deliberate attacks and natural disasters have increasingly disrupted CIS operations, causing significant societal losses [25]. Notable examples include the December 2022–January 2023 substation shootings in North Carolina, which left 45,000 residents without power [26], and Hurricane Idalia's 2023 devastation in Florida, paralyzing infrastructure and inflicting billions in damages [27].

In response, governments and international organizations have prioritized CIS protection. The European Union launched the European Programme for Critical Infrastructure Protection (EPCIP) in 2006 to safeguard CIS across member states, while the U.S. established Presidential Policy Directive 21 (PPD-21) to formalize CIS security as a national priority. These efforts underscore the escalating risks of CIS failures in today's geopolitical climate, necessitating advanced security measures and resilience strategies to mitigate disruptions [28]. To bolster resilience, the U.S. Department of Homeland Security (DHS) classifies CIS into 16 interdependent sectors, including energy, water, transportation, healthcare, and communications [29]. However, CIS interdependencies across sectors create complex, interconnected networks [30], where a single failure can trigger cascading effects, amplifying service disruptions [31]. Research has extensively explored CIS interdependencies, focusing on topology design [32], evaluation frameworks [33], and mitigation strategies to curb cascading failures [34].

Many researchers have actively explored and evaluated systemic resilience, a task that demands mastery of the systemic approach. A shared focus among these studies is the use of resilience assessment frameworks to analyze system performance during hazards. Designing critical infrastructure systems with resilience in mind is particularly vital, as demonstrated in prior research. For instance, Cimellaro et al. [35] studied the resilience of hospital systems in Memphis, Tennessee, during an earthquake. Shafieezadeh et al. [36] conducted a seismic resilience assessment of critical infrastructure in a hypothetical case study of Santa Cruz, California. Bristow et al. [37] contributed a cognitive advantage by examining large-scale multi-infrastructure network resilience under hazards and assessing the impact of interconnected systems. Aydin et al. [38] evaluated urban transportation network resilience in Kathmandu, Nepal, under earthquake conditions. Meanwhile, Zukhruf et al., Janić, Chen et al., Argyroudis et al., He et al., and Srivastava et al. [39–43] respectively investigated resilience in container port networks, high-speed rail transportation, the Guangdong-Hong Kong-Macao Greater Bay Area, critical infrastructure under multi-hazard events, San Francisco Bay's fuel supply network against coastal floods, and resilient rail network modeling. According to the aforementioned studies, it seems that operational implementation of resilience in critical infrastructure systems in recent decades has become part of the necessity of system design. Implementing a comprehensive resilience assessment framework requires a proper understanding of the system structure and recognizing the function of disruption by hazards. Based on the analytical path of the current study, applying the systemic approach paves the way for resilience evaluation of a system. On the other hand, the implicit use of the systemic approach by these researchers does not explicitly present the foundations of designing a resilient system. The achievement provided by researchers includes:

- Outlining the implementation pathway of resilience.
- Reducing cognitive ambiguity about the concept of resilience.
- Bridging strategic resilience with operational resilience.
- Promoting the integration of the systemic approach.
- Highlighting future challenges in the field of systemic resilience.
- Providing operational programs for stakeholders in the resilience field during a hazard occurrence.

Moreover, the cognitive advantage of focusing on the design process of a resilient system regarding improving stakeholder decision-making during a hazard includes creating a holistic view of the resilient system design and connecting chains of relevant concepts.

1.3. Key Challenges in Critical Infrastructure Resilience

Designing resilient critical infrastructure systems requires an integrated approach to address evolving threats and systemic vulnerabilities. The growing complexity of risks—from unpredictable "black swan" events to cascading failures—demands robust, adaptive solutions that enhance preparedness and recovery.

Uncertainty and Knowledge Gaps: Unknown threats ("black swan events") and unexpected severity of natural disasters, low-probability incidents, and accidents create inherent contradictions in crisis planning. As Boin & McConnell [45] highlight, how can planners prepare for phenomena that defy their predictive models? This challenge intensifies with global changes and rising terrorist threats.

Complexity and Cascading Failures: The increasing intricacy of large sociotechnical systems amplifies risks from combined organizational and technical failures, leading to unforeseen crises and cascade effects. Critical Infrastructures (CIs) are deeply interconnected, particularly due to reliance on information and communication technologies [46]. These connections manifest as dependencies (one-way) and interdependencies (two-way), which can be physical, geographic, cyber, or logical [47]. Strengthening risk management in such networks is costly and time-consuming [48]. Weak Defense Barriers: Inadequate or poorly maintained protection mechanisms further heighten vulnerabilities [49, 50].

Procedural and Operational Failures: Errors in procedure (misapplication or poorly designed protocols), ineffective safety training, and delayed response times exacerbate risks [51, 52].

In addition to the apparent achievements in this field, there are major challenges in enhancing the scope of cognitive and operational benefits from resilient systems, which will be addressed in the present paper. This study consists of two main parts: the systemic approach and resilient design, following two fundamental challenges:

1. What is the journey from the idea of systemic thinking to its implementation?
2. What are the indicators of a resilient system?

This study focuses on examining and analyzing the design process of a resilient system. Designing a system based on resilience is important considering functional goals and unavoidable hazard occurrences at three levels: environment, society, and economy. A system designed with specific functional objectives is put into operation, and the proposed chain, including exposure-abstraction, systemic thinking, strategic-operational resilience, and resilient system, will help enhance the operational capacity of this structure. Figure 1 illustrates the proposed design process for a resilient system, which will be further detailed in subsequent sections.

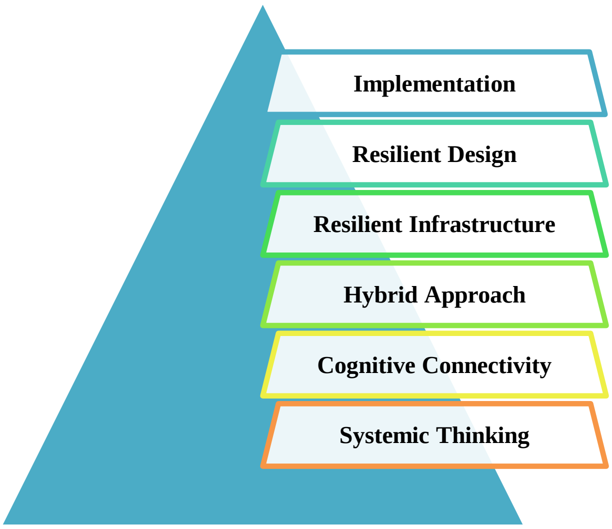

Figure 1. Proposed process for designing a resilient system

Focusing on implementing the systemic approach aims at evaluating resilience during a hazard occurrence. Although the systemic approach is implicitly applied in resilience analysis, it is not explicitly mentioned as important or the method of designing a resilient system before a hazard occurs. This is because the resilience of a system during and after a hazard is related to the pre-hazard design based on resilience. This design will help increase resilience before a hazard and maintain it during the occurrence of events. Due to the performance decline of a system during a hazard, a reduction in resilience occurs in the system, leading stakeholders to strive to return performance levels to pre-hazard values. For this reason, maintaining resilience is particularly important in most large-scale infrastructures compared to increasing it during a hazard occurrence.

1.4. Goals and Achievements

The primary objective of this study is to address the operational gap in resilience assessment of critical infrastructure systems, which has predominantly remained conceptual. The research problem stems from the absence of an operational framework for resilience-based design despite its theoretical richness, such that designing systems resistant to natural hazards (e.g., earthquakes and floods) and human-induced hazards (e.g., terrorist attacks) poses a challenge. By connecting and focusing on the systemic approach as the core axis of resilience, this research pursues three key objectives: first, formulating operational foundations for implementing resilience in critical networks such as railway, road, and port transportation; second, identifying and structuring the resilient performance of systems during hazard occurrences; and third, articulating future challenges for enhancing the resilience of critical infrastructures.

The core achievements of this research involve addressing three fundamental gaps in the resilience literature: reducing conceptual ambiguity through operational definitions of planning, impact absorption, recovery, and adaptation capabilities; bridging strategic resilience (macro-level policies) and operational resilience (field implementation) by providing decision-making tools for stakeholders; and promoting the integration of the systemic approach in infrastructure design by establishing a holistic view that enables the chained integration of related concepts. These contributions not only provide operational pathways for enhancing resilience during crises but also lay a foundation for future research in complex system safety by identifying future challenges (e.g., unpredictable events and intensified technological dependencies).

The development of systems, along with existing complexities and emerging hazards, vividly emphasizes the application of the conceptual capacity of resilience. Presenting key indicators of a resilient system will assist in the process of strategic resilience implementation to operational resilience. A resilient system is inherently resilient, correlated, and self-organizing. These indicators are verifiable at the strategic level of a resilient system and are accompanied by operational challenges at the operational level. As a result, summarizing the findings in the conclusion section, the mentioned items have been compiled.

2. Methodology

The research methodology of the present study involves providing a comprehensive perspective aimed at analyzing the systemic approach in relation to resilience. To understand the concepts used, findings from distinguished researchers in this field have been utilized, and these findings will be analyzed to examine the process of designing a resilient system. Moreover, the necessity of identifying key indicators of a resilient system has been established. To provide tools for implementing this process, three logical principles—observation, assertion, and argument —have been employed [53]. Observation pertains to the background of studies in the field of systems science, while the assertion involves critically analyzing the conditions for implementing the systemic approach. Furthermore, the argument demonstrates the importance of the systemic approach as a key aspect of the resilience concept. It is worth noting that these three principles are continuously used throughout the article, and the benefits derived from them are presented. As a cognitive advantage and an analytical achievement based on observation, assertion, and argument, one can highlight the formulation of the cognitive journey of systemic thinking, increasing the operational capacity of the resilience concept, and presenting core concepts related to resilient systems (key indicators). Figure 2 illustrates the methodology process of the current research study.

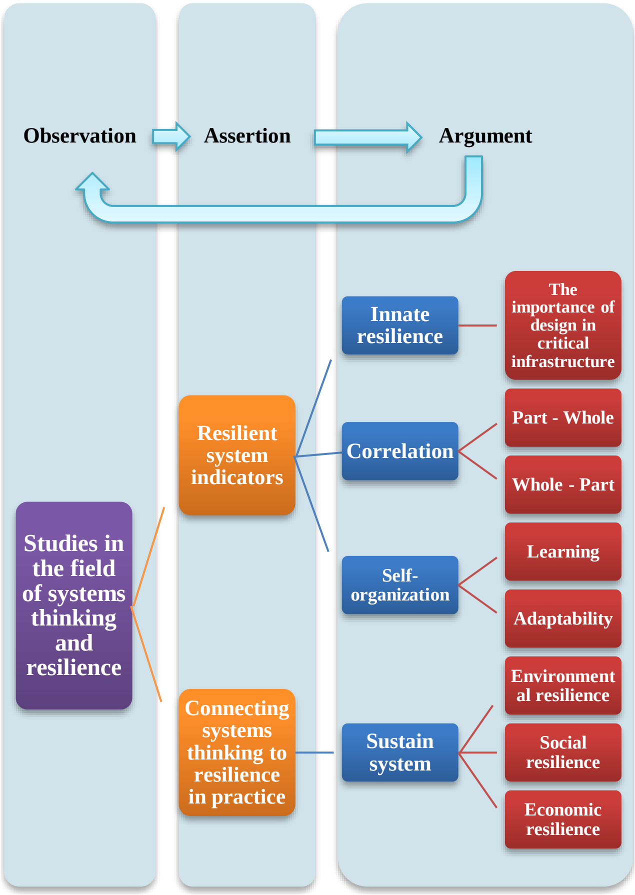

Figure 2. Application areas of the analytical tools observation, assertion, and argument in resilient system design

Employing this three-principle methodology (observation, assertion, argument) significantly reduces cognitive opacity and enhances conceptual coherence in linking systems thinking with resilience. By structurally integrating these principles, the framework clarifies complex interdependencies and provides a robust understanding of infrastructure resilience requirements in operational contexts. This methodological rigor bridges theoretical abstraction with practical implementation imperatives.

This study employs a three-principle methodology (observation, assertion, argument) to reduce cognitive ambiguity and enhance conceptual coherence in systems-resilience research. As depicted in Figure 2, observation synthesizes foundational literature on systems thinking and resilience; assertion critically identifies resilient system indicators and bridges theoretical-practical gaps; while argument yields key outputs: the systemic thinking cognitive journey, operational resilience frameworks, and core indicators. The reproducible process (literature review → indicator analysis → synthesis) enables transparent knowledge integration but faces potential subjectivity in assertion, mitigated through triangulation and peer validation. Grounded in scientific logic—where observation anchors evidence, assertion tests validity, and argument drives integration—the methodology's efficacy is demonstrated via application to the 2025 Shahid Rajaee Port explosion case, confirming its utility in deriving actionable infrastructure resilience insights.

3. Integrating Systems Thinking and Infrastructure Resilience

This section establishes a meaningful nexus between systems thinking and critical infrastructure resilience, adopting a comprehensive perspective to bridge systemic principles with strategic resilience implementation in practice. It addresses core operational challenges—including fragmentation in risk management and adaptive capacity gaps—by leveraging several proposed frameworks and synthesizing recent findings. Through this integration, the analysis translates theoretical foundations of systems science into actionable insights for enhancing infrastructure robustness, responsiveness, and recovery coherence amid complex disruptions. Figure 3 provides an overview of the conceptual connection between systems thinking and resilient infrastructure.

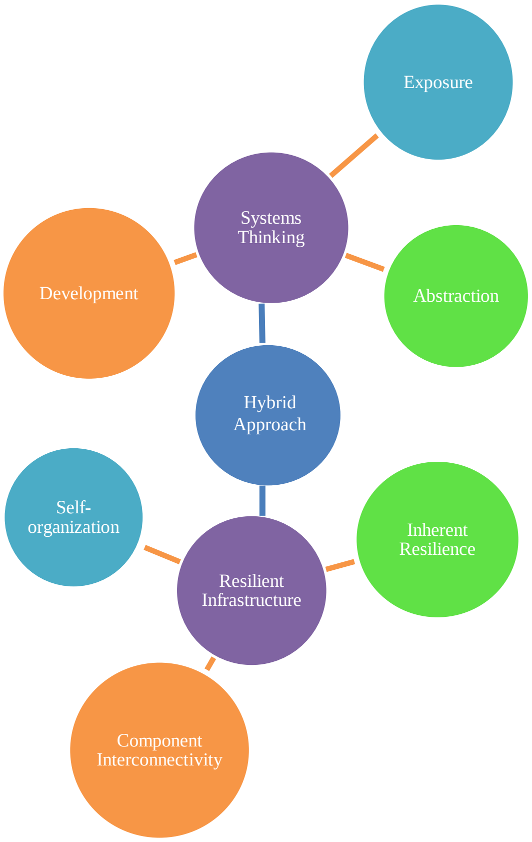

Figure 3. Conceptual overview of systems thinking in resilient infrastructure design

3.1. Systemic Approach

To meaningfully depict the cognitive advantages of previous studies in the field of system design, this section focuses on the triadic connection of exposure, abstraction, and development. Exposure signifies the rationale behind ideation, the necessity of cognitive recognition, and the qualitative description of the systemic perspective. Abstraction will address the efforts made in defining systemic thinking, identifying functions, and existing cognitive gaps, while in the development stage, through redefinition and expansion of function, systemic thinking is linked to resilience and the need for designing resilient and sustainable systems. The cycle of exposure, abstraction, and development is illustrated in Figure 4 and will be explained in detail below. It is important to note that the boundaries between exposure, abstraction, and development are not completely distinct and overlap in analysis; repeating this cycle will reduce cognitive ambiguity.

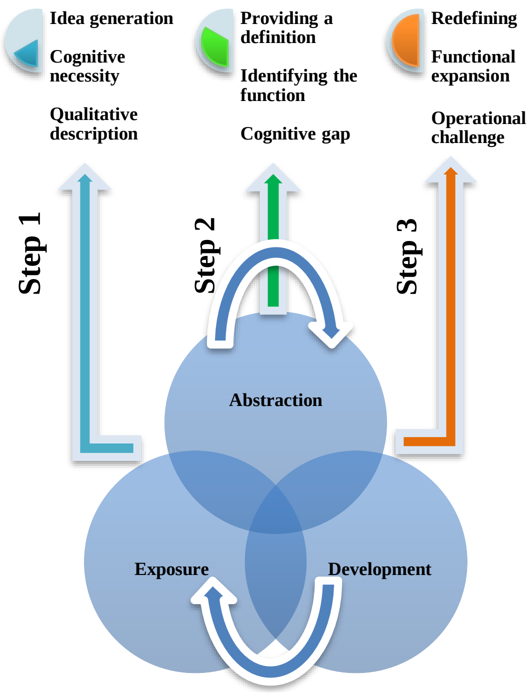

Figure 4. The exposure, abstraction, and development cycle of systems thinking

To address the first question posed in the introduction, it becomes clear that systems thinking has profoundly influenced the design of resilient systems. The systemic approach is employed to improve the performance and efficiency of critical infrastructure—an objective intrinsically tied to resilience. Confronted with these complexities as a cognitive imperative, the researcher adopts systems thinking as a foundational framework. In exploring and articulating this concept, the mechanisms of systems thinking are clarified. Such conceptual clarification fosters a shared understanding among scholars and facilitates a precise definition of the term. At an abstract level, the researcher must grapple with defining systems thinking, transforming this shared understanding into a structured framework. Moving from description to definition requires engagement with literature that embodies systems thinking. This process occasionally adopts a reductionist lens due to overlaps with specific cognitive domains of systems thinking. Throughout their work, researchers have defined complex systems with unpredictable behaviors—systems often marked by dispersion, ambiguity, and overlapping content. Such fragmentation creates a perceptual space for the systemic approach, one that reveals gaps in comprehensiveness and cognition. These gaps then lay the groundwork for the evolution of the systemic approach, particularly when definitions clash with holistic perspectives. This tension stems from acknowledging cognitive challenges while emphasizing the functional necessity of the approach.

Beyond structuring a definition of systems thinking, greater emphasis appears to lie in applying this approach through developmental efforts. During this phase, the researcher redefines systems thinking, extending its functionality by integrating related concepts like resilience. Many scholars seek to enhance systems thinking's utility by linking it to resilience for operational purposes. The analytical mapping of this trajectory—alongside its practical challenges—is contextualized within real-world resilience frameworks.

3.1.1. Exposure

This section addresses the central question of how exposure influences the abstraction of the systemic approach. Richmond [54], a prominent researcher in the field of systemic thinking, coined the term in 1994. He explains systemic thinking as follows:

"We must learn in a new way as interdependencies increase. It is not enough to be smarter than a clever stone. We need a common language, framework, and shared knowledge to collaborate with other specialists. Since understanding interdependencies requires systemic thinking, we need a linguistic Esperanto that enables us to act responsibly."

Based on Richmond's explanation, systemic thinking can be described through various stages. The Merriam-Webster [55] online dictionary defines a system as a group of interacting or interdependent elements forming a unified whole. Meadows [56] argues that a system is more than just a collection of parts. While a reductionist approach may help derive the initial structure of an idea, it often increases ambiguity in the cognitive development of systemic thinking. Dominici [57] criticizes this reductionist method, stating that while it simplifies the cognitive understanding of a concept, it fails to provide a complete grasp of dynamic and complex scenarios. Richmond [54] further characterizes systemic thinking as the art and science of inferring system behavior while deepening the understanding of their underlying structure. He emphasizes that those who adopt systemic thinking position themselves to see both the forest and the trees. However, this description does not fully clarify the relationship between the key components of systemic thinking.

Senge [58], another pioneer in the field, states that systemic thinking provides a broad perspective for seeing the bigger picture and understanding interconnected relationships rather than focusing on isolated elements. This approach is also vital for observing changing patterns instead of static snapshots. Mitchell [59], a complexity theorist, notes in his book Complexity: A Guided Tour that a whole cannot emerge merely from a collection of parts. Fiksel [60], a leading researcher in resilience and sustainability, defines a system as a set of interconnected components performing related functions within a structure. According to this definition, systems encompass a wide range of biological, engineering, and social systems. Systems theory examines how components interact with their external environment and evolve through dynamics. Rather than focusing on a system's specific components, this theory analyzes the correlations between them in a unified manner. Such an approach reveals holistic system characteristics, like resilience, which cannot be understood by merely analyzing individual components [61].

3.1.2. Abstraction

Abstraction signifies the fundamental understanding that arises from confronting a cognitive gap. This understanding is the origin of the emergence of a concept and is essential for comprehending the function and development process of a concept. Considering the role of structured definitions in perceiving the systemic perspective, this section delves into the analysis of systemic thinking. Transitioning from descriptive definitions to structured definitions, which involve resolving content gaps, has helped create a common understanding across different cognitive domains. Abstraction, up to the development of the systemic approach, involves connecting structured definitions until they are redefined, taking into account the practical necessity.

On the other hand, the implementation of this thinking has played a crucial role in addressing the challenges of system performance degradation and designing resilient systems. Efforts to develop systemic thinking emphasize the importance of creating a consistent definition in this regard. Cognitive gaps and overlaps in this approach lead to unbalanced development, but the implementation of a comprehensive space reduces cognitive dispersion in this context. Sweeney and Sterman [62] found that a significant part of systemic thinking involves the ability to represent and assess the complexity and dynamics arising from the interaction of system components over time. They define the skills of systemic thinking as follows:

- Understanding complexity and dynamics in line with how a system behaves due to interactions among its components over time.
- Discovering and representing feedback loops in system behavioral patterns.
- Identifying flow relationships.
- Understanding the reasons for delays and their impact on processes.
- Identifying nonlinear processes.
- Recognizing and challenging the boundaries of mental models.

Hopper and Stave [63], highlighting the necessity of creating a comprehensive definition that addresses existing cognitive gaps, referred to the following aspects to enhance the dynamic understanding of system indicators:

- Recognizing interconnections.
- Identifying feedback.
- Understanding dynamic behavior.
- Distinguishing types of flows and variables.
- Using conceptual models.
- Creating simulation models.
- Policy-making to test processes.

Building on Hopper and Stave's research, Kopainsky, Alessi, and Davidsen [64] state that systemic thinking includes attention to long-term planning, feedback loops, nonlinear relationships between variables, and organized collaborative planning. Squires, Wade, Dominick, and Gelosh [65] defined systemic thinking as part of a research project to accelerate the teaching of modern systems engineering. Systemic thinking is the ability to think abstractly to integrate multiple perspectives, understand the conditions of complex fuzzy systems, recognize the operational breadth of a system, identify internal and external dependencies, understand behavioral complexity, and predict system behavioral scenarios. Prominent researchers in the field of systemic thinking aim to create a common perspective on some characteristics of this approach. They refer to the components that form these systems as "stuff" The behavior of these elements includes dynamic organization, feedback loops, delays, synergy, and uncertainty [66-70]. In addition to pointing out the common structure of these definitions, the cognitive gap existing in this approach can also be explained. The cognitive gap in this approach can lead to analytical errors in the widespread adoption of systemic thinking. To reduce this ambiguity, it is necessary to emphasize the implementation of a comprehensive approach in analyzing the behavior of complex systems. It is also understood that designing a resilient system is not exempt from this rule.

In the statements provided, researchers' efforts to provide a comprehensive definition of systemic thinking are evident. Despite these efforts, the primary challenge in this field remains the response to unpredictable behaviors of system behaviors. An approach must not only consider the breadth of understanding but also the boundary conditions and functional concepts. Additionally, the complexity of system behavior and the necessity of implementing resilience increase the operational challenges.

In complex systems, due to the sequential and combined effects of low-impact events, harmful consequences are created, and disruptions are not solely caused by high-impact events. On the other hand, the systemic approach is defined not by thinking about system components alone but by understanding the dynamic relationships between them. Given the points mentioned, a proper understanding of system resilience is crucial as it involves the system's ability to exit the threshold of performance stability due to disturbance events.

In facing complexities, traditional methods for cost-benefit and risk analysis can be overwhelming [71]. Increasing the scope of understanding and analytical studies of the behavior of inherently resilient systems can address this challenge. Deep exploration into the key indicators of resilient systems in the fields of ecology, social, and commercial sectors facilitates achieving this goal. Recognizing common indicators of these systems that ensure continued performance during unforeseeable hazard events is beneficial. The capacity needed in critical infrastructure systems due to the unpredictability of failure scenarios requires implementation.

3.1.3. Development

The evolution of systemic approaches to leverage system resilience has presented both conceptual and practical challenges. To establish the connection between strategic resilience capacity and operational implementation within systemic frameworks, we must first clearly define the concept. Subsequently, we examine the core challenge of designing resilient systems that meet sustainability criteria. Given resilience's ecological origins and the influence of its developmental context, systemic resilience researchers carefully analyze these ecological foundations.

The synthesis of systemic thinking and ecosystem resilience leads us to design critical infrastructure according to sustainability principles. For this study, we define critical infrastructure as an integrated system of components working toward common performance objectives within a specific geographic area, designed to achieve predetermined levels of environmental, social, and economic performance. At its core, resilience strategy focuses on maintaining critical infrastructure performance in service of sustainability goals. Holling [13] originally connected resilience to system sustainability measurement and shock absorption capacity. This fundamental definition - evaluating performance continuity and disturbance absorption while maintaining system relationships - remains foundational in ecological studies.

Meerow and Newell [72], through their comprehensive review of urban resilience literature, framed resilience as a practical capability. They characterize urban resilience as an urban system's capacity (encompassing its social, ecological, and technical networks across multiple scales) to sustain, adapt, and rapidly recover acceptable performance during disruptions. Resilience represents a complex, multidimensional concept encompassing system survival capacity during changes, closely tied to sustainability [73]. Ecological resilience differs markedly from critical infrastructure resilience, where robustness against threats is paramount. Natural systems establish new equilibrium points post-disruption that may differ from pre-event states. These new equilibria may show decreased, stable, increased, or multiple states. Unlike engineered systems, natural systems face no urgency for recovery nor performance competition with other systems.

Remarkably, natural systems maintain resilience even when showing reduced resilience capacity or extended recovery periods post-disruption. This demonstrates their inherent resilience, fundamentally linked to dynamic sustainability. For critical infrastructure, resilience must align with stakeholder performance expectations. Effective resilience activation depends on appropriate stakeholder expectations, conceptual understanding, and implementation frameworks. Moreover, such systems typically require steady or improved resilience shortly after disruptions. Consider contrasting resilience requirements between economic institutions and urban transportation systems. The competitive commercial environment makes rapid resilience maintenance and enhancement feasible for economic institutions. This difference stems from varying impact scales and disruption frequencies affecting these systems differently. Transportation systems generally require more severe disruptions to experience resilience degradation than economic institutions.

Performance priorities also differ significantly. While economic performance dominates institutional priorities, transportation systems emphasize environmental and social performance. This comparison underscores the critical alignment of environmental, social, and economic performance with stakeholder expectations. It's crucial to recognize that critical infrastructure systems lack inherent resilience, and their operation doesn't automatically ensure sustainability. True resilience emerges from system design incorporating strategic principles, while sustainability results from maintaining and enhancing resilience across all performance dimensions. For instance, an economic institution focusing solely on economic gains while neglecting environmental or social concerns may achieve resilience but fail at sustainability. Comprehensive resilience and sustainability require stakeholder policies that maintain or improve all three performance dimensions during disruptions. The following discussion will identify key resilient system indicators to strengthen this concept's operational implementation.

3.2. Hybrid Approach

Despite extensive efforts to define "systemic thinking" (from Richmond to Senge), existing definitions suffer from structural ambiguity. While emphasizing systemic holism (as opposed to reductionist approaches) is essential for understanding dynamics, this perspective overlooks the absence of a coherent framework for analyzing unpredictable behaviors. Furthermore, excessive focus on "understanding dynamic relationships" without providing behavioral analysis and comprehension mechanisms has created a theory-application gap in designing resilient systems.

Conversely, the misalignment between ecological resilience (Holling) and critical infrastructure constitutes a fundamental flaw: While a "new equilibrium" post-disruption may be sustainable in ecosystems, infrastructures (e.g., transportation networks) must return to pre-disruption performance levels or enhance them. This contradiction in defining "Acceptable Performance" is evident in the economic institution vs. urban transportation system example—where stakeholders hold divergent expectations regarding economic, social, and environmental performance levels. The Multi-scale Framework is formulated around three core pillars:

- **Strategic-Operational Integration:** Converting macro-level resilience policies (e.g., Sendai Framework [74]) into executable technical metrics (e.g., minimum performance threshold, maximum recovery delay).
- **Stakeholder-Driven Design:** Defining "Optimal Performance Level" based on environmental, social, and economic priorities of each subsystem (e.g., port networks prioritizing logistical security vs. rail networks emphasizing social sustainability).
- **Key Indicator-Based Modeling:** Enabling resilience implementation in infrastructure by operationalizing key resilience indicators through cognitive frameworks.

Key contributions resolve three fundamental ambiguities: operationalizing resilience capabilities (inherent, interdependent, and self-organizing) within complex environments; establishing a conceptual bridge between ecological resilience (acceptance of new equilibrium states) and engineered resilience (restoration to baseline functionality); and introducing multidimensional performance metrics aligned with stakeholder expectations. Concurrently, this research acknowledges inherent modeling limitations, including the inability to fully predict chaotic behaviors arising from compound natural-human hazards and quantitative constraints in assessing adaptive capacities of socio-technical systems. Implementation barriers further manifest through requirements for comprehensive historical data to calibrate dynamic models—particularly for high-consequence, low-probability events—and entrenched institutional resistance to shifting from reactive response paradigms toward preventive resilience. Stakeholder conflicts present additional constraints, specifically regarding disagreements over acceptable performance levels during prolonged crises (necessitating economic-social trade-offs) and resource allocation challenges among interdependent sectors (exemplified by budget distribution dilemmas between power grids and healthcare systems).

3.3. Resilient Infrastructure

To ensure the resilient performance of a system during a hazard, it is essential that the system possesses key indicators that signify systemic resilience. These indicators guarantee sustainable service delivery at an acceptable performance level during various hazard scenarios. Key indicators of a resilient system include inherent resilience, component interconnectivity, and self-organization, as depicted schematically in Figure 5. These indicators can be inferred from the dynamic and sustained performance of resilient systems in ecosystems. Efforts have been made to implement and analyze the functioning of these indicators in critical infrastructure systems.

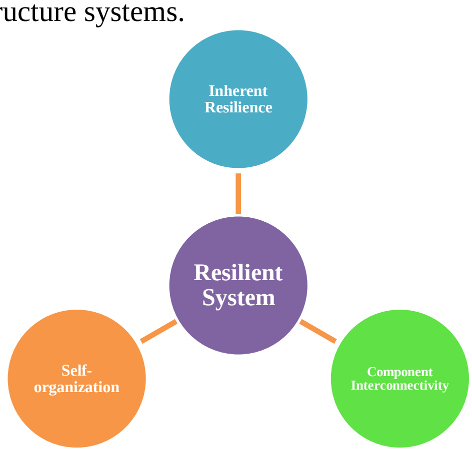

Figure 5. Resilient system indicators

3.3.1. Inherent Resilience

When examining the inherent resilience of systems, we must first clearly differentiate between ecological systems and critical infrastructure systems. After establishing this distinction, we can analyze the developmental stages required to build inherent resilience capacity in critical infrastructure systems.
Fiksel [61] emphasizes that inherent resilience in complex systems emerges from creating an adaptive environment coupled with a central control mechanism. This inherent resilience represents a system's capacity to withstand, adapt to, and even enhance performance levels when facing unpredictable threats. A crucial aspect of this definition involves the presence and function of a central control mechanism and its fundamental connection to the core principles of resilience - a relationship that warrants deeper exploration. Mitchell [59] provides important context by explaining that dynamic systems theory focuses on explaining and predicting macro-level behaviors in systems where complex, variable patterns emerge from interactions among numerous components. These dynamic systems transition between different states over time. In contrast, chaotic systems introduce measurement uncertainties regarding component positions and movements, where even minor variations in initial conditions can lead to significant prediction errors for secondary values.
Building on these theoretical foundations, we examine several key principles for designing inherent resilience in infrastructure systems, as visually represented in Figure 6. This schematic simultaneously illustrates: (1) the cognitive progression from researcher exposure to inherent resilience activation, and (2) the fundamental differences in inherent resilience between ecological systems and critical infrastructure systems. Beyond the complexity inherent to both types of systems mentioned, the presented model offers two aspects worthy of consideration. The first aspect pertains to the intrinsic nature of resilience in the operation of ecological systems, while the second focuses on the necessity of designing and activating resilience in infrastructure systems. Ecological systems inherently exhibit chaotic behavior, dynamism, and survivability. Consequently, such systems are referred to as inherently resilient.

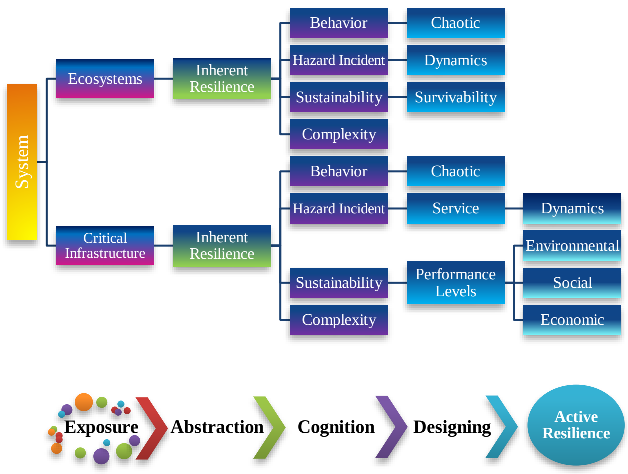

Figure 6. Inherent resilience scenarios in infrastructure systems compared to ecosystem systems

A researcher, considering the necessity of recognizing and implementing resilience, must draw inspiration from the functioning of ecological systems. It is imperative to design preparatory measures to activate inherent resilience in critical infrastructure systems. Quantitative and qualitative evaluation tools for chaos in critical infrastructure systems lay the groundwork for designing inherent resilience. This is contingent upon these systems being able to continue service delivery even during hazard events and adhering to sustainability criteria at key levels. On the other hand, emulating ecological systems to design a resilient infrastructure system without increasing cognitive capacity and positioning of related and shared concepts is not feasible.

3.3.2. Component Interconnectivity

Generally, a system is composed of interacting components (dynamic interactions) with specific objectives, and changes in the performance of these components can lead to unpredictable behaviors at a macro level. Earlier, it was mentioned that every system operates at three fundamental performance levels: environment, society, and economy. The preservation of resilience at these levels signifies a resilient system. Additionally, since a critical infrastructure system is comprised of diverse components with varying degrees of importance at key performance levels (environmental, social, and economic), the analysis of the interconnectivity between components can be conducted in two ways: part-to-whole and whole-to-part. Figure 7 shows the impact of components in the two aforementioned ways at basic performance levels.

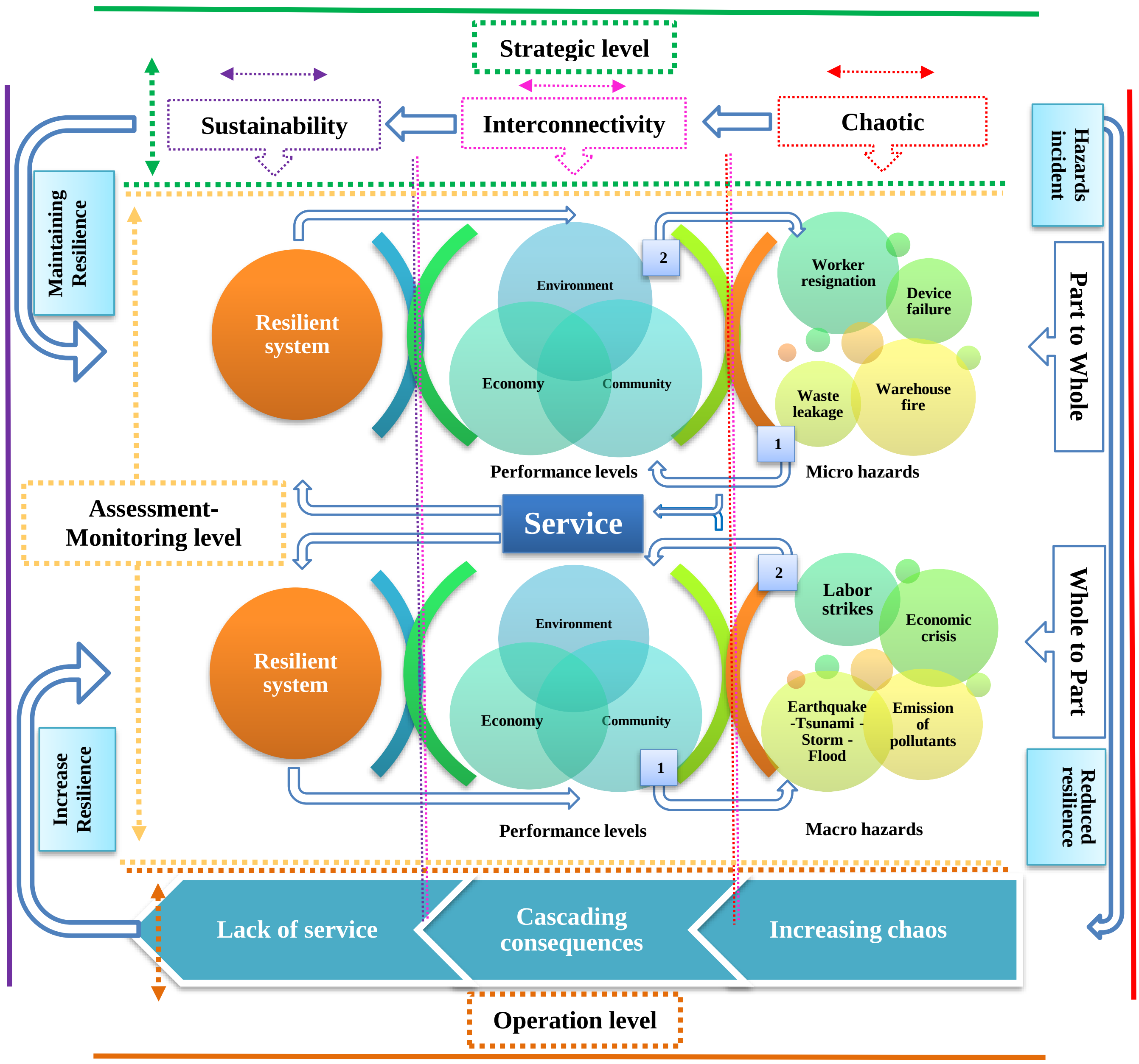

Figure 7. Interconnectivity diagram between system components in two modes: part to whole and whole to part

Evaluating correlations between components in infrastructure systems is crucial due to their chaotic nature, which leads to unpredictable behavior and cascading effects across multiple impact domains during hazards. Henri Poincaré [59], the 19th-century French mathematician renowned for his work on the Three-Body Problem, provides fundamental insights into this chaotic behavior. He posits that with precise knowledge of natural laws and the universe's current state, we could theoretically predict its future state.

Chaos evaluation becomes feasible when assuming an ideal system design and access to diagnostic tools, provided the infrastructure operates in a dynamic, chaotic environment. Notably, Taciroglu [75] and colleagues have emphasized resilience assessment while acknowledging limitations in studies due to systems' chaotic social-level behavior compared to more measurable economic performance. To address these cognitive challenges, this study first establishes that understanding chaos effects takes precedence over measuring its magnitude. Evaluating chaos scale in infrastructure during hazards - involving breadth, intensity, and impact domain analysis (given comprehensive diagnostic tools) - proves complex and time-intensive. This evaluation is possible by assessing hazard consequences through part-to-whole and whole-to-part correlations, which offer three key benefits: reducing chaos assessment ambiguity, simultaneously incorporating reductionist and holistic resilience perspectives, and maintaining both performance and sustainability levels. The functionality of these correlation perspectives will be further elaborated.

A resilient system at strategic level exhibits chaotic yet interconnected stability. During normal operation, hazards increase micro- and macro-level chaos, reducing resilience through component interdependencies. Post-hazard, operational measures manage chaos, cascading effects, and service disruptions, ultimately restoring infrastructure functionality.

Hazards affecting critical infrastructure span natural events (earthquakes, floods, storms) and anthropogenic disasters (pandemics, human-caused damage) [76]. Methodologically, hazards divide into random (widespread disruption) and targeted (intentional, limited impact like terrorism) types [41]. Temporally, they occur as single, multiple, or cascading events [42], where composition considers different hazard types and sequence examines time intervals between events. The core challenge lies in assessing hazard-triggered chaos within resilient systems. This study classifies all hazards as either micro-level (affecting components) or macro-level (affecting system-wide performance). For example, micro-hazards include equipment failures or local accidents, while macro-hazards encompass pandemics or economic crises - all impacting social, economic, or environmental performance differently.

Micro-hazards create limited component changes that cumulatively reduce key performance levels, whereas macro-hazards, though less frequent, severely impact multiple performance levels simultaneously. Both decrease overall resilience. The part-to-whole and whole-to-part approach analyzes these sequential effects, focusing on damage propagation rather than chaos magnitude to enable predictive response.

In critical infrastructure, part-to-whole correlations transform component-level hazards into system-wide behavioral changes, creating variable resilience patterns. Conversely, whole-to-part correlations translate system-level disruptions into component resilience variations. Consider these examples:

- **Part-to-whole:** Multiple employee resignations (components) trigger port strikes, reducing social resilience, causing financial losses (economic resilience), and ultimately system resilience.
- **Whole-to-part:** War-induced economic policies lead to workforce reductions, decreasing economic then social resilience, increasing workload pressure, and causing further resignations.

Regardless of resignation causes, stakeholders can evaluate chaos effects and develop operational scenarios to maintain services. While understanding strike motivations parallels chaos measurement, creating economic resilience strategies addresses chaos effects. For instance, port strike mitigation might involve mechanization or temporary staffing solutions.

3.3.3. Self-Organization

Learning capacity at the strategic level and operational adaptability form the foundation of self-organization. A truly resilient and dynamic system must demonstrate adaptive capabilities to recover from performance disruptions caused by hazards. Consequently, self-organization emerges as the natural outcome of a system's adaptive performance. Kauffman [59], a prominent complexity science researcher, provides a fundamental definition of self-organization in his seminal work "The Origins of Order: Self-Organization and Selection in Evolution." He posits that complex, self-organizing behavior arises when network structures reach sufficient complexity, enabling multiple nodes to influence and regulate other nodes within the system.

The manifestation of self-organization varies significantly between ecological systems and infrastructure systems due to their divergent performance objectives. Misunderstanding these distinctions can lead to fundamental cognitive errors. Ecological systems prioritize survivability and sustainability principles in their performance goals, while infrastructure systems focus on meeting stakeholder expectations and maintaining productivity. For resilient infrastructure systems, we define self-organization as the dynamic, sustainable interactions that occur during hazard events - whether or not a central control mechanism is present. This operational definition serves two critical purposes: maintaining system productivity during disruptive events and ensuring alignment with stakeholder objectives. Figure 8 visually represents this self-organization cycle within resilient systems.

Figure 8. Self-organizing cycle in a resilient system

Before examining the self-organization cycle in detail, we must establish three distinct temporal phases: pre-hazard, during-hazard, and post-hazard periods. The initial phase represents the system's normal operational state where it maintains active resilience. During this pre-hazard period, the system develops crucial learning capabilities by analyzing past incidents and resilience fluctuations, thereby preparing for potential future events.

The concept of "lessons learned" is formally defined through a collaborative framework by NASA, ESA, and JAXA [77] as: *"Knowledge or understanding gained through experience - whether positive (such as successful missions or experiments) or negative (including failures or disasters). Effective lessons must produce operational impacts by either: (1) identifying improved plans, processes, or decisions that reduce future risks, or (2) reinforcing successful practices that enhance positive outcomes."*

When hazards occur, the system enters the second phase where resilience declines markedly, potentially causing service disruptions. The subsequent recovery phase involves stakeholders and operators implementing corrective actions through operational preparations and strategic decisions. This process demonstrates adaptability - defined as decision-makers' capacity to positively influence system resilience [78]. Successful adaptation enables recovery, ultimately restoring and even enhancing the system's resilience.

When this cyclical process culminates in restored service delivery, the system demonstrates its self-organizing capability and qualifies as truly resilient. The complete cycle illustrates how learning, adaptation, and recovery mechanisms interact dynamically across all three phases to maintain system resilience.

4. Resilient Design

This section presents the analysis, implementation, and actionable recommendations derived from the study, alongside its inherent limitations and future research directions. It evaluates how systems thinking can be operationalized by connecting a hybrid approach to key resilient infrastructure indicators through a detailed case study of the 2025 Shahid Rajaee Port explosion. Central to this analysis is a three-step, iterative design framework for resilience enhancement in critical infrastructure: 1) Systems Thinking, 2) Resilience Indicator Identification, and 3) Resilience-Based Design. By concurrently leveraging strategic resilience principles and a systems-oriented service continuity mindset during hazard events, this framework enables the meaningful implementation of resilience—effectively translating "resilience in theory" into resilience in practice—to ensure uninterrupted infrastructure functionality.

4.1. Implementation

It examines the case study of the Shahid Rajaee Port explosion, a facility critical to the International North-South Transport Corridor (INSTC), and the role of Shahid Beheshti Port (Chabahar) in enhancing the resilience of Iran's maritime domain. Critical Infrastructure (CI), defined as assets "essential for maintaining the vital functions of society... the disruption or destruction of which would have a significant impact" [79], underpins economic and social well-being across sectors like transportation, energy, and communications. Focusing on Rajaee Port (27.1142°N, 56.0615°E) and Beheshti Port (25°17′34″N, 60°38′59″E), the frameworks integrates operational performance, hazard assessment, and sustainability metrics to evaluate disruptions to cargo handling (TEU) and regional connectivity. The strategically vital Persian Gulf and Makran Sea region hosts Iran's pivotal ports—Shahid Beheshti and Shahid Rajaee—which handled 66,142 TEUs and 2,126,244 TEUs respectively in 2022–2023 [80], cementing their status as economic linchpins within the INSTC.

The region's vulnerability is multifaceted, situated in a seismically active zone with historical precedents like the 1945 Mw 8.1 Makran earthquake and tsunamis [81, 82], and facing environmental threats including marine degradation, rising salinity, and climate change [83, 84]. The INSTC—a 7,200 km multimodal corridor linking the Indian Ocean to Northern Europe—relies on these ports to transform regional economies into logistics hubs. However, seismic risks from the poorly understood Makran Subduction Zone (MSZ) [82] threaten corridor integrity, trade routes, and regional stability. Shahid Rajaee, handling 80% of Iran's container traffic near the Strait of Hormuz [80], and Shahid Beheshti, Iran's sole oceanic gateway to Afghanistan and Central Asia, face dual pressures: sustaining growth amid INSTC expansion while mitigating seismic and climate-driven marine hazards. Despite shared transboundary risks, environmental cooperation remains fragmented by geopolitical rivalries, hindering initiatives like ESCAP's Tsunami Preparedness Trust Fund [82]. The catastrophic explosion at Shahid Rajaee Pier on 26 April, 2025 (officially reported as causing 70 fatalities, 1,242 injuries, and significant structural damage) starkly exposed systemic vulnerabilities [85, 86]. Figure 9 shows an aerial view of the explosion and the geographical location of the study area.

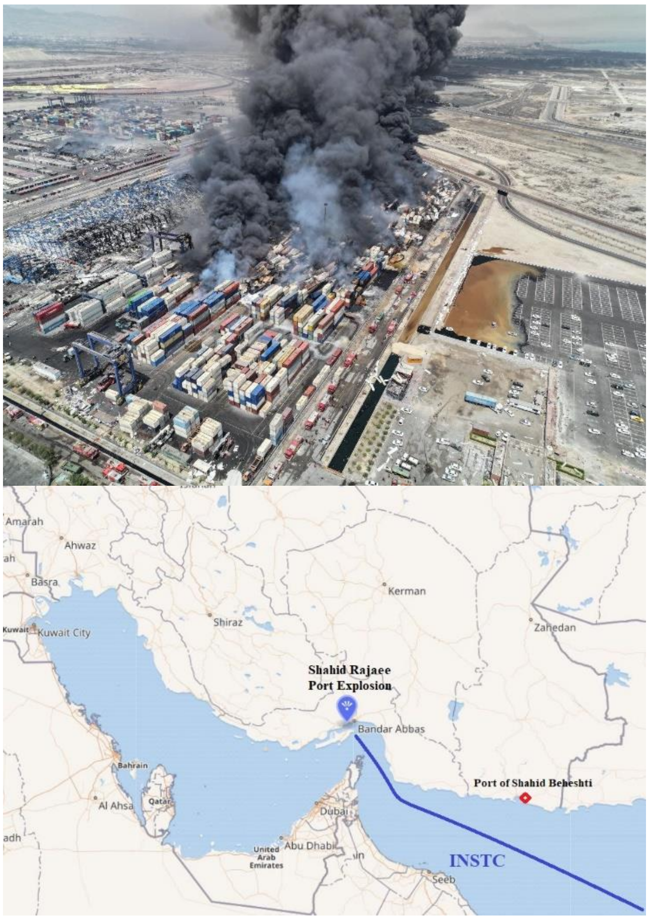

Figure 9. Overview of the study area (Shahid Rajaee and Shahid Beheshti ports)

This event necessitates a resilience framework emphasizing adaptive capacity, integrating operational recovery protocols, damage assessment, and sustainability metrics to ensure trade continuity and ecological health. The proposed approach addresses interconnected challenges—from tectonic uncertainties and climate impacts to governance gaps—by fostering inherent resilience, optimizing component interdependency, and enabling self-organization. Such a framework is essential to safeguard the INSTC's role as a global trade artery, enhance regional stability, and balance economic, social, and environmental performance against both acute shocks and chronic stressors.

4.2. Qualitative Assessment

A qualitative analysis is conducted of the catastrophic explosion at Shahid Rajaee Port wharf and its cascading impacts on the International North-South Transport Corridor (INSTC), applying the critical infrastructure resilience frameworks proposed in this study.

The detonation initiated sequential failures: widespread fires engulfed adjacent containers containing flammable materials, necessitating 20-hour firefighting operations with aerial support and provincial reinforcements before extinguishment at 08:00 AM on April 27 [87]. This forced complete suspension of maritime operations to prioritize emergency response [88], halting commercial activity at Iran's primary trade gateway for two days before limited customs resumption [89, 90]. The disruption paralyzed a significant portion of Iran's supply chains for essential goods and revenue streams [91, 92], though nearby oil infrastructure remained operational. Physical destruction included a demolished office building [93], extensive structural damage to surrounding buildings [94, 95], and shattered vehicle windows across the facility [96]. Initial estimates placed total damages at approximately $198.81 million USD, encompassing victim compensation ($10 million), infrastructure reconstruction ($43.75 million), equipment repairs ($2.5 million), container losses ($124.69 million), vehicle damage ($7.88 million), passive defense implementation ($9.38 million), and auxiliary support costs ($0.625 million) [97].

4.2.1. Hybrid Connection

Table 1 demonstrates how the hybrid approach serves as a critical bridge between systems thinking and operational resilience implementation. By analyzing past failures (left column) and future imperatives (right column), it reveals how the approach's three pillars—strategic-operational integration, stakeholder-driven design, and indicator-based modeling—convert theoretical resilience concepts into actionable infrastructure safeguards, turning systemic vulnerabilities into managed risks.

Table 1. Bridging past failures to future resilience: the Hybrid Approach as an operational catalyst

Aspect	Past Impact (Without Hybrid Approach)	Future Imperative (With Hybrid Approach)	Past-Future Bridge
Strategic-Operational Integration	- No technical metrics from macro-frameworks - Inadequate hazardous material zoning at Rajaee Port	- Codify automated monitoring against INSTC benchmarks - Enforce minimum performance thresholds for cargo handling (TEU)	Convert reactive policies → Proactive technical standards
Stakeholder-Driven Design	- Flammable container proximity unidentified - No subsystem-specific priorities (e.g., Rajaee's logistical security)	- Formalize multi-agency councils - Define port-specific "Optimal Performance Levels" for crises	Transform blind spots → Risk-mapped resilience
Indicator-Based Modeling	- No real-time disruption thresholds - Cascading fire propagation unmodeled	- Deploy AI-enhanced cognitive simulations - Operationalize resilience indicators (e.g., recovery delay)	Shift from post-event analysis → Pre-emptive cascading failure mitigation

4.2.1.1. Necessity and Retrospective Impact

The hybrid approach's integration of strategic policy translation, stakeholder-centric design, and indicator-based modeling is imperative for operationalizing resilience in critical infrastructure. By converting macro-frameworks like the Sendai Framework into technical metrics (e.g., minimum operational thresholds for cargo handling), embedding subsystem-specific priorities (e.g., Rajaee Port's focus on logistical security versus Chabahar's role in regional redundancy), and cognitively operationalizing resilience indicators, it bridges systemic vulnerabilities with executable safeguards. Had this approach been implemented prior to the 2025 Shahid Rajaee Port explosion, it would have mitigated cascading failures through pre-emptive measures: stakeholder-driven risk mapping would have identified flammable container proximity as a critical vulnerability, strategic-operational integration would have enforced stricter hazardous material zoning, and indicator-based modeling would have established real-time TEU disruption thresholds—collectively curtailing the 20-hour firefighting exigency, avoiding the two-day operational shutdown, and reducing the $198.81 million losses in container assets ($124.69M) and infrastructure ($43.75M).

4.2.1.2. Future Implementation Imperative

To prevent recurrence, future resilience must institutionalize this hybrid methodology across Iran's maritime corridors. For Rajaee and Beheshti Ports, this entails: (1) codifying strategic-operational linkages via automated performance monitoring against INSTC connectivity benchmarks; (2) formalizing stakeholder-driven design through multi-agency councils to define port-specific "Optimal Performance Levels" for crisis scenarios; and (3) deploying AI-enhanced cognitive models to simulate cascading impacts (e.g., fire propagation trajectories) using key resilience indicators. Concurrently, passive defense allocations ($9.38M) must fund modular infrastructure designs, while auxiliary support systems ($0.625M) should enable rapid resource redistribution—transforming resilience from reactive expenditure to proactive investment. Such systemic hardening, anchored in the three-pillar hybrid framework, would not only shield supply chains but also elevate Chabahar's role as a fail-safe node within the INSTC, ensuring continuity amid disruptions.

4.2.2. Inherent Resilience in the Southern Marine Zone of Iran

The Shahid Rajaee Port explosion exposed critical vulnerabilities in Iran's INSTC-dependent maritime infrastructure. Inherent resilience, defined as a system's organic capacity to resist, adapt, and self-optimize against unpredictable threats through decentralized adaptability anchored to a central control nucleus, therefore becomes essential. Unlike engineered resilience (retrofitted safeguards), inherent resilience mimics ecological systems: chaotic yet survivable due to dynamic reconfiguration capabilities. For southern Iran's ports, this translates to infrastructure designed to metabolize shocks like living organisms—maintaining uninterrupted service during events like the Rajaee explosion without external intervention. Implementing inherent resilience requires:

- **Chaos-Theoretic Foundations:** Quantitative modeling of port systems as dynamic chaotic entities (e.g., simulating container fire propagation through sensitivity-to-initial-conditions analysis).
- **Control Nucleus Architecture:** A distributed decision-making hub (e.g., AI-driven port operations center) enabling autonomous subsystem adaptation—including INSTC cargo rerouting to Shahid Beheshti Port during crises.
- **Metabolic Flexibility:** Modular infrastructure designs (e.g., fire-resistant container zoning) supported by passive defense allocations, permitting localized damage absorption without systemic failure.

- **Cognitive Capacity Development:** Training personnel in ecological resilience principles (e.g., ecosystem redundancy emulation) via stakeholder-driven councils.

4.2.2.1. Potential Impacts on Rajaee Port's Operational Continuity

With inherent resilience operational:

- **Resistance Phase:** Chaotic behavior modeling would have flagged flammable container clusters as high-risk zones, enabling preventive dispersion—preventing fire cascades and minimizing container losses.
- **Adaptation Phase:** The control nucleus would have initiated INSTC rerouting to Chabahar within hours, sustaining regional cargo flow during Rajaee's 48-hour closure.
- **Self-Optimization Phase:** Post-incident, "dynamic memory" systems (e.g., AI-based fire pattern analysis) would have reconfigured wharf layouts, significantly reducing recovery time and infrastructure repair costs.

4.2.2.2. Strategic Requirements for Southern Maritime Corridors

To embed inherent resilience:

- **Short-term:** Incorporate chaos metrics into the hybrid framework's indicator-based modeling, using Rajaee explosion data to establish TEU disruption thresholds.
- **Medium-term:** Establish Beheshti Port as an ecological resilience model—capitalizing on its geographical isolation for backup operations.
- **Long-term:** Direct national passive defense funding toward adaptive infrastructure, evolving ports from static facilities to "living" systems that prosper amidst instability.

The Rajaee disaster demonstrates that conventional risk management remains inadequate for INSTC-critical nodes. Inherent resilience—merging ecological adaptability with engineered control—would transform southern Iran's maritime infrastructure from fragile to antifragile, guaranteeing continuous operation by design. This fundamental change necessitates shifting resources from reactive recovery to chaos-informed preparedness, creating ports that are not just durable but inherently evolutionary.

4.2.3. Ports Interconnectivity

The interdependence of components within Iran's southern maritime domain necessitates a systemic case study of North-South Corridor (INSTC) resilience, driven by the criticality of uninterrupted coastal infrastructure service delivery during both localized and large-scale hazards. As illustrated in Figure 10, the study area—encompassing Shahid Rajaee Port and Shahid Beheshti Port—historically faces multi-hazard exposures including earthquakes and tsunamis. This contextual complexity underscores the urgency of analyzing coastal resilience through the lens of component interdependencies, particularly regarding the INSTC's operational continuity.

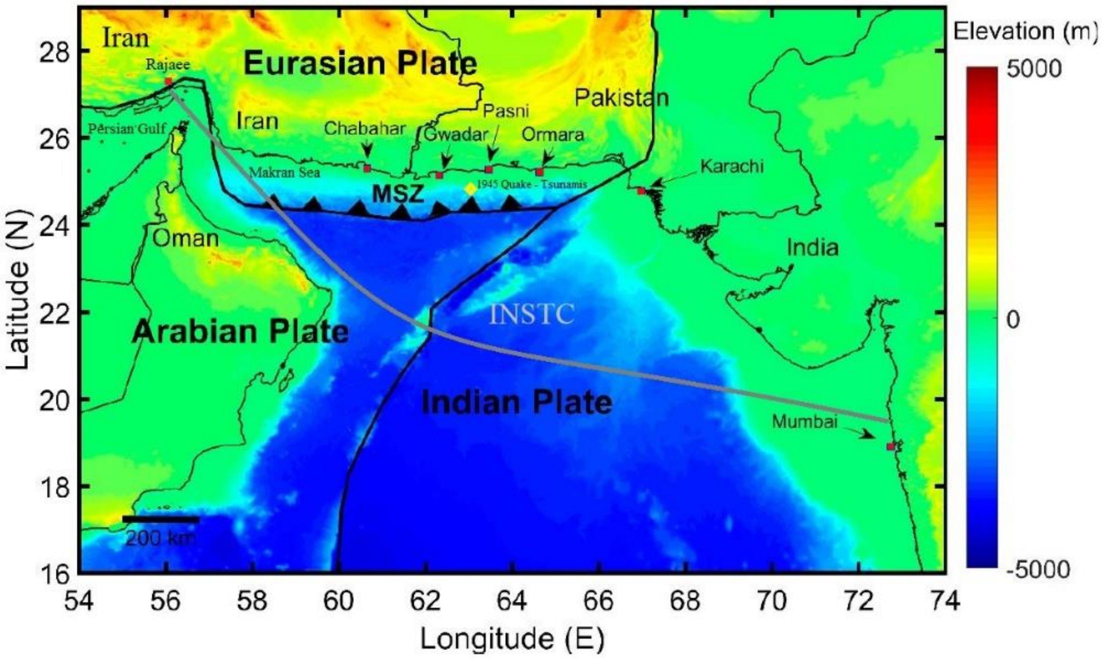

Figure 10. An overview of natural hazard contexts in the Makran region

Service collapse at Rajaee Port—demonstrated during the 2025 event and potentially replicated in seismic scenarios given the region's high historical seismicity—accentuates Chabahar Port's role as a fail-safe node for sustaining the INSTC. The resilience and sustainability of this corridor hinge on the functional synergy between Rajaee (Persian Gulf) and Chabahar (Makran Sea), where the latter provides critical redundancy during Rajaee's operational suspension. However, this backup efficacy faces systemic constraints: uneven hazard distribution (e.g., Rajaee's earthquake susceptibility versus Chabahar's flood exposure) and cascading risk potential threaten to compromise socioeconomic and environmental performance levels across the corridor. To evaluate these interdependencies, a qualitative analysis of hypothetical full-collapse scenarios at Rajaee Port is essential. This assessment reveals how cascading events—triggered by historical hazards or human-induced disasters—propagate INSTC-wide disruptions, while simultaneously analyzing and assessing Chabahar's capacity to mitigate corridor paralysis. By modeling these systemic vulnerabilities, the study establishes how strategic backup port utilization preserves baseline functionality, thereby transforming theoretical redundancy into operationalized resilience for Iran's critical maritime infrastructure.

4.2.3.1. Major Earthquake at Rajaee Port

Rajaee is located in an active seismic zone, where there is a possibility of major earthquakes. Although Chabahar Port is exposed to earthquakes and tsunamis (indicating a single or cascading hazard event), it is considered less critical than Rajaee Port due to its lower container handling capacity and the assumption of collapse. This has led to the analysis of a large-scale event at Rajaee Port as the worst-case scenario. A hypothetical earthquake could damage quay cranes, breakwaters, and utilities, reducing Rajaee's TEU capacity to collapse levels.

Backup Role of Chabahar. Chabahar would assume Rajaee's cargo-handling responsibilities to sustain INSTC operations. However, Chabahar's limited capacity (historically lower TEU throughput than Rajaee) would strain its operational efficiency, leading to delays and congestion.

Resilience. The corridor's overall resilience would decline moderately, as Chabahar's backup capacity prevents a total shutdown but cannot fully offset Rajaee's pre-collapse throughput.

Sustainability. Economic performance would dip due to slower cargo processing, while social stress (e.g., workforce displacement) and environmental risks (e.g., oil pollution spread) would rise. However, no sustainability metric would reach zero.

4.2.3.2. INSTC Resilience

The ports of Rajaee and Chabahar, distinguished by their unique climatic diversity and strategic geographic separation, hold significant potential to enhance the resilience of the INSTC, with this climatic variation introducing differences in the type and timing of hazard events such as earthquakes, tsunamis, and storms that necessitate adaptive infrastructure planning. Chabahar's location along the Makran Sea offers a natural advantage during hazard scenarios—particularly tsunamis—due to its relatively sheltered position compared to other coastal zones, though unlocking its full potential as either an independent hub or backup to Rajaee demands targeted investments in port infrastructure including modernized terminals and expanded hinterland connectivity networks. Strengthening these elements would mitigate operational disruptions while solidifying Chabahar's role as a linchpin in sustaining INSTC's continuity amid crises, despite its exposure to cascading disasters like seismic events triggering tsunamis that reveal systemic vulnerabilities requiring proactive frameworks. Consequently, Iran must adopt a dual strategy leveraging Chabahar's strategic importance: first, prioritizing climate-resilient coastal infrastructure tailored to its diverse hazard profile through tsunami-resistant structures and earthquake-proof logistics hubs; second, aligning risk mitigation with Chabahar's unique geographic assets as Iran's sole oceanic port to reduce container transport costs/time along INSTC routes. Table 2 examines the resilience dynamics between Iran's Rajaee and Chabahar ports within the INSTC, contrasting centralized efficiency against decentralized redundancy.

Table 2. Interdependence analysis of INSTC's port system: centralization vs. decentralization trade-offs

Aspect	Analysis
Component Interdependencies	- Rajaee and Chabahar form a climatically diversified dyad - Asymmetric hazard exposure: Rajaee faces Persian Gulf earthquakes; Chabahar sheltered from tsunamis but faces Makran-specific risks - Functional synergy: Chabahar's oceanic access reduces INSTC transport costs/time; Rajaee provides scale
Whole-to-Part Approach	- Centralized risk propagation: Rajaee's hub status means disruptions (e.g., 2025 explosion) cascade corridor-wide - Systemic vulnerability: Single-point failure paralyzes INSTC supply chains for essential goods - Macro-level impact: Rajaee's 48-hour shutdown in 2025 caused $198.81M losses, highlighting centralized fragility
Part-to-Whole Approach	- Decentralized redundancy: Chabahar's geographic isolation enables failover capacity during Rajaee's collapse

	- Risk paradox: Underinvestment in Chabahar's hinterland connectivity increases INSTC vulnerability despite redundancy potential - Performance trade-off: Over-reliance on Rajaee's scale vs. Chabahar's strategic dispersion
Centralization vs. Decentralization	- Centralization (Rajaee Focus) ✓ Pros: Economies of scale, optimized logistics ✗ Cons: Single-point failure risk, catastrophic cascades - Decentralization (Chabahar Development) ✓ Pros: Risk distribution, multi-hazard adaptability ✗ Cons: Duplicated infrastructure costs, coordination complexity

Decentralizing logistics dependencies from Rajaee while enhancing Chabahar's capacity will create a balanced service network that distributes risk and improves systemic adaptability without compromising Rajaee's resilience upgrades. Ultimately, Iran's role alongside cooperation with India and Russia remains vital for strengthening INSTC resilience, where aligning Chabahar's development with national/regional sustainability priorities—including Persian Gulf and Makran Sea disaster risk reduction and environmental safeguards—ensures strategically ecologically sound growth. Integrating resilience throughout Chabahar's expansion, from decentralized logistics networks to multi-hazard preparedness, will establish it as a sustainable trade hub that secures the INSTC against disruptions while reinforcing Iran's role in fostering a stable, environmentally responsible Eurasian trade corridor, with ports interconnectivity establishing regional systemic boundaries, strategically positioning critical mega-system components, and accounting for resilience-reducing factors like hazard types, event sequences, and cascading risks to foster integrated economic, social, and environmental performance ensuring sustainable corridor-wide service delivery.

4.2.4. Self-organizing Ports

This analysis examines how the port's self-organization cycle—spanning pre-event learning, crisis response, and post-event adaptability—reveals replicable strategies for enhancing southern Iranian ports' robustness within the corridor. Table 3 synthesizes how this repeatable process strengthens the INSTC's adaptive capacity through qualitative operational and strategic outcomes.

Table 3. Operational and strategic benefits of the repeatable self-organization cycle in southern Iranian ports

Benefit Dimension	Specific Outcome
Corridor Network Fluidity	Dynamic failover activation to Shahid Beheshti Port maintains INSTC connectivity during critical disruptions
Operational Responsiveness	Decentralized coordination significantly accelerates cargo recovery through stakeholder improvisation
Risk Intelligence	Incident-derived knowledge continuously reshapes hazardous material protocols
Infrastructure Evolution	Strategic investments consistently prioritize distributed redundancy and passive defense mechanisms
Stakeholder Alignment	Collaborative rerouting frameworks sustain corridor-wide productivity objectives
Resilience Standardization	Cyclical learning establishes transferable preparedness benchmarks for port systems

4.2.4.1. Pre-event

Shahid Rajaee Port functioned as a resilient strategic node in the INSTC pre-explosion, leveraging accumulated learning from routine operational disruptions to optimize cargo handling (TEU) and corridor connectivity. Institutional knowledge from past incidents informed risk mitigation protocols, while real-time data integration supported service continuity as Iran's primary trade gateway (handling 85% of container traffic). However, learning gaps persisted regarding large-scale kinetic hazards, with contingency plans prioritizing conventional operational risks over catastrophic physical destruction scenarios. The port's pre-event resilience was thus anchored in throughput efficiency but lacked structural redundancy for high-impact shocks.

4.2.4.2. During Event

The 2025 explosion triggered cascading failures, as fires in adjacent containers caused an immediate reduction in resilience. With the wharf rendered inoperable and fires remaining uncontrolled for 20 hours, decision-making during the crisis became fragmented. The emergency shutdown of maritime operations reflected triage priorities—prioritizing lives over supply chain continuity—while exposing the system's rigidity. Rajaee's centralized control model faced coordination challenges, delaying firefighting escalation and crisis communications. Consequently, service disruptions paralyzed regional logistics, leaving Iran's essential imports stalled and demonstrating how single-point vulnerabilities threaten corridor-scale resilience.

4.2.4.3. Post-event

Recovery commenced with the partial resumption of customs operations after 48 hours, enabled by operational adaptability. This process focused on enhancing resilience through physical hardening and risk distribution. Within weeks, restored services at Rajaee Port reached acceptable pre-incident levels, demonstrating how adaptability transforms recovery into enhanced operational capacity.

4.2.4.4. Self-Organization Cycle Completion

The system achieves self-organization by closing the resilience loop, where post-event adaptations institutionalize learning (e.g., revised hazardous cargo protocols and INSTC rerouting blueprints). Beheshti Port's role as a failover node validates distributed control principles, aligning with INSTC's productivity goals. The $198.81M loss highlights the cost of centralized fragility, establishing decentralized responses as the new resilience benchmark. As Rajaee rebuilds, its integration with Beheshti and INSTC partners demonstrates dynamic, sustainable interaction—proving self-organization's critical role in balancing operational performance with hazard resilience in critical infrastructure.

4.3. Operational Recommendation, Limitations and Outlook

To leverage the hybrid approach effectively, prioritize enhancing inherent resilience by diversifying critical component redundancies and decentralizing decision nodes, ensuring core functions persist under disruption. Systematically map and strengthen component correlations through cross-functional simulations and real-time dependency monitoring; this mitigates cascading failures by identifying brittle interdependencies. Simultaneously, foster self-organization by embedding adaptive protocols (e.g., dynamic resource reallocation algorithms) and empowering local units with predefined autonomy thresholds, enabling rapid reconfiguration without top-down intervention during crises. Operationalizing resilience thus demands phased action:

- **Short-term:** Anchor chaos metrics in national standards using Rajaee's $198.8M loss data.
- **Medium-term:** Scale Shahid Beheshti Port into a modular backup nucleus for INSTC.
- **Long-term:** Transition from reactive recovery budgets to preventive metabolic capacity investments.

Current implementations face constraints in quantifying nonlinear component correlations, especially in large-scale systems where emergent interactions complicate predictive modeling. Self-organization capabilities are hindered by legacy infrastructures lacking interoperability, limiting agile responses. Furthermore, inherent resilience assessments often overlook contextual vulnerabilities (e.g., geopolitical or environmental shocks), while data gaps in stress-testing rare scenarios reduce confidence in correlation-based risk forecasts. While this frameworks advances resilience design, inherent limitations persist:

- **Chaos predictability:** Compound hazards (e.g., earthquake-induced fires) defy full modeling.
- **Stakeholder friction:** Conflicting performance expectations (economic vs. environmental) impede consensus.
- **Data scarcity:** Historical gaps in low-probability events weaken scenario calibration.

Future work should develop AI-driven frameworks to dynamically model evolving component correlations, enhancing predictive accuracy for cascading impacts. Investing in modular, interoperable architectures will expand self-organization potential across scales. Longitudinal studies on inherent resilience drivers—particularly socio-technical feedback loops—can refine design principles. Integrating these elements will advance adaptive hybrid systems capable of antifragility, transforming resilience from reactive robustness to proactive evolution.

5. Conclusion

This study resolves the critical cognitive gap in systemic resilience by synthesizing ecological abstraction (inherent capacity), socio-technical dynamics (component correlations), and evolutionary adaptation (self-organization). Where traditional approaches faltered—reductionist hazard-focused models or misapplied ecological equilibrium concepts—our hybrid framework bridges theory and practice. The 2025 Shahid Rajaee Port disaster exemplifies this systemic disconnect; centralized governance and inflexible infrastructure exacerbated vulnerabilities in the system. By embedding chaos-aware cognition and multi-scale stakeholder priorities, the framework transforms resilience from a reactive protocol to a proactive design philosophy.

The Rajaee explosion underscores the critical importance of inherent resilience—comprising organic resistance, adaptation, and optimization—for essential infrastructure nodes. Our analysis shows that port systems must function like living organisms in absorbing and responding to shocks through decentralized decision-making (intelligent control core), embedded metabolic flexibility (fire-resistant modular zoning), and the use of chaos modeling (container dispersion algorithms). Had inherent capacity been operational pre-2025, Rajaee's resistance could have prevented fire cascades; adaptation would have rerouted INSTC cargo to Shahid Beheshti Port within hours; and self-optimization would have cut recovery costs significantly. The $198.8M loss thus underscores a strategic imperative: ports must evolve from static facilities to "living infrastructures" thriving in instability.

The interdependence of components within Iran's southern maritime corridor necessitates the development of intelligent redundancy structures. The

2025 explosion at Shahid Rajaee Port clearly demonstrated the vulnerability of the International North-South Transport Corridor (INSTC) system to sudden shocks, despite the backup role of Shahid Beheshti Port (Chabahar). Earthquake scenario analysis further confirms this systemic weakness: while Rajaee Port faces seismic risks, Chabahar Port is primarily exposed to flood and storm threats. This uneven hazard distribution, combined with operational capacity disparities between the two ports (Rajaee's high container traffic volume versus Chabahar's more limited throughput capability), significantly compromises the effectiveness of backup systems. The 2025 incident revealed three critical lessons: mere redundancy is insufficient without operational coordination and adaptive capacity between components; single events can rapidly escalate into cascading failures (fires, communication breakdowns, transit disruptions); and Chabahar must be strengthened not just as a backup facility but as an integral node within a resilient network. True resilience requires:

- **Balanced redundancy:** Synchronizing port capabilities to handle throughput shocks.
- **Cascade buffers:** Modular firewalls between correlated components (e.g., isolating energy grids from cargo hubs).
- **Multi-hazard alignment:** Redirecting passive defense funds toward adaptive interdependencies, not isolated hardening.

Post-Rajaee recovery highlighted self-organization's role in closing the resilience loop. This contrasts starkly with the event's fragmented top-down crisis response. Embedding self-organization necessitates:

- **Stakeholder-driven learning loops:** Local councils translating ecological principles (e.g., ecosystemic redundancy) into technical protocols.
- **Dynamic institutional memory:** AI-aided pattern recognition (e.g., fire-spread algorithms) informing real-time reconfiguration.
- **Autonomy thresholds:** Predefined authority for subsystem adaptation during chaos, avoiding decision paralysis.

This study redefines resilient infrastructure as a dynamic synthesis, encompassing an inherent capacity for shock absorption, correlation-aware redundancy to mitigate cascading failures, and self-organization that enables adaptive evolution. The Shahid Rajaee Port disaster illustrates how resilience aligned with sustainability depends critically on this triad of characteristics, transforming traditional infrastructure from brittle and static to antifragile and responsive. These findings suggest a paradigm shift in infrastructure design priorities: the focus should move from promoting rigid, centralized systems toward fostering flexible, metabolism-ready structures; from designing for equilibrium toward preparing for disequilibrium; and from limiting subsystem autonomy toward empowering decentralized components capable of independent yet coordinated response.

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