
Engineering System Resilience to Global Risks: A Resilience Engineering Approach in Modern Infrastructure

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ABSTRACT

The increasing exposure of modern infrastructure systems to global risks such as climate change, multi-hazard disasters, cyber disruptions, and pandemics has highlighted the need for a shift from reliability-based to resilience-based engineering approaches. This study aims to analyze the role of resilience engineering in enhancing the robustness, adaptability, and recovery capabilities of engineering systems under uncertain and complex conditions. The research adopts a qualitative approach using a systematic literature review (SLR) method, with data collected from reputable international journals published between 2021 and 2025. The analysis employs thematic and comparative synthesis to identify key dimensions of resilience, including absorptive, adaptive, and recovery capacities, as well as their integration with risk management frameworks. The findings reveal that resilience engineering significantly improves system performance by enabling infrastructure to anticipate, absorb, and recover from disruptions, while maintaining critical functionality. However, challenges such as multi-hazard modeling, cascading failures, and the lack of standardized resilience metrics remain critical issues. The study concludes that a holistic and integrative approach, combining technical, socio-economic, and environmental dimensions, is essential to develop resilient infrastructure systems capable of addressing global risks and ensuring sustainable performance

Keywords: Global Risk, Infrastructure Resilience, Resilience Engineering, System Adaptability, System Robustness

INTRODUCTION

The increasing frequency and intensity of global risks in the contemporary era—ranging from climate change-induced extreme weather events, multi-hazard disasters, cyber disruptions, to global pandemics have fundamentally reshaped the way modern engineering systems and infrastructures are designed, operated, and managed. Traditional engineering paradigms that primarily emphasize reliability and efficiency are no longer sufficient to address the complexity and uncertainty associated with these emerging risks. Modern infrastructure systems are now expected not only to function

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reliably under normal operating conditions but also to withstand, adapt to, and rapidly recover from extreme disruptions. This shift has led to the growing importance of resilience engineering, a multidisciplinary approach that focuses on enhancing the capacity of systems to anticipate, absorb, adapt, and recover from adverse events while maintaining critical functionality (Zuo, 2021; Chester et al., 2021; Mehvar et al., 2021).

In classical engineering design, reliability has been the dominant metric used to evaluate system performance, defined as the probability that a system performs its intended function without failure under specified conditions. While reliability remains an important aspect of system design, it is inherently limited in addressing unexpected and extreme events that fall outside predefined operational boundaries. In contrast, resilience extends beyond reliability by incorporating the system's ability to respond dynamically to disruptions and maintain service continuity even when components fail. This paradigm shift from reliability to resilience reflects a broader recognition that modern engineering systems operate within complex, interconnected socio-ecological-technical environments, where uncertainties and interdependencies play a critical role in shaping system behavior (Zuo, 2021; Mehvar et al., 2021; Mottahedi et al., 2021).

The emergence of resilience as a central concept in engineering is closely linked to the increasing complexity of infrastructure systems and their exposure to cascading failures. Modern infrastructures, such as power grids, transportation networks, water systems, and cyber-physical systems, are highly interconnected, making them vulnerable to systemic disruptions. A failure in one component can propagate across the network, leading to widespread service disruptions and significant economic and social impacts. For instance, cyberattacks on critical infrastructure can disrupt power supply systems, while extreme weather events can simultaneously affect transportation, communication, and energy networks. These interconnected risks highlight the need for a holistic approach to system design and management that considers not only individual components but also the interactions and dependencies within the system (Chester et al., 2021; Linkov et al., 2022; Schweikert & Deinert, 2021).

Resilience engineering offers a comprehensive framework for addressing these challenges by shifting the focus from risk avoidance to capacity enhancement. Unlike traditional risk management approaches that primarily aim to prevent failures, resilience engineering emphasizes the development of system capabilities to monitor, anticipate, absorb, adapt, and recover from disruptions. This capacity-oriented approach recognizes that not all risks can be predicted or prevented, and therefore, systems must be designed to function effectively under uncertainty. By integrating resilience principles into engineering design and management, organizations can improve their ability to respond to unexpected events and maintain critical services, even in the face of severe disruptions (Mehvar et al., 2021; Chester et al., 2021; Mottahedi et al., 2021).

Despite the growing recognition of resilience engineering, significant challenges remain in its practical implementation, particularly in the quantification and measurement of resilience. One of the key issues is the lack of standardized metrics and methodologies for assessing resilience across different types of infrastructure systems. Various approaches have been proposed in the literature, including stochastic performance-time models, Markov-based simulations, and multi-hazard resilience frameworks, each offering unique insights into system behavior under uncertainty. These methods aim to quantify resilience in terms of system performance degradation and recovery over time, considering factors such as absorptive capacity, adaptive capacity, and recovery capability.

However, the diversity of methodologies and the absence of a unified framework make it difficult to compare results and apply them consistently in real-world scenarios (Cheng et al., 2021; De Iuliis et al., 2024; Wu et al., 2024).

In addition to methodological challenges, the integration of resilience considerations into engineering practice is further complicated by the need to account for multiple dimensions, including technical, economic, social, and environmental factors. For example, resilience assessments often require the evaluation of trade-offs between system robustness, cost efficiency, and sustainability. Techniques such as fuzzy expert judgment and cost-based analysis have been used to incorporate expert knowledge and economic considerations into resilience evaluation. Furthermore, importance measures have been developed to identify critical components within a system and prioritize interventions for resilience enhancement. These approaches highlight the multidimensional nature of resilience and the need for interdisciplinary collaboration in developing effective solutions (Abbasnejadfar et al., 2022; Wang et al., 2024; Mottahedi et al., 2021).

The application of resilience engineering principles in modern infrastructure systems has demonstrated significant potential in improving system performance under adverse conditions. In power systems and cyber-physical systems, resilience is analyzed in terms of the system's ability to maintain stability and recover from disturbances, with advanced analytical techniques such as bifurcation analysis and complex network modeling being used to study system behavior. Similarly, in transportation networks, resilience indices based on flood scenarios and network robustness have shown that proactive planning strategies can enhance system resilience by approximately 7–8% compared to reactive approaches. These findings underscore the importance of incorporating resilience considerations into infrastructure planning and management to improve system performance and reduce vulnerability to disruptions (Rezvani et al., 2024; Tachaudomdach et al., 2021; Otalvaro & Watson, 2025).

Furthermore, resilience engineering has been applied in various other domains, including water systems, mining operations, building facilities, and geotechnical engineering. In these contexts, multi-component Markov models, expert-based frameworks, and disaster-resilient design concepts are used to optimize system performance and recovery strategies. For instance, digital monitoring technologies and data-driven approaches enable real-time assessment of system conditions and support decision-making processes during disruptions. These applications demonstrate the versatility of resilience engineering and its potential to enhance the performance and sustainability of diverse infrastructure systems (Mottahedi et al., 2021; Joo & Sinha, 2023; Bayeroju et al., 2024).

However, despite these advancements, a critical research gap remains in the integration of resilience engineering concepts across socio-ecological-technical systems. Existing studies often focus on specific aspects of resilience, such as technical performance or economic impact, without adequately considering the interactions between different system dimensions. Additionally, there is limited research on the modeling of cascading failures and multi-hazard scenarios, which are increasingly relevant in the context of global risks. The lack of standardized resilience metrics further complicates the comparison and validation of different approaches, highlighting the need for a more comprehensive and unified framework for resilience assessment and management (Mehvar et al., 2021; Chester et al., 2021; De Iuliis et al., 2024).

In response to this gap, the novelty of this study lies in its integrative approach to resilience engineering, which combines multiple dimensions of resilience—technical, economic, and socio-

environmental—into a unified analytical framework. Unlike previous studies that focus on isolated aspects of resilience, this research emphasizes the interconnected nature of modern infrastructure systems and the need for holistic solutions that address system complexity and uncertainty. By synthesizing various resilience assessment methods and applying them within a comprehensive framework, this study aims to provide new insights into the design and management of resilient engineering systems in the face of global risks (Linkov et al., 2022; Freddi et al., 2021).

Accordingly, the main objective of this study is to analyze the role of resilience engineering in enhancing the robustness, adaptability, and recovery capabilities of modern engineering systems under global risk conditions. This objective is expected to contribute to the development of more resilient infrastructure systems that can effectively respond to the challenges posed by climate change, technological disruptions, and other global risks, thereby ensuring sustainable and reliable service delivery in the future.

METHOD

This study employs a qualitative research approach with a descriptive-analytical design to examine the role of resilience engineering in enhancing the robustness, adaptability, and recovery capabilities of modern engineering systems under global risk conditions. The research is conducted using a systematic literature review (SLR) method to ensure a comprehensive and structured synthesis of existing knowledge related to resilience engineering, infrastructure systems, and global risk management. The data utilized in this study are secondary data obtained from peer-reviewed international journals, conference proceedings, and indexed publications (Scopus and Web of Science) published between 2021 and 2025 to ensure relevance to recent developments. The data collection technique involves several stages, including identification, screening, eligibility, and inclusion, based on predefined keywords such as “resilience engineering,” “infrastructure resilience,” “multi-hazard systems,” “cyber-physical systems,” and “global risk.” Inclusion criteria focus on studies that discuss resilience concepts, quantitative assessment methods, and applications in critical infrastructure systems, while exclusion criteria eliminate non-academic sources, duplicated publications, and studies lacking methodological clarity.

The data analysis technique applies a thematic analysis combined with comparative synthesis to identify key patterns, conceptual frameworks, and methodological approaches across the selected literature. Initially, the collected studies are categorized into core themes, including resilience concepts, risk-resilience integration, quantification methods, and infrastructure applications. A coding process is then conducted to extract relevant variables such as absorptive capacity, adaptive capacity, recovery capability, system performance, and multi-hazard impacts. The analysis is further strengthened through cross-study comparison to identify similarities, differences, and emerging trends in resilience engineering practices. To ensure validity and reliability, the study employs data triangulation, comparing findings from multiple sources and perspectives. The final stage involves synthesizing the results into an integrative framework that explains how resilience engineering can be applied to modern infrastructure systems to enhance their performance under uncertainty and global risk conditions, thereby providing both theoretical contributions and practical implications.

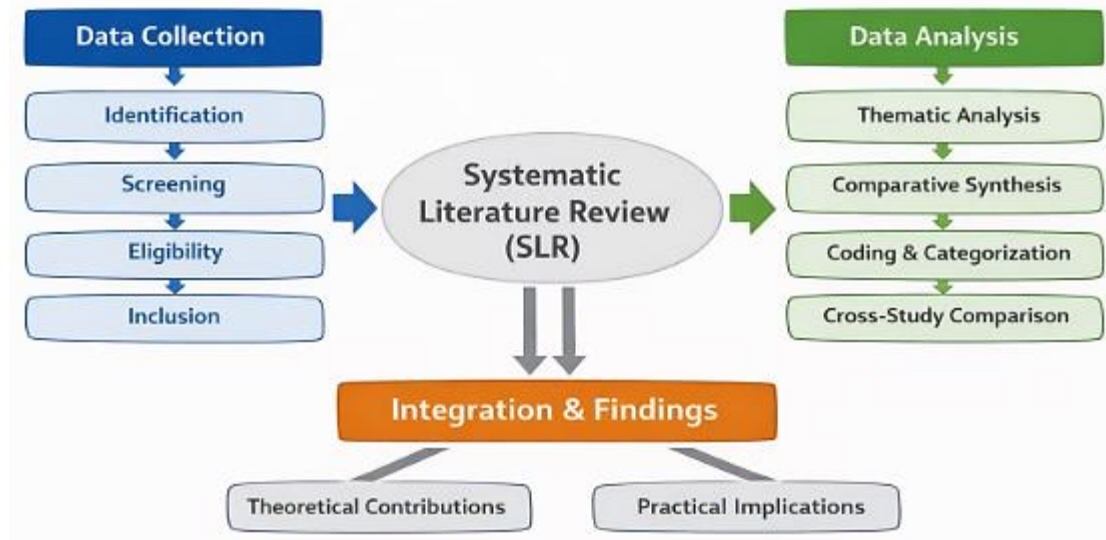


Figure 1. Diagram Conceptual Research

RESULTS AND DISCUSSION

The results of this study were synthesized from the selected literature to identify the key dimensions of resilience engineering in modern engineering systems under global risk conditions. The findings are categorized into core aspects, including resilience dimensions, risk integration, quantitative methods, and infrastructure applications, as presented in Table 1.

Table 1. Synthesis of Resilience Engineering Dimensions and Their Impact on Modern Engineering System Performance

No	Aspect	Key Variables	Findings	Impact on System Resilience and Performance
1	Resilience Dimensions	Absorptive, Adaptive, Recovery Capacity	Systems can maintain function and recover under disruptions	Increased robustness and faster recovery
2	Risk–Resilience Integration	Risk Assessment, Fail-safe, Recovery Strategy	Risk analysis complemented with resilience-based approach	Improved system continuity under uncertainty
3	Quantitative Methods	Markov Models, Simulation, Performance-Time Analysis	Enables measurement of system degradation and recovery	Better decision-making and planning
4	Critical Component Analysis	Importance Measures, System Ranking	Identification of critical nodes in infrastructure systems	Targeted improvement and resource optimization
5	Multi-Hazard and Uncertainty	Multi-hazard Models, Stochastic Analysis	Systems evaluated under complex and cascading disruptions	Enhanced preparedness and adaptability

6	Infrastructure Applications	Power Systems, Transport, Water, CPS	Resilience frameworks improve system stability and performance	Increased sustainability and operational reliability
7	Socio-Technical Integration	Human, Environmental, Economic Factors	Integration of multi-dimensional aspects remains limited	Need for holistic resilience framework

Based on Table 1, it can be interpreted that resilience engineering provides a comprehensive framework for enhancing the performance of modern engineering systems in the face of global risks. The integration of resilience dimensions, including absorptive, adaptive, and recovery capacities, plays a critical role in ensuring system robustness and continuity under disruptive conditions. Additionally, the combination of traditional risk assessment methods with resilience-based approaches enables systems to maintain functionality even when failures occur, highlighting the importance of moving beyond purely preventive strategies.

Furthermore, the application of quantitative methods such as Markov models and simulation techniques allows for more accurate measurement and prediction of system behavior under uncertainty, supporting more effective decision-making processes. The identification of critical system components through importance measures also facilitates targeted interventions, improving resource allocation and system efficiency. However, the findings reveal that the integration of socio-technical dimensions remains a significant challenge, indicating a need for more holistic and interdisciplinary approaches in resilience engineering. Overall, the results confirm that resilience engineering is essential for improving the adaptability, sustainability, and long-term performance of modern infrastructure systems in an increasingly uncertain and complex global environment.

Discussion

The findings of this study, as synthesized in Table 1, provide a comprehensive understanding of how resilience engineering contributes to enhancing the robustness, adaptability, and recovery capabilities of modern engineering systems under global risk conditions. The discussion reveals that the increasing exposure of infrastructure systems to climate change, multi-hazard disasters, cyber threats, and global disruptions has necessitated a paradigm shift from traditional reliability-focused approaches toward resilience-oriented system design and management. This shift reflects the growing recognition that engineering systems must not only function under normal conditions but also maintain performance and recover rapidly when subjected to extreme and unforeseen disturbances. In this context, resilience engineering emerges as a critical framework that enables systems to operate effectively in uncertain and dynamic environments (Zuo, 2021; Chester et al., 2021; Mehvar et al., 2021).

One of the central insights derived from the findings is the importance of redefining system performance metrics from reliability to resilience. Traditional reliability metrics focus on the probability of failure-free operation under predefined conditions, which limits their applicability in complex and unpredictable environments. In contrast, resilience encompasses a broader set of

capabilities, including the ability to anticipate disruptions, absorb shocks, adapt to changing conditions, and recover functionality within an acceptable timeframe. The results indicate that incorporating absorptive, adaptive, and recovery capacities into system design significantly enhances overall system performance. This aligns with existing literature that emphasizes resilience as a multidimensional construct that integrates technical, social, and environmental aspects of infrastructure systems (Zuo, 2021; Mottahedi et al., 2021).

Furthermore, the findings highlight the critical role of integrating risk management and resilience engineering in modern infrastructure systems. While traditional risk assessment techniques—such as fault tree analysis, probabilistic risk assessment, and fail-safe design—remain essential, they are insufficient on their own to address the complexities of global risks. The discussion shows that resilience engineering complements these approaches by focusing on maintaining system functionality during disruptions and enabling rapid recovery afterward. This integrated perspective allows organizations to move beyond reactive strategies toward proactive and adaptive system management. Previous studies support this view, noting that the combination of risk assessment and resilience analysis provides a more comprehensive understanding of system vulnerabilities and capabilities, particularly in the context of cascading failures and interconnected infrastructures (Linkov et al., 2022; Schweikert & Deinert, 2021; Mohammed, 2025).

Another key finding relates to the application of quantitative methods in assessing and enhancing system resilience. The use of stochastic models, Markov processes, and performance-time analysis enables a more precise evaluation of how systems behave under varying levels of stress and disruption. These methods allow researchers and practitioners to model system degradation and recovery trajectories, providing valuable insights into system performance over time. The results indicate that such quantitative approaches are essential for identifying critical vulnerabilities, evaluating alternative strategies, and supporting decision-making processes. However, the diversity of methodologies and the lack of standardized metrics present challenges in comparing results and applying them consistently across different infrastructure systems. This observation is consistent with prior research that calls for the development of unified frameworks and standardized indicators for resilience assessment (Cheng et al., 2021; De Iuliis et al., 2024; Wu et al., 2024).

In addition to methodological considerations, the identification and prioritization of critical system components play a crucial role in enhancing resilience. The findings demonstrate that importance measures can be used to rank system components based on their contribution to overall system performance, enabling targeted interventions and efficient resource allocation. By focusing on critical nodes within the system, organizations can implement incremental improvements that significantly enhance resilience without requiring extensive system-wide modifications. This approach is particularly relevant in large-scale infrastructure systems, where resources are limited and strategic prioritization is necessary. Empirical studies support this finding, highlighting the effectiveness of importance-based methods in optimizing system performance and resilience (Wang et al., 2024; Wu et al., 2024).

The discussion also underscores the significance of addressing multi-hazard and uncertainty conditions in resilience engineering. Modern infrastructure systems are increasingly exposed to multiple and interacting hazards, such as extreme weather events, cyberattacks, and operational failures, which can occur simultaneously or sequentially. The findings indicate that multi-hazard modeling and stochastic analysis are essential for capturing the complexity of these interactions and evaluating system resilience under realistic scenarios. These approaches enable the identification of cascading effects and interdependencies within the system, providing a more comprehensive understanding of system behavior under extreme conditions. Previous research emphasizes that

incorporating multi-hazard considerations into resilience assessment is critical for developing robust and adaptive infrastructure systems capable of withstanding complex and dynamic risks (De Iuliis et al., 2024; Wu et al., 2024).

Moreover, the integration of economic and expert-based approaches into resilience assessment provides valuable insights into the trade-offs between cost, performance, and resilience. The use of fuzzy expert judgment and cost-based analysis allows for the incorporation of qualitative and quantitative factors, enabling a more holistic evaluation of system resilience. The findings suggest that considering economic impacts and expert knowledge is essential for developing practical and implementable resilience strategies, particularly in resource-constrained environments. This aligns with previous studies that highlight the importance of integrating economic considerations and stakeholder perspectives into resilience engineering frameworks (Abbasnejadfar et al., 2022; Mottahedi et al., 2021).

The application of resilience engineering principles across different types of infrastructure systems further demonstrates its versatility and effectiveness. In power systems and cyber-physical systems, resilience is analyzed in terms of system stability, adaptability, and recovery under operational stress and disruptions. Advanced analytical techniques, such as bifurcation analysis and complex network modeling, are used to study system behavior and identify critical thresholds. The findings indicate that these approaches can significantly enhance system resilience by enabling proactive management and rapid response to disturbances. This is supported by existing literature that emphasizes the importance of resilience in ensuring the stability and reliability of energy systems and other critical infrastructures (Zuo, 2021; Schweikert & Deinert, 2021; Otalvaro & Watson, 2025).

In transportation networks, the use of resilience indices and scenario-based analysis has shown that proactive planning strategies can significantly improve system performance compared to reactive approaches. The findings indicate that infrastructure systems designed with resilience in mind can achieve measurable improvements in performance, including increased robustness and reduced recovery time. For example, studies have shown that proactive planning can enhance resilience by approximately 7–8%, demonstrating the tangible benefits of incorporating resilience principles into infrastructure design and management. This highlights the importance of forward-looking strategies and long-term planning in building resilient infrastructure systems (Rezvani et al., 2024; Tachaudomdach et al., 2021).

Similarly, in water systems, mining operations, and building infrastructure, resilience engineering approaches have been applied to optimize system performance and recovery strategies. The use of multi-component Markov models, expert-based frameworks, and disaster-resilient design concepts enables the development of integrated solutions that address both structural and operational aspects of resilience. The findings suggest that combining structural reinforcement, recovery planning, and digital monitoring technologies can significantly enhance system resilience and sustainability. This is consistent with prior research that emphasizes the importance of integrated and interdisciplinary approaches in addressing complex infrastructure challenges (Mottahedi et al., 2021; Joo & Sinha, 2023; Bayeroju et al., 2024).

Despite these advancements, the discussion reveals several critical challenges and research gaps that must be addressed to fully realize the potential of resilience engineering. One of the most significant challenges is the integration of socio-ecological-technical dimensions into a unified framework. Existing studies often focus on individual aspects of resilience, such as technical performance or economic impact, without adequately considering the interactions between different system components and stakeholders. This limitation highlights the need for more comprehensive

and interdisciplinary approaches that integrate technical, social, and environmental perspectives (Mehvar et al., 2021; Chester et al., 2021).

Another important challenge is the modeling of cascading failures and complex interdependencies within infrastructure systems. The findings indicate that current models often fail to capture the full extent of interactions between system components, particularly in multi-hazard scenarios. This limitation reduces the accuracy and applicability of resilience assessments, emphasizing the need for more advanced modeling techniques that can account for dynamic and nonlinear system behavior. Additionally, the lack of standardized metrics for resilience assessment complicates the comparison and validation of different approaches, highlighting the need for the development of universally accepted frameworks and indicators (De Iuliis et al., 2024; Mottahedi et al., 2021).

Furthermore, the discussion emphasizes the importance of adopting stress-testing approaches and advanced analytical platforms to enhance resilience assessment and management. Unlike traditional risk assessments that focus on predicting and preventing failures, stress testing evaluates system performance under extreme conditions, providing valuable insights into system vulnerabilities and resilience capacities. The integration of intelligent analytics platforms, including artificial intelligence and data-driven models, can further enhance the ability to monitor, analyze, and respond to system disruptions in real time. These approaches are essential for developing adaptive and resilient infrastructure systems capable of responding to the challenges of the Anthropocene era (Chester et al., 2021; Linkov et al., 2022; Freddi et al., 2021).

In conclusion, the discussion confirms that resilience engineering plays a crucial role in enhancing the performance and sustainability of modern engineering systems in the face of global risks. By integrating resilience principles into system design and management, organizations can improve their ability to anticipate, absorb, adapt, and recover from disruptions, thereby ensuring the continuity of critical services. However, achieving this goal requires addressing existing challenges, including methodological limitations, integration issues, and the need for interdisciplinary approaches. The findings highlight the importance of developing comprehensive and standardized frameworks for resilience assessment and management, which can support the design of robust, adaptive, and sustainable infrastructure systems in an increasingly uncertain and complex world

CONCLUSIONS

This study concludes that resilience engineering plays a fundamental role in enhancing the robustness, adaptability, and recovery capabilities of modern engineering systems in the face of escalating global risks. The findings demonstrate that shifting from a reliability-oriented approach to a resilience-based framework enables infrastructure systems to maintain functionality under extreme disruptions through the integration of absorptive, adaptive, and recovery capacities. Furthermore, the combination of resilience engineering with conventional risk management approaches, supported by quantitative methods such as stochastic modeling and system performance analysis, provides a more comprehensive strategy for managing uncertainty and complexity. The study also highlights that the effective implementation of resilience engineering requires a holistic integration of technical, socio-economic, and environmental dimensions, as well as proactive planning and stress-testing approaches. Therefore, resilience engineering emerges as a critical framework for designing sustainable and adaptive infrastructure systems capable of responding to dynamic and interconnected global challenges.

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