

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

Miko Mei Irwanto^{1✉}

STT Bina Tunggal, Indonesia²

e-mail: miko.irwanto@yahoo.com

ABSTRACT

Modern infrastructure systems are increasingly exposed to complex and interconnected global risks, including natural disasters, climate change impacts, cyber threats, and cascading systemic failures. Traditional risk management frameworks have proven insufficient to address the dynamic and uncertain nature of these challenges. This study examines the application of resilience engineering principles as a comprehensive framework for strengthening engineering systems against global risks. Through a systematic literature review of 20 peer-reviewed publications spanning 2013–2026, this paper synthesizes current theoretical foundations, methodological approaches, and practical implementations of resilience engineering in modern infrastructure contexts. The findings reveal four core resilience dimensions, absorptive, adaptive, restorative, and transformative capacity – that collectively define a system's ability to withstand, respond to, and recover from disruptive events. Key strategies identified include multi-hazard life-cycle assessment frameworks, performance-based resilience metrics, interdependency modeling, and socio-ecological resilience integration. The study also highlights critical research gaps, particularly in quantifying transformative resilience and operationalizing resilience indices for heterogeneous infrastructure networks. This review contributes to the growing body of knowledge on resilience-based infrastructure design and policy, offering actionable recommendations for engineers, urban planners, and policymakers.

Keywords: *critical infrastructure; global risks; multi-hazard resilience; resilience engineering; sustainability.*

INTRODUCTION

The accelerating complexity of global risk landscapes is creating unprecedented challenges for the integrity and operation of modern infrastructure systems. During the past two decades, a rising number of disruptive events, spanning extreme weather, seismic hazards, pandemic-driven supply chain breakdowns, and major cyberattacks, have revealed vulnerabilities in infrastructure once deemed resilient (Chester et al., 2021; Mehvar et al., 2021). These diverse threats no longer act in isolation; instead, the increasing integration of physical, digital, and social infrastructure magnifies their impacts and generates cascading failure modes that surpass conventional engineering assumptions. As a result, managing infrastructure resilience now requires multidisciplinary approaches, adaptive risk assessment, and governance



frameworks that recognize interdependencies across technical, organizational, and social domains (Chester et al., 2021; Mehvar et al., 2021).

Conventional risk management approaches—rooted mainly in probabilistic hazard assessment and deterministic design standards—are increasingly inadequate for the dynamic, uncertain, and highly interconnected threats that characterize today’s infrastructure environment (Curt & Tacnet, 2018; Park et al., 2013). Because these traditional methods emphasize predicting and preventing single-point failures, they often fail to capture cascading effects, emergent behaviors, and rapid changes in exposure or vulnerability. Consequently, a shift toward resilience-based thinking has become essential in infrastructure engineering. Resilience engineering reframes the objective: instead of focusing solely on preventing failure, it emphasizes the system’s capacity to absorb shocks, adapt under stress, and restore critical functions quickly and efficiently (Hickford et al., 2018; Yu et al., 2020). This perspective requires integrated planning, continuous monitoring, and flexible operational strategies that account for interdependencies across physical, cyber, and social domains, enabling infrastructure to maintain service and recover under a wide range of adverse conditions (Curt & Tacnet, 2018; Park et al., 2013).

Although resilience engineering has attracted substantial scholarly attention, the literature still lacks a comprehensive synthesis of its core principles as applied to modern infrastructure exposed to global risk conditions. Many existing reviews concentrate on narrow problem areas, such as seismic resilience of bridges (Capacci et al., 2022), transport network robustness (Hayes et al., 2019; Rezvani et al., 2024), or the reliability of energy systems (Mottahedi et al., 2021), and therefore do not fully capture the cross-sectoral, multi-hazard character of present-day challenges. This fragmentation limits our ability to compare strategies, transfer lessons across sectors, and design integrated interventions that address cascading failures and interdependencies among infrastructure types. A consolidated synthesis would help identify common principles, methodological gaps, and priority research directions for resilience assessment and practice across transport, energy, water, and digital systems under compound global threats.

This study addresses that gap by conducting a systematic literature review to investigate how resilience engineering principles have been conceptualized, operationalized, and implemented across multiple infrastructure sectors. Its novelty rests on an integrative framework that bridges traditional engineering resilience metrics with socio-ecological systems theory, life-cycle assessment methods, and the specific demands of emerging cloud-native digital infrastructures (Krisna, 2026; Ponugoti, 2024). By synthesizing theoretical constructs and practical measures from diverse domains, the study aims to reveal commonalities and tensions in resilience practice, highlight methodological advances and limitations, and propose actionable guidelines for cross-sectoral application. The central research question guiding this work is straightforward: How can resilience engineering principles be systematically applied to strengthen modern infrastructure systems against complex global risks?

METHODOLOGY

This study employs a systematic literature review methodology to synthesize the state of knowledge on resilience engineering in modern infrastructure. The review protocol follows an adapted PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, structured around four phases: identification, screening, eligibility assessment, and inclusion.

The literature search was conducted across major academic databases including Scopus, Web of Science, and Google Scholar, using search terms combining 'resilience engineering,' 'infrastructure resilience,' 'critical infrastructure,' 'global risks,' 'multi-hazard,' and 'resilience metrics.' The search was restricted to peer-reviewed journal articles and conference proceedings published between 2013 and 2026, ensuring both theoretical depth and contemporary relevance.

A total of 20 high-quality sources were identified and included in the final synthesis, comprising publications from leading journals in infrastructure engineering, sustainability science, risk analysis, and urban planning. Included sources were required to: (1) address resilience in the context of engineered systems or physical infrastructure; (2) propose or evaluate quantitative or qualitative resilience frameworks; and (3) discuss at least one category of global risk as a threat driver.

Data extraction focused on four analytical dimensions: (a) resilience definitions and theoretical framing, (b) methodological approaches and resilience metrics, (c) infrastructure domains and hazard types addressed, and (d) key findings and research gaps. Thematic synthesis was employed to identify convergent patterns and divergent perspectives across the literature, enabling the development of an integrative resilience engineering framework.

Table 1. Summary of Key Literature on Resilience Engineering in Infrastructure Systems

Author(s)	Focus Area	Key Contribution	Year
Chester et al.	Urban infrastructure under Anthropocene uncertainty	Adaptive governance framework for complex infrastructure resilience	2021
Mehvar et al.	Vital infrastructure systems resilience	Multi-disciplinary resilience challenges and research agenda	2021
Akiyama et al.	Sustainable and resilient infrastructure life-cycle	Multi-hazard life-cycle assessment innovations	2025
Hickford et al.	Interdependent infrastructure systems	Resilience engineering theory-practice gap analysis	2018
Capacci et al.	Aging bridges and road networks	Seismic resilience of deteriorating infrastructure	2022
Argyroudis et al.	Transport assets in multi-hazard settings	Quantitative resilience assessment framework	2020

Author(s)	Focus Area	Key Contribution	Year
Bocchini et al.	Civil infrastructure sustainability	Unified resilience and sustainability approach	2014
Curt & Tacnet	Critical infrastructure systems	Review of current resilience approaches	2018
Park et al.	Engineering systems risk-resilience integration	Integrated catastrophe management framework	2013
Yu et al.	General resilience engineering principles	Cross-domain resilience principles synthesis	2020

Source: Author synthesis from reviewed literature (2013–2026)

RESULTS AND DISCUSSION

The following subsection presents the review’s first major finding, an overview of the theoretical foundations of resilience engineering, summarizing key definitions and conceptual differences identified across the literature.

A. *Theoretical Foundations of Resilience Engineering*

The systematic review reveals a rich but fragmented theoretical landscape underpinning resilience engineering in infrastructure contexts. Resilience has been variously defined as the ability to anticipate, absorb, adapt to, and rapidly recover from a potentially disruptive event (Ganin et al., 2015); as the capacity to maintain or restore desired system functionality after a disturbance (Bocchini et al., 2014); and as a dynamic property encompassing both resistance and transformative change (Chester et al., 2021). These definitional variations reflect differing disciplinary emphases but collectively point toward a four-dimensional model of infrastructure resilience.

Park et al. (2013) were among the first to formally integrate risk and resilience approaches within a unified engineering framework, arguing that risk-based approaches quantify the probability and consequences of failure, while resilience-based approaches address the system's capacity to maintain performance under disruption. This integration has since been operationalized through quantitative resilience metrics – most notably the resilience triangle (Bocchini et al., 2014), which measures the area of performance loss over time as an inverse resilience indicator.

Yu et al. (2020) advanced the theoretical discourse by proposing general principles for resilience engineering applicable across diverse system types, identifying modularity, diversity, redundancy, and adaptive capacity as fundamental structural properties. These principles resonate with findings from Mottahedi et al. (2021), whose systematic review of critical infrastructure resilience identified a consistent emphasis on network redundancy and adaptive management as resilience enablers across energy, water, and transportation sectors.

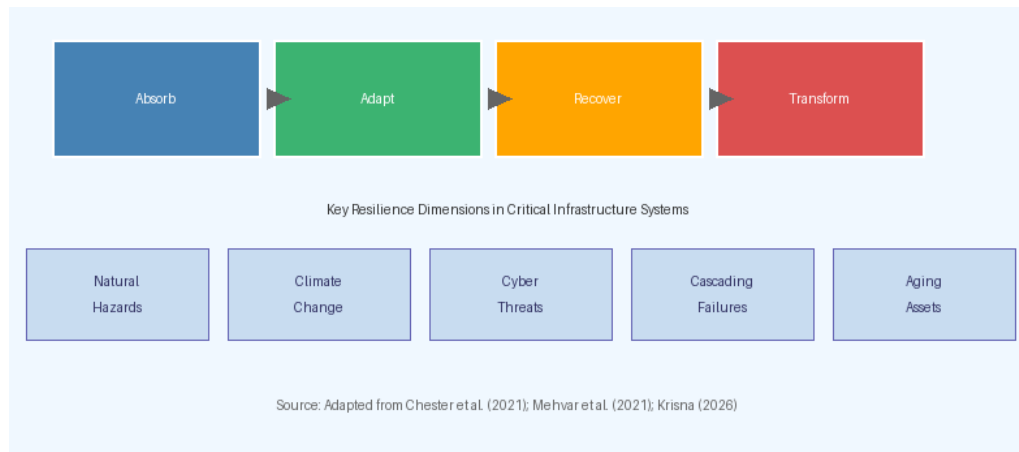


Figure 1. Resilience Engineering Framework for Modern Infrastructure Systems

Figure 1 illustrates the four core resilience phases adapted from the synthesized literature. The absorb phase reflects the inherent structural and functional capacity to withstand disruption without loss of performance; the adapt phase captures dynamic system adjustments during and immediately after a disturbance; the recover phase denotes the restoration of performance levels; and the transform phase involves systemic restructuring that enables enhanced future resilience (Chester et al., 2021; Mehvar et al., 2021; Krisna, 2026).

B. Multi-Hazard Resilience Assessment Frameworks

A recurring theme in the reviewed literature is a clear shift from single-hazard design toward multi-hazard resilience assessment frameworks that account for interacting and compounding threats. For example, Akiyama et al. (2025) propose an innovative life-cycle framework that explicitly incorporates multiple hazard exposures, seismic events, flooding, wind loading, and progressive deterioration, into a unified probabilistic performance assessment. By evaluating performance over the asset life span and quantifying how different hazards combine and propagate impacts, their approach supports optimization of design and maintenance strategies to maximize long-term resilience under compound risk conditions. Such frameworks move the focus from short-term, event-specific protection to holistic planning that anticipates sequences of stressors and trade-offs across service life, enabling more robust decision making for infrastructure investment and adaptation.

Argyroudis et al. (2020) developed a quantitative resilience assessment framework specifically for transport infrastructure assets exposed to multiple hazard scenarios, demonstrating through case studies on bridges and road networks that resilience indices vary significantly depending on hazard sequence, system interdependencies, and recovery resource availability. Their framework incorporates fragility curves, time-dependent performance functions, and recovery modeling to produce

comprehensive resilience profiles for critical transport assets.

Capacci et al. (2022) extended this multi-hazard approach to aging infrastructure, demonstrating that deterioration significantly amplifies seismic vulnerability and reduces resilience across bridge networks. Their review highlights the interaction between material degradation, functional performance, and post-event recovery capacity, underscoring the need for life-cycle resilience management that accounts for aging effects – a dimension largely absent from earlier resilience frameworks.

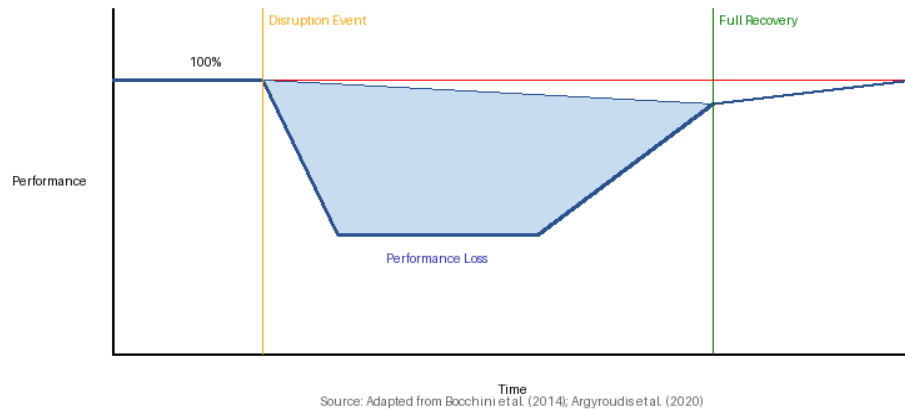


Figure 2. Infrastructure Performance Loss and Recovery Curve (Resilience Triangle)

Figure 2 illustrates the resilience performance curve, commonly referred to as the resilience triangle, adapted from Bocchini et al. (2014) and Argyroudis et al. (2020). In this representation, the baseline performance level denotes normal system functioning prior to disruption, while the post-disruption trajectory traces the decline and subsequent recovery of service over time. The shaded area between the trajectory and the baseline quantifies the total resilience loss, capturing both the depth of functionality reduction and the time required to restore services. Crucially, the curve's shape and duration reflect three interacting factors: the disruption's severity and duration, the system's absorptive capacity to withstand initial impacts, and the effectiveness and speed of recovery actions. Variations in any of these elements, such as faster repair protocols, redundant system design, or slower, more severe shock events, alter the triangle's area and slope, thereby changing the measured resilience outcome.

C. Socio-Ecological and Interdependency Perspectives

Hayes et al. (2019) make a compelling case for integrating socio-ecological resilience theory into transport infrastructure design, arguing that the social, institutional, and ecological dimensions of infrastructure systems are as critical as their physical attributes. By drawing on adaptive cycle theory and panarchy concepts, they propose a framework in which infrastructure resilience is treated as an emergent property of coupled

human-infrastructure-nature systems, rather than a fixed engineered characteristic.

This socio-ecological perspective aligns with Chester et al.'s (2021) argument that infrastructure resilience in the Anthropocene requires governance innovations capable of navigating deep uncertainty, contested values, and dynamic environmental change. Their framework calls for flexible, adaptive infrastructure management that embraces uncertainty rather than attempting to eliminate it, a fundamental departure from deterministic engineering design traditions.

Mehvar et al. (2021) identify infrastructure interdependencies as one of the most significant and underaddressed challenges in resilience research. Their comprehensive review documents how failures in one infrastructure system, such as energy disruption following flood events, can trigger cascading failures across interconnected water, transport, and communications networks. Quantifying and managing these interdependencies requires new modeling approaches, including network theory, agent-based simulation, and systems dynamics, tools that remain at the frontier of resilience engineering practice

D. Digital Infrastructure and Cloud-Native Resilience

An emerging frontier in resilience engineering concerns the resilience of digital and cloud-based infrastructure systems. Ponugoti (2024) presents a cloud-native approach to enterprise system resilience that leverages microservices architecture, containerization, and automated fault tolerance mechanisms to achieve continuous availability under adversarial conditions. This work signals a convergence between physical infrastructure resilience and digital systems engineering that has important implications for smart city and Industry 4.0 infrastructure.

Krisna (2026) synthesizes these perspectives within an Indonesian infrastructure context, demonstrating that resilience engineering principles developed in high-income country settings require significant adaptation to account for institutional capacity constraints, climate exposure profiles, and the heterogeneous nature of infrastructure asset bases in emerging economies. This finding highlights the importance of contextualizing global resilience frameworks to local conditions a theme that should inform future research and policy.

Table 2. Core Resilience Dimensions and Associated Engineering Strategies

Resilience Dimension	Definition	Key Engineering Strategies	Key References
Absorptive	Capacity to withstand and resist disruption with minimal performance loss	Structural redundancy, hardening, material-based design standards	Bocchini et al. (2014); Mohammed (2025)

Resilience Dimension	Definition	Key Engineering Strategies	Key References
Adaptive	Capacity to adjust operations dynamically during disruption	Flexible design, real-time monitoring, distributed control	Ganin et al. (2015); Yu et al. (2020)
Restorative	Capacity to restore performance levels efficiently post-disruption	Recovery planning, resource pre-positioning, maintenance protocols	Argyroudis et al. (2020); Capacci et al. (2022)
Transformative	Capacity to fundamentally restructure for enhanced future resilience	Adaptive governance, systemic redesign, policy innovation	Chester et al. (2021); Hayes et al. (2019)

Source: Author synthesis from reviewed literature

Table 2 synthesizes the four core resilience dimensions identified across the reviewed literature, mapping each dimension to its definitional characteristics, associated engineering strategies, and primary reference sources. The framework reveals a progressive spectrum from passive resistance (absorptive) to active transformation (transformative), reflecting the increasing sophistication of resilience engineering practice over the past decade.

E. Research Gaps and Future Directions

Despite significant progress, the review identifies several critical research gaps that limit the operationalization of resilience engineering in practice. First, quantification of transformative resilience remains methodologically underdeveloped; most existing metrics capture absorptive and restorative capacity but fail to measure the qualitative systemic changes that constitute transformative resilience (Chester et al., 2021; De Iuliis et al., 2024).

Second, the integration of climate change projections into resilience assessment frameworks remains inconsistent. Akiyama et al. (2025) and Hayes et al. (2019) make important strides in this direction, but the majority of reviewed frameworks treat climate as a static hazard parameter rather than a dynamic, non-stationary risk driver. Future research must develop resilience assessment methodologies capable of accommodating non-stationarity in hazard frequency and intensity.

Third, Rezvani et al. (2024) demonstrate the potential of Urban Resilience Indices for scenario-based risk reduction in road networks, yet such indices remain difficult to generalize across heterogeneous infrastructure typologies and governance contexts. The development of standardized, interoperable resilience metrics that enable cross-sectoral

and cross-national comparison represents a priority research agenda for the field (De Iuliis et al., 2024; Mottahedi et al., 2021).

Finally, the human dimension of infrastructure resilience, encompassing operator behavior, institutional decision-making, and community adaptive capacity, remains undertheorized relative to technical dimensions. Tamburini et al. (2025) offer valuable insights into human-system interaction in high-consequence industrial settings, but broader frameworks for human factors integration into infrastructure resilience are needed, particularly for the socio-technical systems increasingly characteristic of smart infrastructure.

CONCLUSION

This systematic literature review has synthesized the current state of knowledge on resilience engineering principles as applied to modern infrastructure systems facing global risks. The findings demonstrate that resilience engineering has matured from a concept centered on structural robustness and post-event recovery to a comprehensive, multi-dimensional framework encompassing absorptive, adaptive, restorative, and transformative system capacities. Multi-hazard life-cycle assessment, interdependency modeling, and socio-ecological integration have emerged as the leading methodological frontiers, while digital and cloud-native resilience approaches represent an important emerging domain. Significant research gaps remain in the quantification of transformative resilience, climate non-stationarity integration, and the standardization of resilience metrics across infrastructure domains and governance contexts. Future research and practice must prioritize these gaps to deliver infrastructure systems capable of navigating the increasingly uncertain and complex global risk landscape of the twenty-first century.

REFERENCE

- Akiyama, M. (2025). Life-cycle approaches to sustainable and resilient infrastructure: innovations in multi-hazard frameworks. *Structure and Infrastructure Engineering*, 21, 1756–1781. <https://doi.org/10.1080/15732479.2025.2524819>
- Argyroudis, S., Mitoulis, S., Hofer, L., Zanini, M., Tubaldi, E., & Frangopol, D. (2020). Resilience assessment framework for critical infrastructure in a multi-hazard environment: Case study on transport assets. *The Science of the Total Environment*, 714, 136854. <https://doi.org/10.1016/j.scitotenv.2020.136854>
- Bocchini, P., Frangopol, D., Ummenhofer, T., & Zinke, T. (2014). Resilience and sustainability of civil infrastructure: Toward a unified approach. *Journal of Infrastructure Systems*, 20, 4014004. [https://doi.org/10.1061/\(asce\)is.1943-555x.0000177](https://doi.org/10.1061/(asce)is.1943-555x.0000177)
- Capacci, L., Biondini, F., & Frangopol, D. (2022). Resilience of aging structures and infrastructure systems with emphasis on seismic resilience of bridges and road networks: Review. *Resilient Cities and Structures*. <https://doi.org/10.1016/j.rcns.2022.05.001>

- Chester, M., Underwood, B., Allenby, B., Garcia, M., Samaras, C., Markolf, S., Sanders, K., Preston, B., & Miller, T. (2021). Infrastructure resilience to navigate increasingly uncertain and complex conditions in the Anthropocene. *npj Urban Sustainability*, 1, 1–6. <https://doi.org/10.1038/s42949-021-00016-y>
- Curt, C., & Tacnet, J. (2018). Resilience of critical infrastructures: Review and analysis of current approaches. *Risk Analysis*, 38. <https://doi.org/10.1111/risa.13166>
- De Iuliis, M., Cardoni, A., & Cimellaro, G. P. (2024). Resilience and safety of civil engineering systems and communities: A bibliometric analysis for mapping the state-of-the-art. *Safety Science*. <https://doi.org/10.1016/j.ssci.2024.106470>
- Ganin, A., Massaro, E., Gutfraind, A., Steen, N., Keisler, J., Kott, A., Mangoubi, R., & Linkov, I. (2015). Operational resilience: Concepts, design and analysis. *Scientific Reports*, 6. <https://doi.org/10.1038/srep19540>
- Hayes, S., Desha, C., Burke, M., Gibbs, M., & Chester, M. (2019). Leveraging socio-ecological resilience theory to build climate resilience in transport infrastructure. *Transport Reviews*, 39, 677–699. <https://doi.org/10.1080/01441647.2019.1612480>
- Hickford, A., Blainey, S., Hortelano, A. O., & Pant, R. (2018). Resilience engineering: Theory and practice in interdependent infrastructure systems. *Environment Systems and Decisions*, 38, 278–291. <https://doi.org/10.1007/s10669-018-9707-4>
- Krisna, E. (2026). Engineering system resilience to global risks: A resilience engineering approach in modern infrastructure. *Archipel: Journal of Indonesian Interdisciplinary Studies*. <https://doi.org/10.65739/archipel.v1i8.47>
- Kröger, W. (2019). Achieving resilience of large-scale engineered infrastructure systems. In *Resilient Structures and Infrastructure*. https://doi.org/10.1007/978-981-13-7446-3_12
- Mehvar, S., Wijnberg, K., Borsje, B., Kerle, N., Schraagen, J., Kruijf, V. D., Geurs, K., Hartmann, A., Hogeboom, R., & Hulscher, S. (2021). Review article: Towards resilient vital infrastructure systems – challenges, opportunities, and future research agenda. *Natural Hazards and Earth System Sciences*, 21, 1383–1407. <https://doi.org/10.5194/nhess-21-1383-2021>
- Mohammed, A. S. (2025). Practical approaches to enhancing disaster resilience of engineering structures. *The American Journal of Engineering and Technology*. <https://doi.org/10.37547/tajet/volume07issue08-25>
- Mottahedi, A., Sereshki, F., Ataei, M., Qarahasanlou, A. N., & Barabadi, A. (2021). The resilience of critical infrastructure systems: A systematic literature review. *Energies*. <https://doi.org/10.3390/en14061571>
- Park, J., Seager, T., Rao, P., Convertino, M., & Linkov, I. (2013). Integrating risk and resilience approaches to catastrophe management in engineering systems. *Risk Analysis*, 33. <https://doi.org/10.1111/j.1539-6924.2012.01885.x>

(Miko Mei Irwanto)

- Ponugoti, M. (2024). Engineering global resilience: A cloud-native approach to enterprise system. *International Journal of Future Innovative Science and Technology*. <https://doi.org/10.15662/ijfist.2024.0702002>
- Rezvani, S., Silva, M. J. F., & De Almeida, N. M. (2024). Urban resilience index for critical infrastructure: A scenario-based approach to disaster risk reduction in road networks. *Sustainability*. <https://doi.org/10.3390/su16104143>
- Tamburini, F., Iaiani, M., & Cozzani, V. (2025). Analysis of system resilience in escalation scenarios involving LH2 bunkering operations. *Reliability Engineering & System Safety*, 257, 110816. <https://doi.org/10.1016/j.res.2025.110816>
- Yu, D., Schoon, M., Hawes, J., Lee, S., Park, J., Rao, P., Siebeneck, L., & Ukkusuri, S. (2020). Toward general principles for resilience engineering. *Risk Analysis*, 40. <https://doi.org/10.1111/risa.13494>