

From Recovery to Transformation: Conceptualising Long-Term Resilience in Interdependent Urban Infrastructure Systems

Rhea Srivastava¹, Manu Sasidharan, Carmine Galasso

*Department of Civil, Environmental and Geomatic Engineering, University College
London, London, WC1E 6BT, UK*

ABSTRACT

The resilience of infrastructure systems has predominantly been framed around isolated event recovery and bounce-back performance. However, infrastructure systems experience compounding and cascading disruptions alongside chronic stressors, such as asset deterioration and climate change, that generate lock-in and path dependencies over time. These dynamics are amplified by cross-network interdependencies that shape system functionality across successive disruption cycles, producing non-linear behaviours that single-event analyses cannot capture, particularly at the urban scale where infrastructure systems operate as tightly coupled socio-technical networks.

To advance long-term resilience conceptualisation, this study conducted a rapid review and bibliometric mapping of infrastructure resilience and urban transformation literature, followed by structured thematic coding and co-occurrence analysis. The analysis reveals disciplinary fragmentation between infrastructure-oriented and urban transformation studies, producing two parallel conversations around long-term resilience with limited cross-citation, and identifies the inter-event period as the least analytically developed phase across the disruption lifecycle. Four distinct but often overlapping change orientations emerge from the corpus – resistance, recovery, incremental adaptation, and structural transformation – differing in temporal scope and change mechanisms, with a consistent gap between claims about transformation and the empirical evidence supporting them. Building on these findings, the paper develops a trajectory-based reconceptualisation of long-term resilience, arguing that system outcomes across repeated disruption cycles are shaped by how inter-event decisions accumulate into path dependence rather than by event characteristics alone. This provides a basis for future empirical testing and simulation by clarifying candidate indicators and transition triggers for long-term resilience in interdependent urban infrastructure systems.

Keywords: Long-term resilience, Interdependent infrastructure systems, Urban infrastructure, Transformation

INTRODUCTION

Urban infrastructure systems are the foundational networks upon which modern society operates, and their disruption propagates across social, economic, and public health dimensions (Rinaldi et al., 2001; Ouyang, 2014). These systems face compounding

¹ Corresponding Author; Email: rhea.srivastava.24@ucl.ac.uk

pressures from acute shocks, including extreme climate events intensifying in frequency and severity, and chronic stressors such as asset deterioration and climate change, all of which accumulate over time (Feofilovs et al., 2020). For instance, the United Nations Office for Disaster Risk Reduction (2025) estimates direct disaster losses at \$202 billion annually, which rise to over \$2.3 trillion per year when cascading and ecosystem costs are accounted for. Geopolitical turbulence and rapid technological change are simultaneously reshaping the conditions under which these systems operate, introducing new cross-sectoral interdependencies at a pace that existing planning and institutional frameworks were not designed to accommodate. In this context, understanding how infrastructure systems perform not only within a single disruption, but across repeated cycles of shock, recovery, and adaptation, has become an increasingly important challenge.

However, the dominant body of infrastructure resilience literature remains focused on single-event disruption and short-term recovery. Resilience is commonly framed as a system property, assessed around discrete events through measures of performance loss and restoration time (Bruneau et al., 2003; Hosseini et al., 2016). This has produced a substantial body of quantitative methods, including restoration models and network topology approaches, but these largely treat disruptions as isolated episodes, with limited attention to the inter-event dynamics and long-term trajectory change. This gap is more prominent at the urban scale, where infrastructure systems operate as interdependent socio-technical networks, and where the consequences of event-bound resilience framing are most pronounced (Ouyang, 2014; Walsh et al., 2015; Chester et al., 2021).

At this scale, long-term resilience depends on how systems evolve between and across repeated disruption cycles, including whether these cycles lead to incremental improvement, lock-in, or structural transformation – understood here as the emergence of new configurations of governance, technology, and system function (Folke et al., 2010; Rasoulkhani & Mostafavi, 2018). Yet the mechanisms that shape long-term trajectories, and the conditions under which incremental adaptation gives way to structural change, remain undertheorised in infrastructure scholarship. Although panarchy theory, regime shifts and socio-ecological systems research have argued for multi-equilibrium conceptions of resilience, wherein systems shift between stable states under sustained disruption (Folke et al., 2010), these insights have not been systematically integrated into infrastructure-facing analytical work, where resilience is still primarily operationalised within the disruption event itself.

Against this background, this study combines a rapid review with bibliometric mapping to examine how long-term resilience is positioned across infrastructure resilience and urban transformation literatures. It assesses how existing studies distribute across temporal phases of the disruption cycle, and how different forms of change are conceptualised and operationalised across the corpus, with particular attention to the limitations of event-bounded framing. Building on these findings, the paper develops a trajectory-based reconceptualisation of long-term resilience, shaped by the accumulation of inter-event decisions and path dependence. In doing so, it identifies the key agenda for future research.

METHODOLOGY

The study employed a hybrid methodology combining a rapid literature review with bibliometric mapping and thematic synthesis. The rapid review was undertaken to map the conceptual landscape across urban infrastructure resilience, multi-hazard resilience, and long-term systemic transformation, with emphasis on temporal dynamics, modes

of system change, and interdependencies. Publications were retrieved from Scopus using a combination of search terms including 'infrastructure resilience', 'urban resilience', 'long-term resilience', 'transformation', 'transition', and 'interdependency'. Given the exploratory and fragmented nature of the topic, a snowball sampling approach was subsequently applied to a set of high-relevance anchor papers to identify additional studies addressing long-term system dynamics and transformational mechanisms beyond the immediate infrastructure resilience literature. The final corpus comprised 76 papers published between 2010 and 2026.

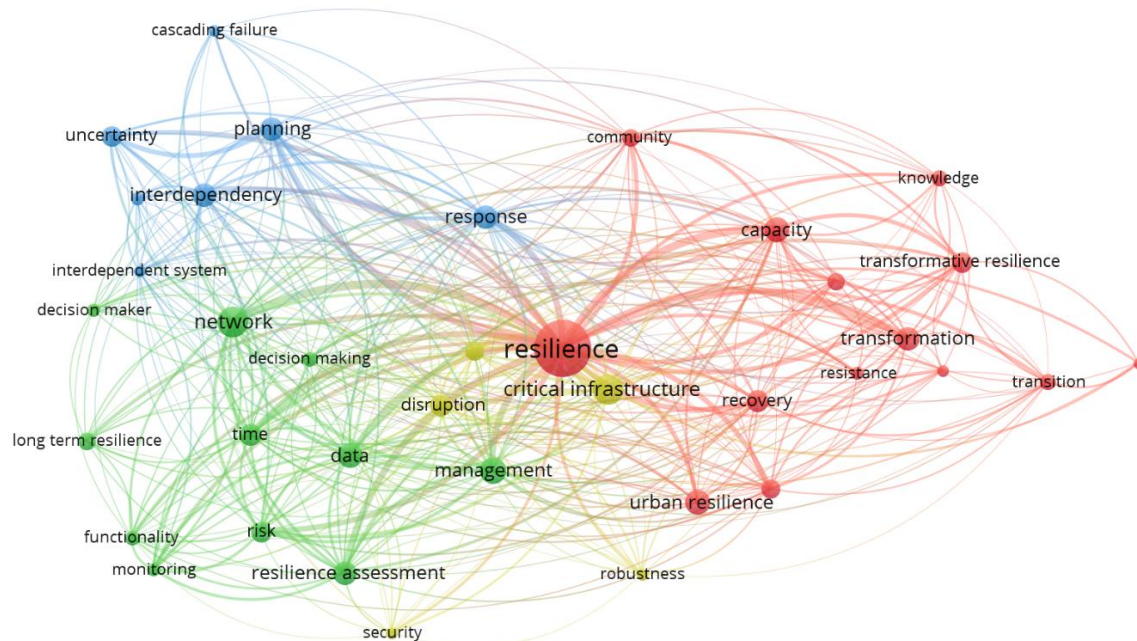
The bibliometric mapping was conducted in VOSviewer™ using keyword co-occurrence analysis to identify dominant concepts and emerging thematic clusters within the literature. This was used to examine whether long-term resilience is centrally embedded in the field or remains conceptually peripheral and weakly connected to adjacent ideas such as transition and transformation. The thematic synthesis examined each paper against two analytical dimensions. First, papers were coded according to the temporal phase addressed across the disruption lifecycle (pre-event preparedness, during-event response, post-event recovery, inter-event adaptation, and long-term system evolution). Second, papers were coded according to the dominant change orientations through which resilience was conceptualised, namely resistance, recovery, incremental adaptation or transformation. Papers engaging with inter-event dynamics and long-term system evolution were examined in greater depth. The reconceptualisation developed later in the paper was derived from these combined bibliometric and thematic findings.

RESULTS

Bibliometric Mapping and Analysis

The bibliometric keyword co-occurrence analysis performed in VOSViewer identifies four dominant thematic clusters, as shown in Figure 1. The largest cluster (in red) centers around the mainstream resilience discourse and includes terms such as transformation, transformative resilience, policy, capacity, and recovery. This cluster contains broader socio-technical system performance vocabulary (resistance, recovery) and socio-ecological transition vocabulary (transformative resilience, capacity) through which resilience and change are often discussed.

The second, and most densely connected cluster (in green) represents the operational infrastructure resilience core, including resilience assessment, network modelling, risk, monitoring, and functionality. Its density suggests a relatively mature body of work focused on performance-based assessment. The third cluster (in blue) groups terms such as planning, interdependency, cascading failure, and uncertainty, indicating a body of work concerned with system interactions and disruption propagation. Response acts as a bridge node connecting it to the central resilience cluster, which also implies that interdependencies and cascading failures in a system are primarily engaged in the context of event response and planning. A fourth, smaller cluster sits between the operational and planning clusters, linking critical infrastructures, disruption, security, and robustness.



The overall map reveals patterns of disciplinary fragmentation that are of direct relevance to this study. As shown in Figure 2, long-term resilience appears as a relatively peripheral term within the system performance cluster, with linkages primarily to network, time, functionality, interdependency, planning, response, and monitoring terms. It is only weakly connected to terms such as transformation, transition and capacity, which sit more centrally within the broader resilience discourse. A surface reading of this might suggest that long-term resilience and structural, transformational change have not been conceptualised together in the literature very often. However, a deeper analysis of the corpus reveals this to be a disciplinary vocabulary gap rather than a conceptual one.

Studies engaging with structural and regime change over long timeframes originate predominantly from urban and transition studies, where transformation and transition serve as the primary vocabulary rather than long-term resilience as a term. Infrastructure-oriented work, on the other hand, addresses the short- and long-term temporal dimension through performance and planning tools. The result is two parallel conversations with limited cross-citation. The thematic synthesis that follows examines what each contributes and where they diverge.

Temporal Coverage of Resilience

The bibliometric map established that long-term resilience takes a peripheral position in literature and has weaker linkages to other clusters. To examine whether this is a genuine analytical gap or just a vocabulary limitation, papers were analysed according to the primary temporal phase they engage with across the disruption lifecycle, spanning pre-event preparedness, during-event response, post-event recovery, inter-event adaptation, and long-term system evolution. As some papers address more than one temporal phase, aggregate counts across categories exceed the corpus total.

The two largest temporal categories emerging from the review are post-event recovery (23 papers) and long-term evolution (35 papers). Post-event recovery papers are concentrated in quantitative empirical work, centered on restoration sequencing, resource allocation, and network topology optimisation following disruption events (Argyroudis et al., 2020; Alkhaleel et al., 2022; Xu et al., 2024). Pre-event preparedness accounts for 10 papers and during-event responses for 12, similarly dominated by risk assessment and network modelling. Across all three phases, resilience is generally assessed in terms of functional loss and restoration within a single disruption cycle.

The long-term system evolution category, although the largest, warrants a closer examination with respect to its operationalisation. A substantial proportion of these 35 papers (51%) are conceptual or review-based (Folke et al., 2010; Seeliger & Turok, 2013; Chelleri et al., 2015; Rogov & Rozenblat, 2018; Shakou et al., 2019; Moghadas et al., 2022) rather than empirically operationalised, while empirical work is more commonly qualitative and observational than simulation-based (Blom & Guthrie, 2017; Casali et al., 2024; Krishnan et al., 2024). Only a small subset (9%) explicitly models multi-cycle system behaviour quantitatively (Rasoulkhani et al., 2017; Rasoulkhani & Mostafavi, 2018; Zischg et al., 2019). This skewed distribution indicates that although long-term resilience is increasingly discussed, conceptual and qualitative engagement has outpaced quantitative operationalisation across the corpus.

The inter-event period refers to the time between successive disruption events, where asset conditions evolve, maintenance and investment decisions accumulate across interdependent systems, and the performance baseline for future events is shaped (Blom & Guthrie, 2017; Rasoulkhani et al., 2017; Rasoulkhani & Mostafavi, 2018). It is arguably the most consequential phase for long-term resilience since it is here that incremental adaptations and decisions can create path dependencies that shape system performance trajectories in the long run. Despite its importance, only 10 papers explicitly address this period (Achilopoulou et al., 2020; Feofilovs et al., 2020; Gilrein et al., 2021; Singh et al., 2023), and even these often focus on preparedness for next event rather than on cumulative trajectory change. While 54 papers engage with multiple temporal phases, this coverage most commonly bridges pre-event and post-event framing without extending into inter-event dynamics. Overall, the evidence suggests that existing literature is well-equipped to assess single-cycle system performance, but much less developed in explaining how infrastructure systems evolve

across repeated disruption cycles. Table 1 summarises the temporal phase distribution along with their primary analytical focus areas.

Table 1 Temporal phase distribution, according to papers covered and methodological approach.

Temporal Phase	Papers	Methodological Approaches
Pre-event preparedness	10	Predominantly empirical quantitative: Risk and vulnerability assessment, fragility modelling, network topology simulation
During-event response	12	Predominantly empirical quantitative: Network topology simulation, real-time performance modelling, agent-based modelling
Post-event recovery	23	Empirical quantitative and conceptual: Stochastic optimisation, fragility-based assessments, resilience curves, restoration optimisation, repair sequencing models
Inter-event adaptation	10	Predominantly conceptual: Qualitative case studies, multi-criteria methods
Long-term system evolution	35	Predominantly conceptual/review (21 of 35): theoretical frameworks, panarchy models, transition theory Empirical qualitative: Qualitative case studies and longitudinal observations Empirical quantitative (underdeveloped): Quantitative multicycle simulation (using system dynamics, agent-based modelling network co-evolution analysis, and time-series modelling)

Conceptualising Change in Infrastructure Resilience

The temporal analysis indicates that infrastructure resilience research remains concentrated within the disruption event cycle and only partially engaged with long-term change. The current dominant landscape treats infrastructure resilience as a static system property assessed around disruptive events, rather than as one that evolves through successive event cycles, adaptations, and structural changes (Park et al., 2013). To examine how change is understood across the literature, the reviewed studies were further analysed according to their dominant change orientation. Four distinct change orientations emerged: resistance, recovery, incremental adaptation, and transformation, as shown in Figure 3. These differ in system scale, temporal scope, mechanisms of change, and the extent to which they imply continuity or reconfiguration of the underlying system.

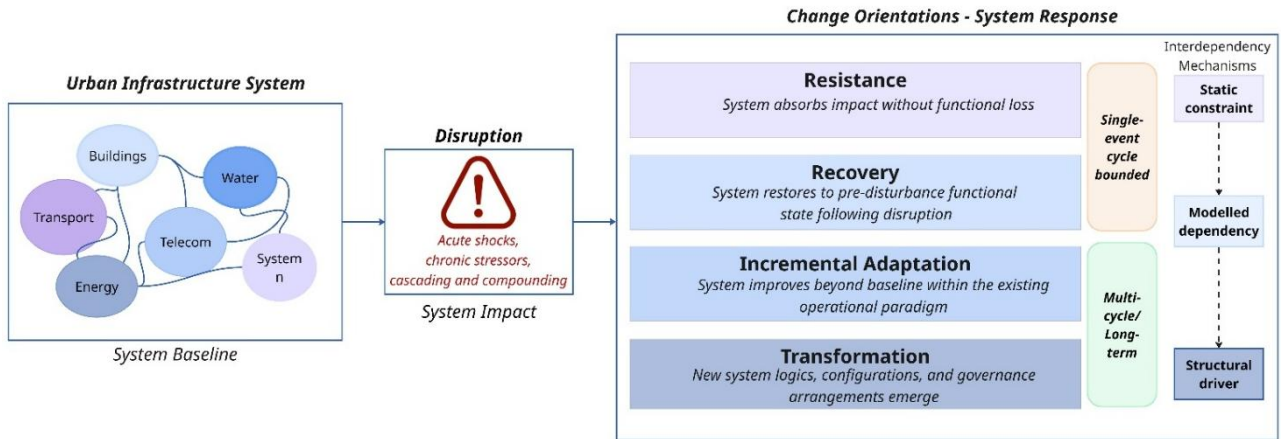


Figure 3. Schematic diagram of the four dominant change orientations identified across the corpus, differentiated by temporal scope and interdependency mechanisms.

Resistance-oriented studies (n=5) focus on preventing or absorbing disturbance such that the system sustains no functional damage and requires no structural alteration. Concentrated in pre-event and during-event phases, these papers engage with acute hazard scenarios where the objective is to maintain continuity of service. To achieve this, the system relies on structural properties operating at the asset and network scale, such as redundancy, excess capacity, and network topology, that allow it to absorb impact without functional loss or reconfiguration, modelled through scenario-driven stochastic simulation and multilayer network cascade analysis (Suo et al., 2021; Rehak, 2019; Lu et al., 2025). Within these, cross-system interdependencies are treated as static structural constraints to be accounted for in network design.

Recovery-oriented studies (n=18) shift the analytical focus from absorption to restoration, with the objective of returning the system to its pre-disturbance functional state. This orientation covers the widest temporal range within the event cycle, engaging pre-event, during-event, and post-event phases, and operates across asset, system, network, and city scales. Following a disruption-induced performance loss, emergency response is mobilised, and repair and restoration activities progressively return the system to its pre-event baseline. Literature draws on mechanisms including resource allocation, diagnostic assessment, restoration sequencing, and network topology optimisation, typically formalised through fragility-based assessment and stochastic optimisation (Argyroudis et al., 2020; Alkhaleel et al., 2022; Xu et al., 2024). Interdependencies are considered more substantively than in resistance-oriented work, with physical and organisational dependencies modelled quantitatively to inform restoration sequencing across systems (Hajializadeh & Imani, 2021; Xu et al., 2024). However, the analytical focus remains largely event-bounded with limited attention to how repeated recovery cycles alter the future system baselines.

Incremental adaptation-oriented studies, the largest change orientation in the corpus (n=28), address how infrastructure systems improve beyond their pre-disturbance baseline, demonstrating the attempts in literature to extend beyond event-cycle recovery towards long-term resilience. This includes what the literature variously terms bounce-forward, build-back-better, antifragility, and adaptation. Spanning post-event, inter-event, and long-term temporal phases at system, network, and city/regional scale, these papers engage a wider hazard profile including multiple independent and compounding events. When a hazard event exposes a performance gap, the system responds through targeted modifications to capacity, technology, or governance, thus

beginning the next disruption cycle from an improved baseline. The mechanisms driving this process include experiential learning, governance and institutional reform, failure accumulation/lock-in, and technology development, examined predominantly through longitudinal qualitative case studies and data-driven empirical analysis (Blom & Guthrie, 2017; Zischg et al., 2019; Casali et al., 2024; Krishnan et al., 2024). Here, physical and functional interdependencies remain central but organisational and governance interdependencies become analytically significant as they shape how decisions and policies enable or constrain the pace and direction of incremental change. While change occurs within the existing operational paradigm, some studies claim that the accumulation of incremental modifications across successive disruption cycles can also possibly shift system performance trajectories over time (Blom & Guthrie, 2017; Casali et al., 2024). This potential for trajectory shift, however, raises the question of when the incremental modification becomes something more fundamentally different.

A subset of papers in the corpus asserts precisely such a fundamental change, wherein new governance arrangements, technical configurations, or system logics emerge rather than existing ones being modified. Termed transformation here (n=22) to keep uniformity in the field, these papers cover long-term and inter-event phases, and engage in all hazard types, including cascading and compounding events. Crisis events act as windows of opportunity where tipping points are crossed, path dependencies are disrupted, and the system undergoes change through socio-technical reconfiguration and governance restructuring (Folke et al., 2010; Walsh et al., 2015; Rasoulkhani & Mostafavi, 2018; Chester et al., 2021). Interdependencies here act as drivers of change rather than constraints. Rasoulkhani and Mostafavi (2018) demonstrate this empirically through multi-agent simulation, showing how coupling between physical infrastructure condition and institutional investment decisions leads to long-term trajectory change.

A further finding is that transformation is neither uniformly intentional nor always positive. Walsh et al. (2015) argue that wildcard events can disrupt the governance interdependencies that otherwise sustain lock-in, unintentionally creating potential for structural change. Moreover, Rasoulkhani et al. (2017) and Casali et al. (2024) have observed negative transformation in their empirical cases, where accumulated stress, deferred investment, or maladaptive lock-in drives the system into a degraded regime.

Furthermore, transformation is often claimed as an outcome even when evidence supports only incremental adaptation (Feofilovs et al., 2020; Timashev, 2020; Moghadas et al., 2022; Yang et al., 2023). Strong normative claims about systemic change are similarly made without the methodological tools to operationalise them, as discussed in the previous section. This suggests that although transformation is increasingly mentioned in resilience scholarship, its empirical markers and threshold conditions remain insufficiently specified. Figure 4 and Table 2 summarise these claim-versus-evidence gaps.

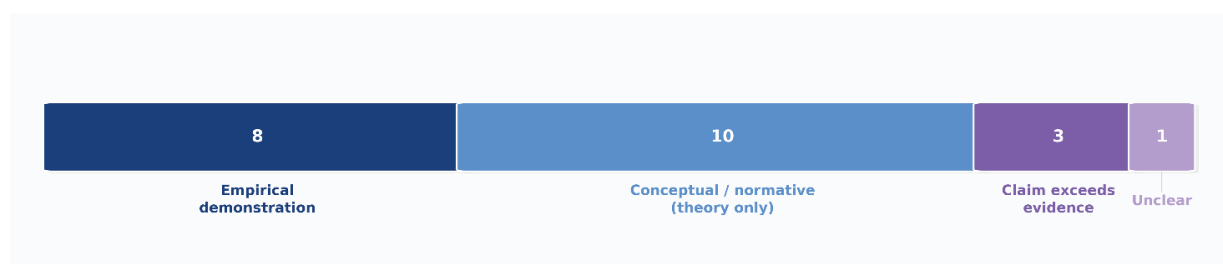


Figure 4. Claim-versus-evidence distribution across transformation papers.

Table 2 Claim-versus-evidence classification of transformation-oriented papers, with authors, claims, and methods.

Category	Authors	Claims regarding transformation
Empirical demonstration (n=8)	Walsh et al. (2015); Rasoulkhani & Mostafavi (2017); Rasoulkhani & Mostafavi (2018); Shen et al. (2023); Maurischa et al. (2023); Wang et al. (2024); Yao et al. (2025); Zhao et al. (2026)	Transformation demonstrated through empirical evidence: new governance regimes, performance regime shifts, and structural reconfiguration following prolonged stress or crisis events. Methods: Empirical-quantitative (Agent based Modelling (ABM), Multi-Agent Systems (MAS)); empirical-qualitative (case studies, interviews, focus groups); mixed methods
Conceptual/normative claim (n=10)	Folke et al. (2010); Matyas & Pelling (2015); Béné & Doyen (2018); Rogov & Rozenblat (2018); Gilrein et al. (2021); Chester et al. (2021); Asadzadeh et al. (2022); Oehmen et al. (2022); Rohne Till et al. (2024); Moglia et al. (2025)	Transformation theorised as movement to a new regime or governance logic. Claims are consistent with the conceptual or review method used, but no empirical test is attempted. Methods: Conceptual/theoretical frameworks; reviews and meta-analyses; mathematical/viability theory
Claim exceeds evidence (n=3)	Chelleri et al. (2015); Shakou et al. (2019); Moglia et al. (2021)	Transformation asserted but evidence does not support the claim: e.g. crowdsourcing framed as regime change, pathways derived without methodological basis. Methods: Empirical-qualitative + conceptual; conceptual framework; scoping review + conceptual
Unclear (n=1)	Seeliger & Turok (2013)	Conceptual boundaries are insufficiently defined to assess claim.

DISCUSSION

The evidence synthesis presented in the preceding sections points to a structural and methodological pattern across the urban infrastructure resilience literature. Resistance- and recovery-oriented studies are predominantly grounded in quantitative network and optimisation approaches, including stochastic optimisation, fragility-based assessment, and topology-driven restoration models that perform effectively in analysing infrastructure behaviour and restoration within single disruption cycles (Argyroudis et al., 2020; Hajializadeh & Imani, 2021; Suo et al., 2021; Alkhaleel et al., 2022; Xu et al., 2024; Lu et al., 2025). In contrast, studies addressing incremental adaptation and transformation rely more on qualitative case studies, longitudinal observation, and conceptual or governance-oriented frameworks. Only a small subset attempts to quantitatively represent recovery across multiple cycles. The include approaches based on multi-agent simulation (Rasoulkhani et al., 2017; Rasoulkhani & Mostafavi, 2018), system dynamics (Wang et al., 2024), or longitudinal network co-evolution analysis (Zischg et al., 2019; Casali et al., 2024). Together, these studies demonstrate that representing long-term recovery trajectory is feasible.

The infrastructure resilience literature has therefore developed strong analytical tools for modelling and assessing system performance within single or independent disruption cycles, but has not yet produced a coherent body of work on how resilience develops or changes across them. Even the studies engaging with long-term evolution tend to use similar performance metrics (impact, restoration, recovery) extended across a longer observation window, with the system's state in each cycle treated as independent of what came before. As a result, the accumulated effects of past decisions, system conditions, and adaptations, commonly understood as path dependence, are not fully integrated into resilience assessment. Consequently, when resilience is primarily examined within isolated event cycles, transformative change often remains outside the observational scope of most studies. Addressing this limitation requires a fundamental reframing of resilience as a trajectory-based property rather than an event-bound outcome.

Rasoulkhani et al. (2017) and Rasoulkhani and Mostafavi (2018) demonstrate this empirically using multi-agent simulation, coupling agent-level investment and adoption decisions with infrastructure condition dynamics over long horizons. Systems with comparable initial conditions follow divergent long-term performance paths as a function of inter-event decisions rather than event characteristics alone. The shock does not only determine the outcome, rather the accumulated state of the system entering the shock does. Rasoulkhani et al. (2017) show that deferred maintenance and underinvestment in one inter-event period reduces the system's functional capacity entering the next disruption, which constrains resources available for post-event recovery, further degrading the next baseline and reinforcing feedback loops that produce path dependence. Wang et al. (2024) reach a related conclusion through system dynamics modelling of urban transportation, showing that long-term performance is shaped more by the stock and flow accumulation of condition and adaptive investment than by the magnitude of any single disruption.

Krishnan et al. (2024), through qualitative empirical analysis, similarly note that planning horizons for single disruption cycles systematically fail to account for this accumulation, producing interventions that optimise short-term recovery at the cost of long-term trajectory. However, the interdependencies that determine whether inter-event adaptive decisions accumulate into trajectory improvement or deepen lock-in are qualitatively acknowledged across the corpus but rarely subjected to the same analytical depth as event-response dynamics. Moreover, much of this body of work focuses on a single class of stressor at a time, either acute disruption events or chronic deterioration, without integrating within a unified multi-cycle framing. Recent stochastic life-cycle research has advanced this agenda by formalising the joint treatment of chronic deterioration and acute shocks through renewal-reward processes (Yang & Frangopol, 2019). Nonetheless, these approaches operate largely at the asset level and rests on a renewal logic where each cycle returns the system to a known reference condition. Such assumptions become increasingly difficult to sustain at the network level, where interdependencies and the cumulative effects of chronic and acute stressors generate path dependence across successive disruption and recovery cycles.

Trajectory framing, therefore, shifts the central analytical question from how quickly a system recovers to what direction the system is moving across cycles, and what inter-event processes are driving that direction. This reframing has direct implications for how the boundary between incremental adaptation and structural change or transformation should be understood, which remains the least operationalised concept in the long-term resilience literature. What constitutes a threshold is likely varied and context-dependent, shaped by the interaction of cascading hazard exposure, chronic stress accumulation, ranging from physical performance degradation below a critical

condition to institutional investment limits, and interdependency coupling dynamics. Empirical cases in the corpus describe these conditions without formalising them.

Figure 5 summarises this conceptual reframing by representing long-term resilience as a multi-cycle trajectory with four divergent change orientations – sustained recovery (including resistance and baseline recovery studies), incremental adaptation, structural transformation, and regressive trajectory – as a function of accumulated inter-event decisions. These orientations are analytically distinct but not mutually exclusive, since a system may exhibit two or more simultaneously across cycles or sub-systems. The framing is intended as a basis for future empirical testing and simulation. Advancing this framing will require modelling approaches capable of carrying path-dependent system states across cycles, represent interdependencies as both slow-coupling processes and acute cascade pathways, and analysing the range of trajectories that emerge through accumulated inter-event decisions.

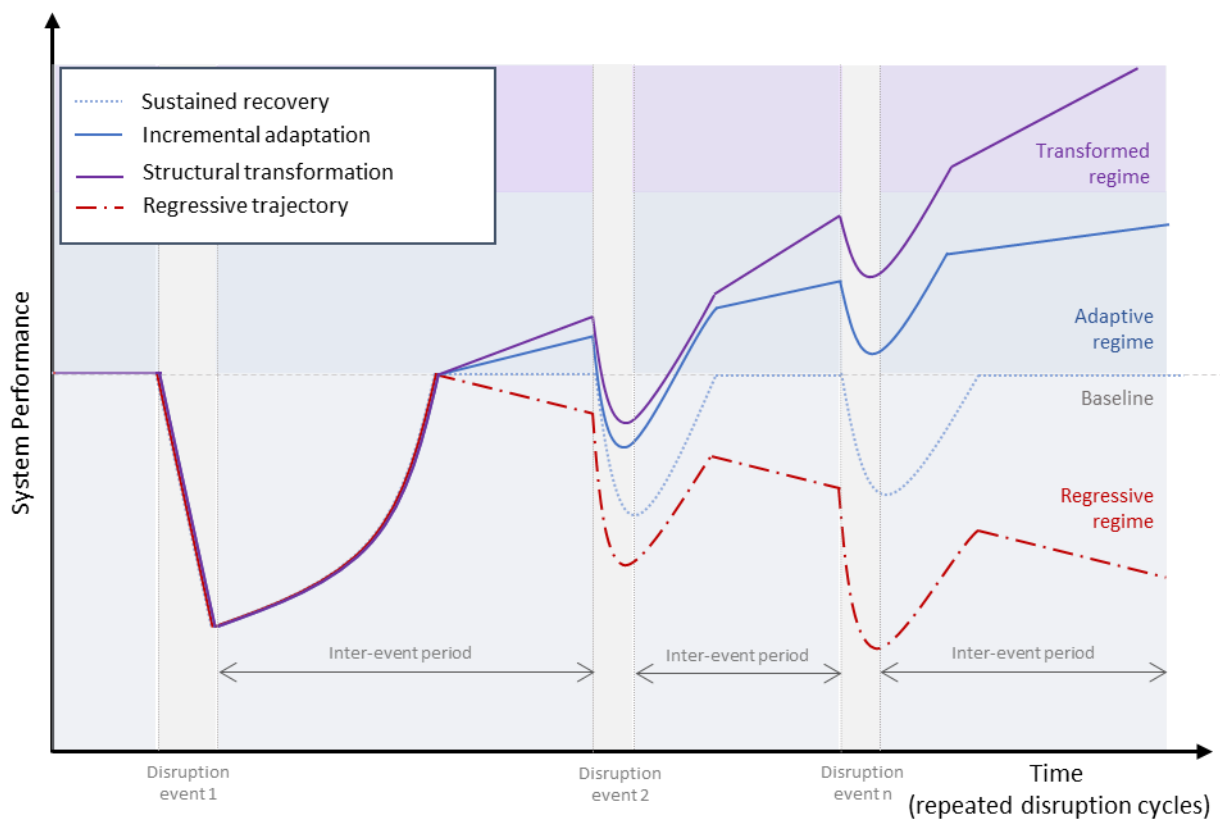


Figure 5. Trajectory-based reconceptualisation of long-term resilience across repeated disruption cycles.

Future work should therefore focus on the empirical evaluation of the inter-event processes that shape long-term resilience in interdependent urban infrastructure systems. First, condition and capacity indicators that capture the cumulative state of assets and the interdependent systems entering each disruption cycle need to be developed, alongside coupling indicators that characterise how disturbance and recovery cascade across systems. Second, the combined accumulation of chronic stressors, such as population demand increase and climate stressors, alongside acute events, such as floods, earthquakes, and pandemics, would need to be tracked over time as a combined pressure indicator acting on this cumulative state, rather than as isolated hazards. Third, the threshold conditions under which accumulated pressure and

propagating disturbance triggers shifts in system behaviour need to be empirically defined. Together, these elements provide the empirical basis for treating the four change orientations identified above, namely sustained recovery, incremental adaptation, structural transformation, and regressive trajectory, to be evaluated as observable outcomes of the system's history. This, in turn, enables long-term resilience to be analysed as an evolving trajectory rather than as a sequence of isolated recovery events. This empirical agenda forms the basis of ongoing work by the authors.

CONCLUSION

Urban infrastructure systems face compounding pressures from acute shocks, chronic stressors, and deepening cross-sector interdependencies that accumulate over time and across disruption cycles. Long-term resilience, conceptualised as the capacity of systems to sustain and evolve performance across repeated disruption cycles, has emerged as a critical but undertheorised dimension of infrastructure scholarship.

This paper examined the positioning of long-term resilience within the infrastructure resilience literature through bibliometric mapping and thematic synthesis. The analysis revealed that infrastructure-oriented work and urban resilience and transformation studies have developed parallel conceptual vocabularies with limited cross-citation, that, as a result, impede the degree to which long-term resilience and structural change have been studied. Within the infrastructure literature itself, empirical and methodological work concentrates within the event cycle. The inter-event period, where adaptive decisions accumulate and long-term trajectories are shaped, remains the least developed phase, making short-term performance metrics frequently decoupled from long-term trajectory change.

Building on these findings, the paper proposed a trajectory-based reconceptualisation of long-term urban infrastructure resilience. Under this view, resilience is understood not simply as capacity to recover from an event, but as the direction of system change across repeated disruption cycles, shaped by the accumulation of inter-event decisions and path dependencies. This framing helps differentiate between sustained recovery, incremental adaptation, structural transformation, and regressive trajectory as analytically distinct long-term outcomes.

A key implication is that future resilience research must move beyond event-bounded assessment towards approaches that can capture cumulative dynamics, feedback, and threshold conditions across time. Identifying these thresholds and operationalising them in empirical and simulation-based work remains an important priority for advancing long-term resilience assessment in interdependent urban infrastructure systems.

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