Leveraging SETS Resilience Capabilities for Safe-to-Fail Infrastructure and Climate Change

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Abstract

As the rehabilitation of infrastructure is outpaced by changes in the profile, frequency, and intensity of extreme weather events, failures become increasingly likely. Towards improving the resilience capacity of cities to adapt for uncertain climate futures, safe-to-fail infrastructure planning and design advocates for identifying social, ecological, and technological systems (SETS) capabilities and leveraging their interactions to plan for failure responses in design and to minimize damages when failures occur. In this paper, we argue that infrastructure planning and governance should transform to effectively utilize safe-to-fail infrastructure approaches by navigating SETS resilience capabilities. From a technological vantage point, traditional infrastructure planning approaches account for social and ecological domains as external design conditions rather than embedded system characteristics. Safe-to-fail approaches directly challenge the isolation of the technological domain by necessitating a recognition that SETS domains are interconnected and interdependent in infrastructure systems, as such capabilities and risks must be managed.

1. Introduction

Climate change and extreme weather events continue to challenge the ability of infrastructure to manage resources, supply critical services like energy and water, and protect human habitats from environmental hazards. Environmental hazards – like extreme heat and heavy precipitation – increasingly disrupt infrastructure services in cities, making the rehabilitation of infrastructure to withstand, readily recover, and adapt (i.e., collectively, infrastructure resilience) an imperative for urban sustainability [1]. Safe-to-fail infrastructure (STF) planning and design has emerged as a way to manage unpredictability and build infrastructure that is more adaptable to unprecedented environmental hazards [2], [3]. Traditionally, infrastructure systems are designed by techno-centric approaches that configure the capacity of physical components to resist failure against expected environmental risks, such as risk-based designs that are focused on probability predictions and advanced calculations (i.e., fail-safe infrastructure; FS) [2], [4]. A focus on rigidity is misaligned with climate change in that the future is increasingly characterized by non-stationarity, where the magnitudes of risks are likely to significantly shift beyond predicted design envelopes within the infrastructure life span [5]. FS planning and design, then, is limited in its ability to respond to hazards that exceed the design envelope (e.g., 100-year design storm), which is normally determined at implementation and based on historical data in the face of anomalous climate conditions, thus making failure inevitable for traditional infrastructure in the era of climate uncertainty.

STF planning and design is emerging as a set of infrastructure capabilities that create agility to handle surprise. Ahern (2011) first described the concept for urban planning as the antithesis of fail-safe, with strategies oriented around multifunctionality, redundancy, diversity, connectivity, and adaptive planning for building urban systems resilience capacity [3]. Kim et al. (2019) focused on the concept in the context of resilient infrastructure development by framing it as planning for system failure during design to elucidate new solution pathways that minimize impacts when failures occur. The Kim et al. framing called for navigation of infrastructure planning and design through key social, ecological, and technological systems (SETS) resilience capabilities as infrastructure failures will affect SETS in unequal ways [6]. STF infrastructure is designed to expect functional and/or structural failures from hazards and respond to probable consequential impacts in SETS. In contrast, FS infrastructure is designed to be defensible from all probable hazards; hence, unexpected system failure may incur detrimental and unintended SETS damages, such as to people, the economy, or ecosystems [6]. Unlike traditional infrastructure planning that follows a set of technical design specifications for safety management, failures of STF infrastructure may be prioritized based on their SETS capabilities and trade-offs within the decision context for more comprehensive risk reduction and urban management. For instance, a dense city experiencing housing problems may allow developments close to flood plains along with vegetated flood mitigation buffers that may overflow, but equip the area with advanced flood warning systems and flood insurance programs [7], [8]. STF requires decision makers to understand SETS interactions (such as adapting to changing environments and in responding to impacts from infrastructure failure) to decide where trade-offs are to be made for achieving systemic resilience goals.

An incomplete consideration of SETS capabilities and too much focus on risk reduction via techno-centric approaches in infrastructure planning have caused cities to experience substantial damages, sometimes even cascading across SETS when infrastructure failures occur. Furthermore, STF as a process of navigating tensions across SETS resilience capabilities remains largely unexplored. In this paper, we posit that a STF infrastructure planning and design approach provides a critical opportunity to support SETS resilience capabilities tackling climate risks. In conclusion, we explore the frontier of infrastructure transformation for urban resilience and climate adaptation.

2. Why SETS Resilience?

Technological systems (T-systems) – such as infrastructure and the built environment – are embedded in social and ecological processes. Simultaneously, T-systems shape social systems, e.g., reducing vulnerabilities from climate hazards, and ecological systems, e.g., delivering ecological services, such that cities comprise interactions within and between each SETS domain [9]–[11]. In response to climate risks, T-focused approaches for infrastructure resilience have emphasized the recovery of physical components and mechanical processes to ensure critical services provision in cities, such as back-up electrical transmissions and redundant water supply mains. In this way, infrastructure resilience has emphasized 'bouncing back' from a perturbation, where the disturbed object's inherent materiality is restored to provide critical functions like electricity and potable water [12], [13]. Studies providing definitions and guidelines for infrastructure resilience abound in the literature, which support planning T-systems that are robust to disturbances, such as extreme weather events under a non-stationary climate [14], [15]. However, these studies tend to focus on reinforcing the ability for infrastructure systems to withstand predetermined hazard envelopes or analyzing risks to infrastructure performance in terms of probability predictions [16]–[19]. Such technocentric approaches are then FS in their view of infrastructure systems resilience and overlook the outcomes of the potential failures of these systems. Moreover, the social context of infrastructure often affects the overall adaptive capacity to climate hazards in cities [20], [21]. Social factors affecting T-systems, such as limited funding available for an infrastructure project and the socially acceptable safety in design [22], largely contribute to infrastructure performance and their capacity to reduce vulnerability from climate hazards. Hence, a few studies have advocated for a need to evaluate infrastructure systems in consideration of its interdependency with other systems [22], [23].

To expand upon the techno-centric approaches presented, we examine social-ecological systems (SES) approaches that have critically framed resilience in terms of the sustainability of human-environment interactions [24], [25]. With the rapidly growing number of cities experiencing extreme weather events, the importance of understanding urban systems as SES and their resilience to climatic hazards has followed [26], [27]. A few key studies have extended the SES perspective to include the role of built infrastructure as a means for delivering and managing ecosystem services for society [10], [11], [28]. However, a limitation of the SES perspective in addressing urban resilience is that it overlooks T-systems as a mediating actor in complex urban systems and underrepresents technology in SES sustainability dialogue [29]. In the institutional analysis and development framework [30], [31], which is a widely adopted framework in SES studies; for example, technological systems are only considered as one of the contextual factors defining biophysical conditions rather than one of the actors along with the social and ecological systems shaping the dynamics of cities.

SES interactions with T-systems have often been marginalized in the design and management of infrastructure systems. In responding to Hurricane Maria, for example, Lugo (2020) outlines the lack of ecological monitoring and administrative capacities (e.g., emergency sensors, institutional information flows, decision autonomy) that led to insufficient anticipatory efforts, further failures, and repair delays for electrical systems in Puerto Rico [32]. At the same time, SES perspectives usually view T-systems as a subset of social systems [33]–[35]. However, as components of infrastructure systems are entangled among SETS components, T-systems must be addressed alongside SES. The SETS view of urban systems is necessary to uncover the synergies and conflicts across SETS domains in addressing climate challenges through infrastructure systems. Through a STF approach, these SETS synergies can be unveiled via infrastructure planning and design as it requires decisions for prioritization of SETS capabilities and potential impact transfers from one domain to another upon system failure, e.g., lack of communication systems due to power loss.

3. Addressing SETS irreducibility through safe-to-fail infrastructure

The STF approach incorporates failure mechanisms and their impacts into infrastructure planning by evaluating SETS resilience capabilities and their interactions, and thus calls for a systemic consideration of SETS dynamics [6]. Infrastructure systems are constructed following technological configurations; however, each SETS domain should be addressed in planning and management to encourage resilience [10], [11], [33]. The marginalization of infrastructure's role in understanding SETS resilience capabilities can lead to an incomplete view of the system boundaries, dynamics, vulnerabilities, and risks. First, T-systems are often viewed as an intermediary between social and ecological systems. For instance, infrastructure has empowered humans to live in harsh environments (e.g., large-scale movement of water via canals and pipelines in dry areas, implementation of dams and levees in flood-prone areas, and adoption of refrigeration and air conditioning in hot areas), connect distant and remote locations (e.g., transportation of people and goods via ship, rail, road, and air), and create global economies (e.g., identification, extraction, and transformation of natural resources into products). Thus, underappreciation for T-systems can translate to an underappreciation for risks/vulnerabilities within the system, as well as mechanisms by which resilience can be enhanced. Second, given the role of infrastructure as a key intermediary in urban systems, risk and resilience principles (or lack thereof) within T-systems are implicitly integrated into the broader SES dynamics. Subsequently, limitations of the FS approach that are prevalent in T-systems become inherent within broader social and ecological systems. More significantly, despite its intentions, FS infrastructure is subject to catastrophic failures as systems are built increasingly robust rather than managing and controlling planned failures in STF infrastructure [6], [35], [36]. Therefore, by underappreciating the influence of T-systems, SES approaches to resilience appear to be unwittingly underappreciating sources of catastrophic failure within broader social and ecological systems. From a technological vantage point, FS approaches account for social and ecological domains as external design conditions rather than embedded system characteristics [6], [36]. STF approaches directly challenge the isolation of the technological domain; more broadly, STF infrastructure necessitates a recognition that social, ecological, and technological domains are interconnected and interdependent in infrastructure systems [33], [36], [37]. Therefore, by applying STF approaches, infrastructure managers must identify known, and anticipate unknown, disturbances to infrastructure systems as SETS, and manage any potential failures [6], [23], [38]. This highlights an important characteristic of SETS thinking in planning infrastructure: SETS are irreducible.

STF approaches address the irreducibility of SETS through the *Infrastructure Trolley Problem* [6]. The *Infrastructure Trolley Problem* reveals the inherent dilemma of incorporating failure in design and planning for consequences of infrastructure failures that may be experienced differently by SETS attributes in a city. In other words, the consequences of STF infrastructure failure will have varying levels of impact and be judged by different values along SETS dimensions in cities. Infrastructure managers implementing a STF approach must identify potential disturbances and associated failure consequences, prioritize diverse values of stakeholders, and navigate the associated trade-offs to implement a design [6], [39]. This navigation encourages infrastructure managers to minimize overall impacts across SETS. Infrastructure managers must also, however, adhere to rules and regulations that lower risks, typically emphasizing public safety and, occasionally, environmental impact [40], [41].

Therefore, technological failure is additionally defined by the consequences on the social and ecological domains – again highlighting the irreducibility of SETS systems. Failure management is not a simple task given the complex urban systems in which infrastructure operate, requiring STF approaches to be iterative with reassessments of prioritizations and trade-offs throughout the infrastructure systems life. Ultimately, for resilience efforts and objectives to be fully realized, SES frameworks should strive to more explicitly recognize and consider the influence and importance of technological systems (i.e., move from SES to SETS perspectives), while T-systems should strive to more explicitly anticipate, consider, and balance the social and ecological impacts that can arise from failure (i.e., move from FS to STF perspectives).

4. Challenges and opportunities of safe-to-fail infrastructure transformation

Several questions for constructing and operating STF infrastructure, with a SETS lens, still need to be answered to address the issues related to resilience governance [42], including (but not limited to): 1) who is responsible for navigating trade-offs of SETS resilience capabilities?; 2) how to engage with stakeholders for prioritizing decisions in addressing the *Infrastructure Trolley Problem*?; and 3) how might the role of institutions change to encourage STF approaches? With the necessity for considering failure consequences in STF infrastructure development, practitioners need to decide whom, where, and why people and infrastructure systems experience certain failure outcomes. In addition, these decisions must entail how resources across SETS will be provided and how the community will respond after the failure (e.g., emergency response plan). FS decisions allow decision-makers to transfer the responsibility of failing infrastructure systems to technological capabilities based on design manuals and climate prediction models or to those that own, operate, or use them. STF infrastructure development, instead, diffuses the responsibility across SETS domains, raising questions regarding to what extent decision-makers should bear the consequences of infrastructure failure. The amount of responsibility that decision-makers have for infrastructure failure outcomes is unclear.

The engagement with multiple levels of stakeholders for assessing SETS resilience capabilities is an important step for STF infrastructure planning decisions and knowledge co-production of climate hazard impact profiles. While tangible costs of infrastructure failure, like property loss, can be easily assumed in absolute economic terms, additional impact categories considered in SETS capabilities are not easily captured without the inclusion of broad stakeholder opinion or valuing [43]–[45]. Infrastructure failure consequences such as displacement, homelessness, livelihood damage, unemployment, environmental losses, and health impacts may be uniquely experienced depending on the affected stakeholders' capacity to respond and adjust to each disturbance [6], [46]. Thus, another challenge for addressing the *Infrastructure Trolley Problem* is social equity in risk mitigation [47]. Stakeholders affected by development decisions across SETS domains must be represented and informed in the decision-making process to prioritize 'safe' and 'acceptable' infrastructure failure consequences [48], [49]. The extent of stakeholder engagement and their representation dictates the various SETS resilience capabilities that infrastructure failures are understood and planned for. For example, if stakeholder engagement is not effective at including vulnerable populations who have a lower capacity to respond to health issues or unemployment caused by infrastructure failures, then SETS trade-off decisions may make the same people more vulnerable to planned failures [50]. In contrast, complete stakeholder engagement is an inherent challenge, especially in cities with large, diverse populations [51].

Several studies have demonstrated approaches for integrating diverse stakeholder views to help elucidate the SETS resilience capabilities and decision-making for climate risk management. Walpole et al. (2020) incorporated practitioners' mental models into ecological restoration decisions [52] and Kim et al. (2021) addressed the practitioners' shared/discrete views in implementing resilience strategies for infrastructure development [53]. Bessette et al. (2017) developed a values-informed mental model for understanding communities' climate risk management decisions [45] and York et al. (2021) demonstrated an inter-level feedback process for a collective climate actions decision-making across individuals and organizations [54]. Particularly, Perrone et al. (2020) demonstrated the value of stakeholder engagement in evaluating the causes, consequences, and policies for flood management from both environmental and socio-economic perspectives through a participatory modeling approach for the Bradano River, Italy [55]. Still, an exhaustive study for integrating SETS resilience capabilities revealed through stakeholder engagement into infrastructure decisions is necessary for STF planning.

Institutions that manage infrastructure systems will need to adapt and transform to accommodate STF infrastructure transformation. Whereas current infrastructure regulations focus on refining design guidelines for system construction and maintenance, STF regulations may also require additional governance capabilities such as community-building (internal and external) and knowledge sharing so organizations may learn from one another. For example, STF development may require sharing of data on infrastructure performance, decision criteria for prioritizing the SETS capabilities, protocols for emergency system operation, and compensation of failure impacts. One regulatory shift that promotes STF development is for city governments to require insurance companies to provide accumulated information on infrastructure risks and damages experienced in the region. This information may be shared with the city government and the affected stakeholders to assess the current SETS capabilities based on the empirical data. Shifts in one sector (e.g., design firms) will require shifts in other sectors, like governmental organizations, utilities, insurance companies, operation, and regulation [56].

Transformation to infrastructure solutions that incorporate SETS resilience capabilities with STF design is steadily occurring. Slow evolution and technology adoption have been two mediums for infrastructure transformation [57], and resilient infrastructure planning methods are being developed to incorporate SETS thinking into future solutions [58]. Slow evolution occurs organically but tends to be path-dependent, while rapid technology adoption requires a window of opportunity in the form of some large disruption to the 'regime' [59]. Additionally, infrastructure transformation experiences resistance when the focus is rarely on designing systems to fail gracefully as much as it is to design optimal solutions with existing parameters [60] or after a crisis event [59]. While STF infrastructure transformation is happening on the course of slow evolution, it is challenging because it requires design practices to be less path-dependent than previously established approaches. The most approachable window of opportunity for the rapid adoption of STF infrastructure would be when existing infrastructure systems reach design capacity and need to be upgraded or replaced; but technological solutions are not always ideal candidate solutions. While projects can focus myopically on efficient optimization for infrastructure planning, commonly featuring path dependency and business-as-usual solutions [61], SETS thinking uses a larger toolset of solution possibilities, which ought to increase the probability of reaching a sustainable solution. For example, as summer temperatures increase in Phoenix, Arizona, cooling and electrical demand loads increase, pushing the power grid closer to critical limits [62]. Power failure during critical summer temperatures have fatal impacts that can lead to human deaths. Technical solutions such as updating aging power lines and adding back-up generators, while at the core of the solution, cannot be the only solution considering its costs and technical thresholds for extreme temperatures. The city has been working with vulnerable communities to diversify responses to power system failures that leverage the various components of SETS capabilities [63]. Public awareness on emergency responses to extreme heat conditions has been promoted and cooling hubs have been installed where the power infrastructure is particularly outdated. Trees and shades have been planted to attenuate the overheating of urban infrastructure systems.

5. Conclusions

Leveraging the capabilities across SETS domains in STF approaches appears to support *graceful extensibility* in resilience engineering. Contemporary framings of infrastructure resilience describe strategies when systems are perturbed within and beyond their design conditions [64]. Within their design conditions, *rebound* (bouncing back) and *robustness* (hardening) are appropriate. However, when perturbations exceed design conditions then extensibility becomes appropriate – extending adaptive capacity in the face of surprise. Extending the capacity of such large and extensive infrastructure systems is a monumental challenge. If extension is viewed purely through a technological lens, then few options exist – e.g., how do you provide water through an alternative technology to millions of city residents when the primary drinking water system has failed? Or how do you decide on the size of drainage pipes when the intensity of a 100-year storm keeps changing? STF leveraging SETS resilience capabilities offers pathways towards *graceful extensibility* by leveraging social and ecosystem capabilities in the planning of failure. For example, The Netherlands' Room for the River calls on social systems when rivers flood and infrastructure fail, to subsidize farmers for lost crops, far cheaper than elevating and maintaining levees [65]. Arizona's Indian Bend Wash has initially leveraged ecosystem capabilities to attenuate flooding when monsoon rains overwhelm the stormwater system [66]. And now, the City of Scottsdale is working on an updated master plan for infrastructure through multiple rounds of community feedback, which not only responds to the shifting hydrologic risks by updating aging infrastructure for flood management, but also asks the question of how social and ecological values of Indian Bend Wash as recreational parks and aquatic centers might affect the community when they are compromised by overflow [67]. It is not that other resilience frameworks do not incorporate capabilities of the three domains, but that STF appears to be aligned with the leveraging of SETS capabilities during the design phase to open up new adaptation strategies and infrastructure transformation aligned with *graceful extensibility* upon surprises.

STF infrastructure planning and design offers transformational opportunities for infrastructure systems to evolve from a techno- or SES-centric solution space to an interactive system leveraging various SETS resilience capabilities; and presents new strategies for navigating disasters in the Anthropocene. External shocks such as extreme weather phenomena are not only disrupting the infrastructure system itself, but also the urban environment including people and property. Despite traditional infrastructure protection achieved by ensuring the robustness of built systems, climate change is altering the perspectives of cities to recognize infrastructure risks that are not predicted with climate models. Thus, there is a coupling between STF infrastructure planning, SETS climate adaptations, desired urban futures, and the likelihood of unprecedented non-stationary weather events. Major institutional and technological changes happening with national and international climate adaptation plans should give cities a chance to adapt to the change by transforming the processes that have contributed to vulnerability rather than focusing on reducing specific risks of climate change by a set of interventions [68]. Infrastructure transformations towards resilience, hence, must take what we know now, and proceed to STF approaches incorporating SETS capabilities dealing with uncertainties and non-stationarity.

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Leveraging SETS Resilience Capabilities for Safe-to-Fail Infrastructure and Climate Change

Highlights

- Safe-to-fail approaches challenge the isolation of the technological domain by necessitating a recognition of social, ecological, and technological system dynamics
- Infrastructure planning and design need to evolve from a techno-centric solution space to incorporating social, ecological, and technological resilience capabilities
- Infrastructure governance should transform to effectively utilize safe-to-fail infrastructure planning approaches

Leveraging SETS Resilience Capabilities for Safe-to-Fail Infrastructure and Climate Change

Declaration of Interest Statement

Nothing to declare.