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Operationalizing Resilience In The Context Of Complex Systems: A Systematic Roadmap

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Scientific advances in resilience of complex social-technical systems have primarily focused on modeling approaches to address challenges in characterizing, quantifying, and optimizing resilience (Fraccascia et al., 2018). In practice, achieving resilience must consider problems of deeply uncertain events, especially in the context of climate change, development, and changes in demographics. This work proposes a new way of thinking about the operationalization of resilience by exploring a three-dimensional framework to guide the next generation of resilience principles and operationalization of resilience in the context of complex social-technical systems. Specific challenges are identified and discussed in the context of the literature on resilience principles (Jackson and Ferris, 2013). A three-level conceptual framework is proposed to classify resilience concepts into capabilities, principles (sub-principles), and domains. A process to map resilience principles to actions is presented as a baseline for achieving operational resilience of complex systems.

Complex social-technical systems refer to a sophisticated arrangement of interconnected subsystems whose combined behaviors or characteristics pose challenges in prediction and management. These systems often require the development of multi-component engineering solutions, designs, or algorithms to effectively manage their unpredictable collective behaviors and their impact on society[1]. In recent years, a series of disasters have led to significant loss of human life, extensive property damage, and service disruptions of complex social-technical systems (Urlainis et al., 2022). In the wake of these events, there has been a notable emphasis on resilient complex social-technical systems, where resilience is the ability to adapt to changing conditions and withstand and rapidly recover from disruption (Gao et al., 2016). Building resilience into complex systems is thus critical to the daily functioning of society and its ability to withstand and recover from disruptions. Operational resilience (a term introduced in the 2007 National Strategy for Homeland Security (Homeland Security Council, 2007)) refers to the process of translating the concept of resilience into practical, measurable, and actionable strategies, policies, and practices. In an effort to advance the research on the operationalization of resilience, prior work attempts to describe the process through generalized resilience principles (Yu et al., 2020). Existing models related to operational resilience usually do not consider the specific complexities and unique characteristics of individual systems and organizations, making it challenging to translate models into practical implementation strategies (Collier et al., 2013; Serre et al., 2018). Particularly, complex social-technical systems exhibit variations in their level of resilience, and existing models do not adequately help identify which policies should be implemented based on the system's current situation (Jabareen, 2013). Although organizations struggle to translate these models into practical implementation strategies (Hernantes et al., 2019), and these efforts

[1] See, for example, (Alderson et al., 2010) for a more comprehensive discussion on the meaning of complexity in infrastructure systems.

encourage incorporating resilience in complex systems, a detailed roadmap that provides a sequence of policies for organizations to implement and operationalize resilience is still lacking.

This work explores the concept of generalized resilience principles across multiple domains and capabilities of complex social-technical systems. Specifically, we argue that system resilience does not depend on the scenarios and instead relies on a set of principles that determine the design and management of a resilient system. These principles are general and can apply to different system domains (technical, social, ecological). At the same time, we recognize that these principles must incorporate conditions from current and future disasters that are influenced by uncertain factors such as development and climate change.

We propose the organization of resilience concepts into a three-level conceptual framework where the most fundamental level refers to resilience capabilities under which a set of resilience attributes are defined. Both capabilities and attributes are defined as "ends" or objectives to be achieved by a resilient system. The third level of concepts constitutes the "means" to achieve these objectives, which we refer to as the ***Resilience Principles***. While there are specific principles associated with each capability, certain resilience principles are common across all capabilities. Our work identifies common resilience principles across all resilience capabilities and describes them for each system domain. Then, resilience attributes are identified along with subprinciples, and they are each mapped to specific actions in each domain to guide the operationalization of resilience in complex systems. Examples from each domain are presented to demonstrate the proposed conceptual framework.

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