11 SUSTAINABLE CITIES AND COMMUNITIES

# PREPARING FOR A CRISIS

## IMPROVING THE RESILIENCE OF DIGITIZED COMPLEX SYSTEMS

Technology can transform societies, make them more equitable, and support and accelerate the achievement of sustainable development goals. But the rapid and ubiquitous advancement of digital technologies comes with risks. As the COVID-19 pandemic starkly demonstrated, those risks are systemic and often shared in an increasingly connected and globalized world. Governments, institutions, and societies must make investments and systemic changes to reduce the likelihood of future shocks and improve resilience to those shocks. Mathematical methods have proven to be invaluable tools to address vulnerabilities in critical systems and processes and build more resilient systems and societies.

At the start of the COVID-19 pandemic, shortages of personal protective equipment, food items, and other basic consumer goods revealed the risks of over-reliance on 'just-in-time' global supply chains. Companies have been using artificial intelligence and machine learning to minimize raw materials and inventories and only order them when needed to get them to consumers on time. It took a global pandemic to confirm what experts had warned for years: this leaner, lower-cost system was not resilient to shock.

Resilience is a system's ability to minimize or quickly recover from a disruption or shock. Building resilience is the key to combating a crisis, whether environmental, social, or economic. To this end, resilience has been elevated to a global priority, if not a normative imperative, in development discourse and policy agendas.

### DIGITAL RESILIENCE

The rapid and global advancement of digital technologies coupled with the availability of vast amounts of data has made societies increasingly dependent on complex systems. From enabling financial transactions to running the power grid, underpinning transportation systems, empowering health care, and supporting the logistics of rapidly delivering supplies and materials, digital technologies have transformed nearly all facets of modern life and society. Yet these changes have made societies more vulnerable to catastrophic disruptions from natural disasters, deliberate attacks, and even simple errors. Making complex systems more resilient is an important challenge as governments, businesses, and society continue to embrace digital technologies.

### KEY MESSAGES

- ☑ Resilience is the ability of physical, natural, or social systems to withstand and recover from disruption.
- ☑ Today's highly digitized complex systems have been created through the availability of vast amounts of data, but dependence on such data makes them vulnerable to disruptions due to natural disasters, deliberate attacks, and even simple errors.
- ☑ Mathematics provides capabilities for modeling, simulating, and assessing the behavior of critical infrastructure components and their associated dependencies.
- ☑ Mathematical methods and approaches are invaluable tools to systematically identify threats, develop options that will reduce exposure to or minimize impacts of such threats, and ultimately build more resilient systems. Collectively, these capabilities will help decision-makers prepare and respond more quickly and effectively to a variety of disruptions.

### DISRUPTION & RESTORATION

The ability to respond quickly to disruption is key to building resilience. For example, in today's complex, interconnected electrical power systems, cascading failures that result from minor power outages can have dramatic consequences, including widespread blackouts. Power grid disruptions can cascade with such speed that an operator may not be able to absorb the vast amounts of data describing the changing state of the system nor react fast enough to prevent the cascading disaster before it leads to a major system-wide blackout. In such cases, fast, reliable mathematical algorithms and tools are necessary to detect and respond to such problems. These algorithms are autonomous when needed, able to handle multiple alternative solutions, and agile enough to shift direction if no solution is good. Multiple such tools have been developed and applied to increase and enhance infrastructure resilience.

A CASCADE model, for example, is a simple probabilistic model that can uncover and describe some of the essential features of electric power transmission system blackouts caused by cascading failure. It can predict what components might fail and where load distributions might cause cascading overloads and failures following a disturbance. CASCADE models can be paired with algorithms to analyze the effect of operator actions to minimize the impacts of blackouts, such as emergency load shedding, and evaluate expected blackout costs.

Mathematical models have also been applied to recovering critical infrastructure following large-scale disruptive events. Increasingly digitized transportation systems, telecom networks, water and sewer systems, and electric power grids supply crucial services to communities and ensure human health and well-being. These services must be efficiently and effectively restored following a natural disaster or other extreme event. Network optimization techniques can be used to model the resilience of these critical infrastructure systems.

After a disruption, decision-makers must schedule repairs by allocating scarce resources. They need to determine the set of components that will be temporarily installed or repaired, assign these tasks to workgroups, and then determine the schedule of each workgroup to complete its assigned tasks. These planning and scheduling decisions can be mathematically modeled and optimized within a scheduling framework.

After an extreme event, there are often interdependencies between restoration efforts and critical infrastructure systems. For example, repairs may be needed at transportation hubs after a hurricane, but these jobs cannot be completed until power is restored. Or, if trees bring down power lines onto a road, the power company must wait for road crews to begin repair and restoration. Complex mathematical theories to deal with interdependencies have been developed using optimization methods. Often these interdependencies cross different infrastructures, requiring decentralized decision-making and scheduling.

## RESILIENT SOLUTIONS

Digital resilience requires design strategies that safeguard a system's ability to maintain, change, and recover capabilities and withstand crises and shocks. Resilience of digitized complex systems must be achieved as a designed-in property. It's possible to mathematically represent the system's structure and operational logic and quantify readiness to adapt and recover. Mathematical and algorithmic approaches can also inform crisis response and recovery efforts and help advance more resilient solutions.

## CONCLUSIONS

Modern digital systems tend to include more and more interconnected components. They enhance the ability to accommodate rapid changes in transportation systems, urban services, and supply chains. Designing ways to create flexibility while minimizing vulnerability to disruptions

Artificial intelligence is being used to increase reliability and reduce losses and accidents during the transmission of electrical energy. © AdobeStock

requires a deeper understanding of the dynamics of interconnected complex systems.

Monitoring highly specialized digital infrastructure systems involves the collection of vast amounts of data from multiple heterogeneous sources in real-time. The avalanche of data requires increasingly abstract mathematical models and matching algorithmic techniques to extract information from data that is relevant for decision-makers.

While most intuitively understand what resilience is, decision-makers need to go beyond intuition; they need tools to measure resilience and to assess the effect of specific actions on the resilience of a complex digitized system. Active collaboration of mathematical scientists and decision-makers can help develop such tools.

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