DANGEROUS CONNECTIONS

The benefits of web-based interactions between systems are accompanied by some risk. Individuals who seek to exploit the interconnection between systems can impact the grid, as well as any other systems dependent upon it.

"We can imagine hazards to infrastructure from things like hurricanes and earthquakes, terrorist attacks," says Richard Sause, the Joseph T. Stuart Professor of Civil and Environmental Engineering and director of the ATLSS Engineering Research Center. "But I think we're getting to the point where an attack by hackers that's coordinated and well-planned can do essentially the same thing. So, it's a hazard of a different kind, and we need to think about how to defend against it."

In the case of the power grid and natural gas, "if someone disrupts the natural gas sources or delivery network, that's going to affect the electrical grid since some generators in the grid run on natural gas. And the electrical grid itself provides electrical energy that's used to produce and transport the natural gas to the places that need it. So, if the electrical grid goes down, that would also disrupt the natural gas network. These interdependencies can cause some serious problems," says Blum.

Lehigh researchers work on creating models to determine how an attacker might misuse, for example, the demand-side management component of the smart grid to benefit financially or to simply wreak havoc, as well as what the grid operator can do to detect or mitigate such an attack.

Larry Snyder, associate professor of industrial systems and engineering, provides the mathematical optimization models that advance this type of work.

"If we want to have a good model of the worst a bad guy could do to the system, that's an optimization problem," he explains. "How does a bad guy maximize the damage he can cause if he has limited resources to perpetrate the attack? And the flip side of what the power company can do to mitigate that is also an optimization problem: We have only so much money available. How can we best protect the grid against these attacks, given that the bad guys are going to do their worst?"

> "RESILIENCE IS A LOT MORE THAN JUST THINKING ABOUT THE HARD, PHYSICAL SYSTEMS, THE INFRASTRUCTURE SYSTEMS," SAYS SAUSE. "SOCIAL AND ECONOMIC SYSTEMS ALSO GET DAMAGED AND RECOVER. ... IT'S REALLY ABOUT THE RECOVERY PART OF IT: PLANNING FOR IT, MEASURING IT, OPTIMIZING IT."

MANAGING RISK FROM NATURAL DISASTERS AND CLIMATE CHANGE

Cyber-attacks aren't the only threats to our collective infrastructure systems. Natural disasters such as floods and hurricanes can have devastating effects. Lehigh researchers tackle these problems as well.

During a natural disaster, connecting people by bridges can mean the difference between life and death. And, in the aftermath of such extreme weather events, bridges are also crucial for recovery efforts. Dan Frangopol and his research team use probabilistic modeling and analysis, as well as advanced computer simulation, to assess the effects of natural disasters and other uncertainties on infrastructure.

In their latest research, Frangopol, the inaugural Fazlur R. Khan Endowed Chair of Structural Engineering and Architecture, and his former Ph.D. student, Alysson Mondoro, integrated for the first time the three most common failure modes for bridges exposed to floods, hurricanes, tsunamis and other extreme hydrologic events into a comprehensive risk assessment framework.

The work fills a key gap in the way risk for such bridges is assessed over their life-cycle. Their research was published in *Engineering Structures* (Vol. 159, 2018) in an article titled "Risk-based cost-benefit analysis for the retrofit of bridges exposed to extreme hydrologic events considering multiple failure modes."

Deck, pier and foundation failure are the three most common bridge failure modes. However, the risk assessment of bridges exposed to hazards have typically included only one or two of these.

"Considering only one or two failure modes provides an incomplete picture because the risk level of each mode differs and, when assessed together, they compete with each other," says Frangopol. "Our analysis finds that any risk assessment must incorporate all pertinent failure modes of a structure."

Frangopol and Mondoro illustrate their analytical method using a riverine bridge as an example. They calculated the impact of bridge retrofit actions on possible failure modes in terms of probability of failure, risk and benefit-cost ratio using a logic modeling technique called an event tree.

In the riverine bridge case study, all of the bridge retrofit options resulted in a reduction in the probability of failure for the examined bridge. However, these options did not provide a unilateral decrease in risk.

For example, the addition of retrofit measures to prevent deck dislodgement decreased the probability of failure of the deck, and, in turn, the bridge. However, it increased the probability of failure of the foundation. Since the consequence of a foundation failure is larger, the overall risk is increased.

"Effective management strategies will vary depending on the bridge and the intensity and frequency of the hazard to which it is exposed," says Frangopol. "This may be of particular interest in regions where the impacts of natural and anthropogenic climate changes are felt most acutely."

While the illustrative example focuses on the flooding hazard, the methodology can be applied to other extreme hydrologic events, such as hurricanes and tsunamis.

Frangopol's research on bridge retrofitting is part of an initiative spearheaded by the American Society of Civil Engineers (ASCE). Frangopol, as a member of the ASCE Industry Leaders Council, helps lead ASCE's efforts to achieve a "Grand Challenge" of reducing the life-cycle cost of U.S. infrastructure by 50 percent by 2025.

"Ultimately, life-cycle engineering is about more than us," he says. "We're trying to optimize our world for future generations."

DEVELOPING RESILIENT INFRASTRUCTURE

Disaster, either natural or man-made, inevitably strikes at some point, and the recovery of an affected community's infrastructure systems determines its socio-economic recovery. Another team of Lehigh researchers uses a probabilistic approach to examine how interdependent systems work together during and after a disaster.

This interdisciplinary team, composed by civil engineers, systems engineers, computer scientists, social scientists and economists, is led by Paolo Bocchini, the Frank Hook Assistant Professor in the Department of Civil and Environmental Engineering, and includes Lehigh researchers Snyder; Sause; Lamadrid; and Brian Davison, associate professor of computer science and engineering.

The team focuses on the regional scale rather than the structural scale: How does an entire region recover from disaster?

"Engineers have focused on designing buildings and infrastructure systems able to preserve lives even under extreme events, and they have been quite successful," Bocchini says. "But in recent years the bar was raised. Our society not only asks the built environment to protect lives, but also to remain functional. Even after extreme events, we need our hospitals to be operational, our bridges to be safe, power and water in our houses, and functioning communication systems. Our project aims at modeling, in a probabilistic sense, this complex recovery phase and the interdependencies among the systems involved. We start from the damage in every small structural component, and we zoom out to capture the recovery dynamics of the entire region. With good predictive models, we will be able to optimize mitigation and preparedness efforts."

Through a $2.2 million NSF grant tilted "Probabilistic Resilience Assessment of Interdependent Systems (PRAISys)"—led by Lehigh and with collaborators at Florida Atlantic University and Georgia State University—the team works to "establish and demonstrate a comprehensive framework that combines models of individual infrastructure systems with models of their interdependencies for the assessment the disaster resilience of a community, considering the uncertainty involved."

"Resilience is a lot more than just thinking about the hard, physical systems, the infrastructure systems," says Sause. "Social and economic systems also get damaged and recover. It's broader than even engineers tend to think about, but it's really about the recovery part of it: planning for it, measuring it, optimizing it."

Snyder says: "Much of the modeling and research efforts to date had to make strong simplifications and assumptions on the recovery process. For instance, for a given event, they assumed a predefined recovery time for each infrastructure system. In this project, we look at this process in detail, and we account for the randomness in it."

With infrastructure and energy systems underpinning all aspects of modern society, Lehigh's diverse research community is tackling this work from a variety of angles, within and across disciplines.

"At Lehigh, I collaborate with people who are very similar to me, but I can just as smoothly collaborate with experts different than me," says Kishore. "We're able to look at one problem and use our skill sets to solve the problem together. Then we use that experience to solve an interrelated problem between infrastructure systems. We build on the strengths of one to solve the problems in the second."

Institutes for Greater Impact

This April, Lehigh announced the formation of Interdisciplinary Research Institutes (IRIs) to solidify and further develop strength in focus areas where faculty and students can make significant academic and societal contributions.

Lehigh's IRIs incorporate the work of faculty across campus to grow broad, multidisciplinary research communities around topics where Lehigh research is poised to make the greatest possible impact.

"The power of interdisciplinary thinking is central to Lehigh's vision and mission," says Lehigh President John Simon. "As an academic institution, we were founded upon that very notion. It is, and always has been, infused into everything we do, not quarantined to a particular set of programs or segment of our campus. Interdisciplinary thinking is our best hope for solving today's most vexing challenges, and thus our investment in this space is as multifaceted as our community's interests."

The themes and structure of the three inaugural IRIs were developed through a faculty-led envisioning process initiated in the P.C. Rossin College of Engineering and Applied Science, with input from faculty across the University.

The **Institute for Functional Materials and Devices (I-FMD)** focuses on synthesis, fabrication, processing, and characterization of materials, devices and related systems. Existing research interests include photonics and electronics, metals, ceramics, biomaterials, polymers, and composites, and incorporate devices ranging in size from the nanometer and micrometer scales and beyond.

The **Institute for Data, Intelligent Systems, and Computation (I-DISC)** is devoted to the study of problems that involve massive amounts of data and/or large-scale computations, and developing the science that enables the extraction of useful and actionable information across disciplines and research fields.

Research within the **Institute for Cyber Physical Infrastructure and Energy (I-CPIE)** underpins all aspects of modern society. The demands and side effects of society's reliance upon energy, communications, structural and transportation systems require a broad approach that's focused not only on engineering systems, but on improving people's lives.

Richard Sause's work includes integrated experimental and analytical research on innovative, self-centering, seismic-resistant steel and concrete structures. He received his Ph.D. from the University of California, Berkeley. **Dan Frangopol** is widely recognized as a leading educator and creator in the field of life-cycle engineering. He is a member of the Academy of Europe (London) and the Royal Academy of Belgium and is a Distinguished Member of ASCE.

Paolo Bocchini's research activity is related to the use of probabilistic concepts, computational mechanics, operational research, and other numerical tools in civil engineering problems. He received his Ph.D. from the University of Bologna after completing a dual-advisor program at Columbia University, where he had been a visiting scholar.