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Educating Engineers for Resilience

Critical infrastructures are more than just technology. To increase their resilience, engineers should view them as socio-technical systems.

By Benjamin Scharte

Modern societies depend on the services provided by critical infrastructures. Although technology forms their backbone, human interaction forms their heart. As such, critical infrastructures are actually 'socio-technical systems'. For this reason, the people who design, construct, operate, and maintain them – engineers typically – should appreciate and address both technical and social factors when ensuring these structures continue to yield the services for which they are valued.

Technological development and intensive social interaction (among others, interpersonal, interdisciplinary, interorganizational, intercultural) lead to increasing complexity and interdependency of critical infrastructures. Resilience Engineering provides a suitable framework within which engineers can best incorporate such considerations. These include the ability to deal with complexity, the explicit acknowledgement of the socio-technical nature of critical infrastructures, and ways to address normative and ethical questions of resilience. The objective is to build future-proof critical infrastructure systems. To enable engineers to do that, education is key. When it comes to critical infrastructure resilience, the education of engineers should follow a systemic approach, including findings and implications from the social sciences.

Taking Complexity Seriously

Critical infrastructures are the lifelines of modern societies, supplying them with essential goods and services such as energy, IT, water, food, transport, healthcare, and more. They are complex and interdependent, not only within specific sectors, but also across them, and ongoing digitalization will increase the interdependencies within and across critical infrastructures even more.[1] It is their very complexity and the interdependent interactions between different infrastructure sectors which lead to an abundant as well as highly reliable supply of goods and services. Modern societies rely on these kinds of complex interdependent systems, which enable lifestyles of unparalleled wealth and comfort.

But what is complexity? Imagine being stuck in a traffic jam with no obvious cause. Japanese researchers recreated this situation by asking 22 drivers to follow each

Key Points

- Due to their increasing complexity and interdependency critical infrastructures are becoming more vulnerable, which leads to a growing need for resilience.
- Engineers can help to increase critical infrastructure resilience if they acknowledge their socio-technical nature.
- Educating engineers should encompass complexity theory.
- Engineering studies should include findings from the social sciences on topics such as normative issues or proper communication.

Evening rush hour in central Beijing. Urban traffic is an example of a complex socio-technical system. *Jason Lee / Reuters*

other at a speed of 30 km/h on a circular track. Soon, tiny deviations in speed and distance between some participants led to considerable slowing or even stopping. This is complexity at work.

In a complex system like the one re-created in this experiment, characteristics emerge that cannot be explained by looking solely at the activity of the individual elements. Each driver tries to follow the car in front, keeping speed and distance constant, slowing down or speeding up as necessary. Collectively, these adjustments result in the traffic jam, which is an unintended consequence of the individuals' activities. As one driver slows the next responds, leading to a cascading feedback loop that ultimately influences all of the drivers' behaviors.[2]

Complex or Complicated: Telling the Difference

In complex systems one never knows exactly what is going to happen or how an intervention might influence the system. The system does not function in a deterministic fashion. Deterministic means that system behavior depends on clear and distinct rules. If these rules as well as the specifics of a situation are known, it is possible to accurately predict system behavior. Assuming deterministic behavior rules out the kind of unpredictable feedback loops and emerging behavior that are typical of complex systems.

Unfortunately, engineers are often taught to think deterministically. For them, real-world problems are challenges that can be solved by clever design and innovative technologies. If they just work hard enough, they should be able to come up with a perfect solution. In fact, this hints at an understanding of systems as being complicated rather than complex. A complicated system consists of a huge number of different elements that are related by distinctive causal rules – a deterministic view. It may be hard to understand how such a system works, but it is nevertheless possible if the rules are known. Purely technological systems tend to be complicated rather than complex. Airplanes and cars are examples of complicated systems. Engineers can design and construct those following deterministic principles.[3]

However, this deterministic understanding in engineering is largely inappropriate when dealing with complex systems. As soon as purely technological systems start to interact with non-technological parts of the world, complexity becomes a reality. Airplanes have pilots, maintenance crews, and passengers, they fly through different sorts of weather and climatic conditions, and they are only a tiny part of the whole air traffic system. Neglecting this complexity may lead to disastrous consequences. The notion of Resilience Engineering accepts that following feedback loops and predicting unintended consequences in complex systems is difficult, resource intensive, and time-consuming. Nevertheless, accepting that problems in complex systems cannot easily be solved is becoming an increasingly important trait in engineering.

Critical Infrastructures Are Socio-Technical Systems

In this sense, critical infrastructures are complex systems – they are beyond complicated. They are innately technological, but without people to design, build, operate and maintain them, they could not provide the services society values. The technological parts of the systems are embedded in a societal framework that comprises organizational, political, legal, economic, ethical, normative and other aspects. Engineers should be able to recognize this and understand the tremendous influence it has on their work.[4]

This is a question of engineers' ability to define system boundaries properly. It is often not sufficient to analyze the energy system, for example, and just look at the grid, transformer stations, and power plants. An example of the complexity of energy systems is a November 2006 large-scale blackout in Europe, where a planned, routine disconnection of a power line led to more than 15 million households in Northern Germany not having electricity for two hours. The reasons were a simple change in schedules – the disconnection appeared earlier than planned – and a lack of communication. The transmission system operator who disconnected the power line did not inform other affected transmission system operators that he would do this earlier than planned. The operators had insufficient time to adjust their grids. It was primarily non-technological reasons which led to the blackout.[5] Clearly, there is more to critical infrastructures than technology. Herein lies a central lesson for engineers. The fundamental complexity of critical infrastructures derives from their interdependent, socio-technical nature.

This also means that engineers working on critical infrastructure resilience become part of the system. Being part of the system has several implications. Because of the central role human interaction plays within critical infrastructures, communication is crucial. Suitable and informed communication with relevant stakeholders is decisive for engineers' success. Communication science as well as organizational theory offer insights about the positive and negative aspects of communication in complex environments. For engineers, it is less about the theories behind communication and more about applicable advice on how to communicate their ideas and the results of their work with relevant stakeholders.

Rising Vulnerability Requires Increased Resilience

Complexity and interdependency of critical infrastructures enable societies to prosper. Yet increasing complexity and interdependency can also lead to considerable – and presumably rising – vulnerability. Due to feedback and interaction, small initial failures can trigger widespread, catastrophic breakdown of systems because of so-called cascading effects. All critical infrastructures are inextricably linked to each other. If one of them fails, it is very likely that at least some of the others will fail.[6] As an example, many people do not realize that without power, water will soon stop flowing from the tap. Furthermore, most critical infrastructures are operated with the help of digitalized control systems which are vulnerable to cyber-attacks.

This leads to the assumption that in complex systems it is virtually impossible to prevent all disruptions from happening. Notwithstanding the benefits of thoroughly mitigating risks and preventing disruptions – a classic task for engineers – societies need to prepare their critical infrastructures for the inevitable. Disaster happens, things break, failure is real. This is why critical infrastructures need to be more resilient. Resilience is the ability to adapt generically (generische Anpassungsfähigkeit)[7] to unexpected and severely disruptive events. Specifically preparing for surprises is not possible. Because of that, systems need flexibility, a capacity to learn, and so-called slack resources that can be invested in resilience measures.[8]

A Systemic Approach Includes Normative Implications

Technology provides many ways to increase resilience. Resilience Engineering is about researching the most suitable ways to do so. However, given the complex, socio-technical nature of critical infrastructures, Resilience Engineering has to be more than just developing and applying technology. Engineers should be able to take the systemic context into account. They have traditionally taken a narrow view of resilience, reflecting their deterministic understanding of systems. For them, it is often about bouncing back. Using technologies for this narrow purpose runs the risk of producing the kind of unintended consequences that are typical in complex systems.[9]

Those unintended consequences could, *inter alia,* consist of negatively influencing society. Applying new technologies within the context of increasing critical infrastructure resilience has normative implications, as they could affect personal freedom or privacy. Operating with a deterministic understanding of systems and discounting the complexity of critical infrastructures increases the risk of damage.[10] Engineers cannot be the ones to analyze normative implications, nor is it their task to make moral judgements. Nevertheless, engineers should embrace a systemic understanding of resilience which accounts for unintended societal consequences. They need to be able to recognize the existence of such implications and know how to collaborate with stakeholders to solve problems.

Resilience Engineering: Education is Key

Engineering for resilience will improve the security of future critical infrastructure systems. Although an understanding

Further Reading

Complexity. A very short introduction. *John Holland, 2014, Oxford: University Press*
Comprehensive yet accessible introduction to the theory of complex adaptive systems including some good examples of simple, complicated and complex adaptive systems.

Foresight review of resilience engineering. *Lloyd's Register Foundation (LRF), 2015. Lloyd's Register Foundation Report Series: No. 2015.2*
This study finds that resilience engineering is still in its infancy and identifies research needs and ways forward to establish resilience engineering as a transdisciplinary approach.

Resilience and stability of ecological systems. *Crawford Stanley (Buzz) Holling, 1973, Annual Review of Ecology and Systematics (4), 1–23*
By far the most influential article in all of resilience research, establishing the link between complex systems and the need for resilience.

Handbook on resilience of socio-technical systems. *Matthias Ruth and Stefan Goessling-Reisemann (Ed.), 2019. Cheltenham: Edward Elgar Publishing Limited*
This volume provides up-to-date insights about resilience theory from different disciplinary perspectives.

of Resilience Engineering is still in its infancy, examples exist where engineers are educated in holistic ways that encompass the societal context. These include the Department of Sustainable Systems Engineering (INATECH) at the University of Freiburg in Germany and the Science in Perspective program of the Department of Humanities, Social and Political Sciences at ETH Zürich. Even so, further progress is needed. We should:

- Take complexity seriously: Engineering curricula should extend to the study of complex adaptive systems to teach students about the nature of the systems they are dealing with and the intrinsic limits to knowledge that accompany complexity. This includes the ability to differentiate between complex and complicated systems as well as acknowledging the fact that determinism is not appropriate for critical infrastructures.

- Keep the human in the loop: Engineers should be educated about the concept of critical infrastructures and an understanding of their complex, interdependent nature. Students need to be familiar with the idea of critical functionality, the fact that it is not some technical artifact which is worth preserving but the services the infrastructures fulfill for society. This is especially true for socio-technical aspects of critical infrastructures.

- Recognize that communication is key: Because engineers are part of the systems, they need to be able to communicate adequately with relevant stakeholders. Findings from communication studies and organizational theory should be part of Resilience Engineering education. This could range from the need to translate complicated scientific matters into everyday language to teaching engineers to advocate for resilience in a world driven by maximizing efficiency.

- Pay attention to norms and values: Normative issues should also be part of engineering studies, at least as a way of raising students' awareness about possible negative or positive effects of technologies on society. Digital technologies are an obvious example. They are useful, but with respect to critical infrastructure resilience they could also be used to monitor and control the population. Those designing engineering courses should use case studies about unintended negative consequences of technological development. Collaboration with the social sciences, as well as stakeholders from civil society, is needed.

These recommendations do not represent the full picture of Resilience Engineering. The concept also encompasses strictly technological aspects. However, given the complexity of modern critical infrastructure systems, it has become necessary to approach them with systemic solutions in order to increase their resilience. Making societies and their critical infrastructures more resilient is an interdisciplinary task which necessitates input from a wide variety of expertise.

Selected sources

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Benjamin Scharte is a Senior Researcher with the Risk and Resilience Team at the Center for Security Studies (CSS).

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