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Engineering Systems Design Capabilities for a Resilient Green Transformation

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Abstract. Early calls for environmental protection and sustainability centered on empathic arguments for curtailing consumerism and enacting personal and societal changes in our way of life. However we have now evolved to embrace a 'technology fix' approach, where we aim to reconcile our need to maintain our standard of living with our sustainability goals by developing and deploying 'green technologies' in our critical infrastructure at an unprecedented speed. While cost and sustainability are already in focus, the current discussion misses the third critical performance objective, resilience. In this paper, we explore how we can conceptualize resilience for critical socio-technical systems, and what the unresolved design challenges are to successfully develop and deploy them.

Keywords. Engineering Systems Design, Sustainability, Resilience

Introduction

Early calls for environmental protection and sustainability centered on empathic arguments to enacting personal and societal changes in our way of life, especially curtailing consumerism, e.g. [1]. The key argument was that per-capita consumption had to be reduced and focused on key necessities, in order for all humans to live within our planetary boundaries [2].

However, the political realities of the last decades have led to a different outcome: Instead of demanding tough personal sacrifices from their voters, a political consensus is increasingly embracing large investment with a primary focus to reduce the carbon intensity of our industrial activities, especially related to electricity generation, transportation and heating. The European 'Green Deal' [3], for example, introduces a number of policy initiatives to achieve climate-neutrality in Europe until 2050, with a minimum investment totaling at least 600 billion EUR. While this seems like a large number, it has to be seen on the backdrop of our annual energy-related investments of approximately 1900 billion USD globally, which includes over 600 billion USD annually of oil and gas related energy investments [4].

The climate goals in all of the eight European policy areas (Clean energy, sustainable industry, building renovation, agriculture, pollutants, mobility, biodiversity, financing) rely on transformation of existing infrastructure and significant technological innovation. This offering very exciting prospects for engineers, but contrasts with our spotty track record in delivering large engineering programs and technical infrastructure [5].

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Part of the root causes of our struggle to deliver on complex socio-technical systems is that they are neither purely technical and engineering undertakings, nor are they pure project management challenges, nor business challenges, nor are they pure policy or regulatory challenges [6]–[8]. In this paper, we argue that they are all of the above, and we need to develop and deploy a novel set of capabilities along the systems life-cycle of (re-)engineering, construction, and operation.

Our point of departure is Engineering Systems Design, a relatively new attempt at formalizing design practices for intervening in large-scale socio-technical systems [9], [10]. In the following, we will briefly discuss a set of three major objectives for large system interventions (cost, environmental sustainability and resilience), before moving on to a more detailed discussion of the arguably most often neglected system performance objective, resilience [11].

1. Objectives of large engineering systems interventions: productivity, sustainability and resilience

We understand engineering systems as complex sociotechnical systems that provide solutions to central economic and societal challenges, fulfil important functions in society, and exist over long life spans in which they continue to evolve [9], [10]. These are the systems that underpin our critical infrastructure, for example 'smart' electricity generation, storage and distribution that integrate with an electrified transportation system, or future autonomous transportation systems that integrate with our land and space-based infrastructure for real-time navigation and communication.

Since the start of the industrial revolution, productivity (or cost) has been the driving force behind a significant part of the innovation in these complex systems, and has been the de-facto measure of progress overall in the form of our industrial productivity figures for labor and capital and in the form of economic growth [12].

Much later, in the second half of the 20th century, was the concept of environmental sustainability introduced into the conversation, originally positioned as a counter-position to indefinite economic growth [1], [13] and eventually defining sustainability as a "development that meets the needs of the present without compromising the ability of future generations to meet their needs" [14]. A modern interpretation of sustainability now embraces a "triple bottom line" of economic, environmental and social sustainability [15], however many current policy implementations of sustainability again focus on its environmental meaning [3].

A relatively new addition to our main performance metrics, at least on the level of strategic national and international priorities, is that of resilience. First explored in the study and description of ecosystems, it describes the capability of a system to persist through disruption and change, without the use foresight [16]. It has developed to encompass a wide variety of resilience concepts, from the individual human level, to teams, projects, organizations, societies, technical systems and socio-technical systems [11], [17]. On the backdrop of severe financial crises, the global corona pandemic, and most recently, the novel post-cold-war military confrontation in Europe, it has now also entered the mainstream political conversation as a societal objective, for example in Europe [18], [19] or as a so-called national doctrine in the 2017 National Security Strategy of the United States [20]. As one of many examples, the German Chancellor Olaf Scholz declared recently: "We will therefore strengthen our resilience [...] against attacks on our critical infrastructure and channels of communication." [21].

The green transition, especially the decarbonization of our energy system including electricity, transportation and heating, has long been regarded from a perspective of cost and - naturally – environmental sustainability. The transition planning was therefor primarily driven by environmental and cost considerations, i.e. achieving a decarbonization of our energy system in a fast and affordable way. Resilience considerations were at best treated as boundary conditions (e.g. grid stability) or ignored (e.g. geostrategic dependence of Europe on Russian fossil fuels).

Part of the challenge is that a "design for resilience" method for complex socio-technical systems is in its infancy. The remainder of the paper aims to take stock at the current situation, and to propose avenues for future research.

2. Design for Resilience for Complex Socio-Technical Systems – Where are we?

2.1. Generic Design Capabilities for Complex Socio-Technical Systems: Engineering Systems Design

Before we illuminate the specific "design for resilience" challenge, we will briefly discuss the overall state of affairs of designing complex socio-technical systems.

A foundational practice for the design of complex technical systems is Systems Engineering [22], a design approach that has its roots in the development of the groundbreaking and highly complex aerospace systems of the 1950ies and now also includes a broader 'system of systems' perspective [23].

A number of efforts have been made over the years to extend the technology and engineering-centric practices codified in Systems Engineering to also encompass the social aspects of both the management and execution of the design activity, but also the social elements of the system being designed. This led to a research stream of socio-technical systems design (STSD) [24], [25]. One of the main arguments in support of STSD is that complex systems that we design often meet their technical requirements and specifications, but are still considered failures of the organizations and societies that are supposed to use and operate them – as they failed to capture the relationship between people, organizations and the real-life use of the technical systems.

Other work and research streams focused more practically on the integration of systems engineering practices and their most adjacent managerial practices such as project management [26], program management [27], [28] or cost management [29].

Later, the perspective of 'engineering systems' was introduced to describe large-scale socio technical systems delivering critical societal functions, often based on the confluence or integration of already complex socio-technical systems [9]. This work stream begun to more practically conceptualize the system being designed on a technical artifact level, an organizational, business model and supply chain complex system level, and a regulatory and policy engineering systems level. Most recently, about 60 authors in the field contributed to a handbook [10], aiming to represent the current state of the art in the field. The presents a significant expansion of prior engineering systems thinking. While still showing its foundations in systems engineering and design, it attempts to extend the conceptualization, design, and implementation of engineering systems interventions from its technical roots towards achieving societal objectives and designing for emergent properties such as sustainability and resilience, embracing adjacent fields such as project and program management, as well as policy making. However, it does not (yet) offer specific guidance on designing for resilience [17].

2.2. What does 'Design for Resilience' mean in the context of socio-technical systems?

The three critical questions when discussing the resilience of systems are 'Resilience of what?' , 'Resilience to what?' and 'Resilience how?' [11]. We will discuss each question in turn in the following.

2.2.1. Resilience of what?

The answer to the question 'Resilience of what?' is directly linked to our conceptualization of the socio-technical system that we are designing. From a top-down perspective, we can, for example, start with defining our critical societal services and their associated systems [30]. This includes for example the following systems:

- Electricity - electricity generation, transportation and storage.
- Transportation - land, sea and air transport of goods and people.
- Water - water supply, transportation, and wastewater management.
- Information technology and communication - the internet.
- Food and agriculture - the distribution of food and other necessities of life.
- A range of other systems, including healthcare system, emergency and government service systems, or our financial system.

While there have been proposals for a number of generic system models of critical infrastructure, they are typically targeted towards the assessment of a 'resilience state' of the infrastructure, not towards practical design task. Following the Engineering Systems perspective, we suggest a generic decomposition into three system levels:

1. Resilience of the governance system: The resilience of the governance system considers for example aggregate acceptable service levels, engineering project risks, public support, or geopolitical factors. It shapes elements such governance processes, policy and compliance frameworks and the regulatory environment.
2. Resilience of the business and supply chain system: This broader organizational resilience considers for example liquidity and cash flow issues in the face of market or supply disruptions. It shapes the operational practices of businesses and their contractual relationships with suppliers, customers and other partners. It extends to the resilience of teams and individuals working in these organizations.
3. Resilience of the technical artefacts: Resilience of technical systems covers classic resilience engineering areas, focusing for example on reliability, redundancy, or condition monitoring for predictive and preventive maintenance. Technical artifacts have to be seen as cyber-physical sub-systems, as well as their direct human interaction.

An extension of the 'Resilience of what?' question is the 'Resilience when?' question. While the type of critical socio-technical systems we are considering do already exist, they are continuously evolving through partial re-designs. At its most basic, a life-cycle model must include the following life cycle phases, which have to be considered for each system level described above:

- Resilience during the design process: This suggests, the design process itself is resilient, i.e. is capable of accommodating practically irreducible uncertainty regarding system requirements and system feasibility, as well as resilience

against uncertainty during the architectural design phases, the detailed design and the verification and validation of system performance during testing. This is of practical relevance, as system design activities are notoriously plagued by unplanned design iterations, leading to significant delays and cost overruns.
- Resilience during the production and construction process: This points towards the resilience of production processes and systems, supply chain, but also towards the resilience of project and program execution: Project and program risks are frequently quoted to lead to significant delays, cost overruns, or degradation of system performance.
- Resilience during the operational phase: Operational resilience emphasizes the resilient delivery or provision of the critical services that the system was designed to deliver. Not only including the resilience of the technical sub-systems, but also the resilience of its human operators, the surrounding organization, as well as the associated governance and leadership processes.

2.3. Resilience to what?

The 'resilience to what'-question focusses on the hazard landscape (i.e. sources of disruptions) that the socio-technical system faces. These describe the unanticipated events that potentially disrupt the system, and that the system must subsequently resist and recover from. Disruption and change can occur on significantly different time scales, from milliseconds to decades. A basic hazard model for socio-technical, i.e. socio-cyber-physical systems, includes [31]:

- Hazards posed by humans, either intentionally as acts of terrorism, sabotage or other crimes, or unintentionally, through accidents or accidental operations. These hazards may impact physical or cyber-physical components, as well as other humans and their relationships.
- Hazards posed by physical, non-human influences, for example natural catastrophes, equipment failures, fires or other accidents, on physical or cyber-physical components, as well as humans (i.e. health and safety risks).
- Hazards posed by cyber components, either through malfunctions (bugs) or deliberate attacks (viruses, cyberattacks), on cyber-physical components (e.g. smart IoT controllers) or cyber components (e.g. other software).

What is particularly relevant for the resilience of critical cyber-physical systems is the phenomenon known as 'cascading risks' [32], where cyber hazards affect cyber-physical components, in turn affecting physical plant components which in turn can affect humans. A popular example of this is the Triton cyber-attack on Saudi Arabia that was aimed at causing large-scale physical destruction at petrochemical facilities [33].

2.3.1. Resilience how?

Resilience thinking has developed into a significant number of research streams. Following [17], these include:

- Technical and engineering resilience: resilience as an emergent system property [11], [34], [35]. Resilience in systems engineering, alongside other related emergent properties such as survivability [36], changeability [37], flexibility

[38], [39], or robustness [37], [40]. Resilience engineering in the safety community [41], [42].

- Individual and team resilience: A critical review of the concept of individual psychological resilience [43]; factors shaping individual resilience to high-stress environments [44]; review of 'team resilience' concepts in workplace context [45] and empirical study of influencing factors [46]; relationship of individual psychological resilience and organizational incentives [47]; describing and enhancing resilience of small groups [48]
- Resilience of organizations (temporary and permanent): Theory and practice of resilience in project management [11], [49]; Organizational capabilities enabling recovery and disaster response [50]–[52], including business continuity [53], [54]; Review of 'organizational resilience' concepts, theoretical framing, and quantification approaches [55]–[60]; Capability to learn, adapt and transform [61], [62]
- Resilience of supply chains and inter-organizational networks: Concepts and application of supply chain resilience [63]–[66]; Resilience of extended enterprises and industries [67], [68]
- Resilience of social-ecological systems: 'unfamiliar, unexpected and extreme shocks' [69]; resilience, adaptability and transformability [70]; sustainability as long-term resilience, and resilience as a response to climate change [71]; general social-ecological resilience [72]
- Precautionary principle as an application of resilience thinking in governance: protection of socio-technical systems from harm [73]; implementation in policy making [74], [75]

A common theme among the various fields of resilience research is that resilience is an emergent property of the structure and behavior of the system being considered. Table 1 gives an indication of the variety of resilience properties that are being discussed.

Table 1. Categories of Emergent Resilience Properties, following [11].

Category of resilience properties	Emergent resilience properties
Recovery	Recover, return, self-righting, reconstruction, bounce back, restore, resume, rebuild, re-establish, repair, remedy
Absorption	Absorb, tolerate, resist, sustain, withstand, endure, counteract
Adaptation	Adapt, reorganize, transform, adjust, re-engineer, change, flexibility, self-renewal, innovation
Reaction	Respond, react, alertness, recognition, awareness
Improvement	Improve, grow
Prevention	Prevent, avoid, circumvent
Minimal/graceful deterioration	Minimal, restricted, acceptable, contained, graceful deterioration/degradation
Anticipation	Anticipate, predict, plan, prepare
Coping	Coping, cope
Survival	Survival, persistence
Mitigation	Mitigation, manage consequences
Others	Learning, management, action, resourcefulness

The authors make no claim regarding the completeness of these aspects of resilience as an emergent property, it serves to illustrate the diversity within the concept of resilience. Figure 1 shows a simplification, referred to as the 'resilience triangle'.

3. Designing Resilient Socio-Technical Systems

The challenging question now becomes how to design highly complex socio-technical systems, such as our electricity system, to exhibit emergent system properties of resilience. This applies to the entire design and system life cycle as discussed above, and poses a number of simple questions:

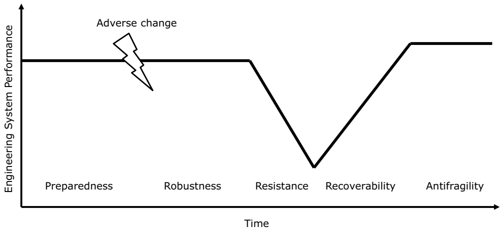

Figure 1. Illustration of the 'Resilience Triangle' [17].

1. How can we have productive conversations on a societal level regarding necessary levels of resilience? How can we have these conversations, even if the topic is not necessarily a visible priority?
2. How can we operationalize societal resilience expectations as resilience requirements for an engineering system design task? How can we manage the complexity of decomposing requirements for an emergent system property such as resilience across a highly complex socio-technical system, and across decades of design, construction and operational use?
3. How can we perform early-stage feasibility studies (and the associated trade-off studies) regarding systems resilience, when requirements are in flux and co-evolving with the solution? How can we perform early-stage trade-off studies against other critical emergent system properties of cost and sustainability?
4. How do we govern and execute a system design process to implement resilience requirements in our designs? How can we propagate resilience requirements from an architectural design to a conceptual design into a detailed design of physical, cyber-physical and organizational system elements?
5. How can we define resilience testing, verification and validation procedures that allow an early understanding of the degree of achieved resilience? How to assess expected system-level resilience from testing of sub-systems and components?
6. How do we support with our design the resilient execution of construction and production processes?
7. How do we leverage operational experience and data to feed-back learnings on resilience performance and resilience requirements from the operational use phase of the system?

We believe that there is much to build on from the domains of systems engineering, socio-technical systems design, and engineering systems design. The biggest gap that we perceive is better integrating the design of policy, regulatory frameworks, and public governance. Only if we succeed in connecting the public and policy makers effectively to the design process of these complex socio-technical systems, will we be able to create and deploy resilient, affordable and sustainable critical infrastructure.

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