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Exploring indicators of system-of-systems resilience: outcomes of a health systems design workshop at an international conference

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Abstract

This contribution departs from an existing model, the Design Framework for Systems-of-Systems Resilience, to explore systems resilience issues across the health, environmental, and economic domains. The reported research activities include 1) a rapid review to collect a set of systems indicators and 2) a design workshop employing causal loop diagramming to map expected causal influences between indicators. Through this exercise, we examine key themes in this research domain and outline directions for further enquiry, while involving members of the design research community in an open dialogue.

Keywords: resilience, complex systems, self-optimising systems

1. Introduction

1.1. Background: System-of-Systems resilience as a continuous design process

The COVID-19 pandemic had devastating consequences around the world and revealed the frailty of numerous national health systems, including ones who had previously been rated as resilient and high-performing (El Bcheraoui et al., 2020). Meanwhile, the global context is affected by a range of ongoing crises and complex issues, including climate change, armed conflict, and aging populations. These issues threaten tightly-interconnected systems crucial to human welfare across the environmental, health, and socioeconomic domains (Nathwani et al., 2021). As a result, the concept of System-of-Systems (SoS) resilience is receiving growing interest among researchers, who argue for the need of new resilience models considering a broad variety of systemic hazards and indicators (Cheng et al., 2022) and examining the resilience of human communities at a local, regional, national, and global scale (Koliou et al., 2020). In the design domain, Taysom & Crilly (2017, 2018) offer a nuanced characterisation of the concept of resilience in socio-technical systems from the perspectives of different stakeholders.

Within this line of research, Dreesbeimdiek et al. (2022) propose the Design Framework for System-of-Systems Resilience, which adopts a characterization of resilience articulated across interconnected, complex adaptive systems (or CAS, see e.g. Buckley, 2017). Building on CAS theory, the authors provide the following definition of community resilience across health, economy and the environment:

> *"Resilience is the process by which health, economic and environmental systems can face change and shock in such a way that they evolve and innovate together to continue to deliver healthy growth for communities."*

On this basis, they develop a Framework emphasising the interplay among health, economic and environmental systems, arguing that systemic stressors ripple through these interconnected domains as they produce their disruptive effects on communities (Figure 1). Building on Fricke and Schulz (2005), they differentiate resilience properties in terms of adaptability, robustness, agility, and flexibility.

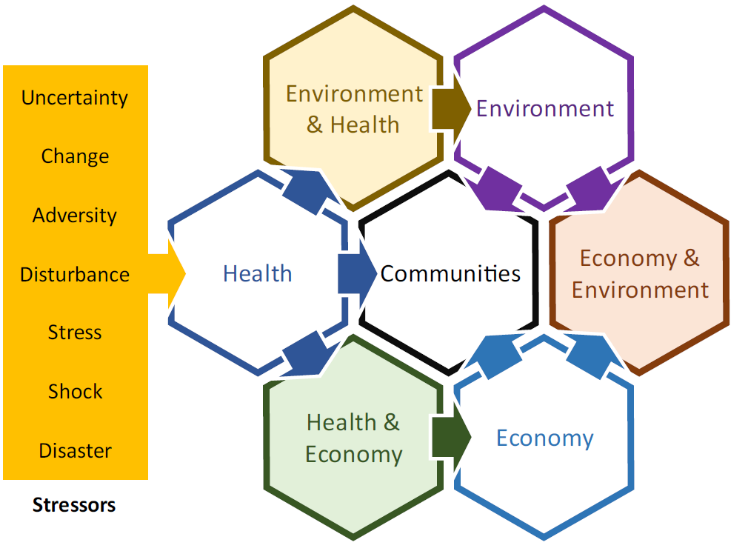

Figure 1. Stressors with exemplary rippling paths through the sub-systems (from Dreesbeimdiek et al. 2022)

As noticeable in the reported quote, Dreesbeimdiek et al. (2022) propose a notion of SoS resilience as a continuous *process*, rather than a system *property* - or, as Hollnagel et al. (2006) define it, an "intrinsic ability". More specifically, the authors argue that since CASs constantly evolve and reconfigure, resilience-enhancing efforts (such as policymaking, strategic planning, risk management, or emergency preparedness and response) should not only arise as a response to discrete disruptions, but rather follow a process-view while continuously anticipating, accommodating, responding, learning and transforming. Within this continuous process, Dreesbeimdiek et al. (2022) identify decision-making on specific resilience strategies and activities as *design* questions, and point out the need for "designing resilience into contemporary systems".

1.2. Vision: informing resilience processes through a composite Index

To inform what they describe as continuous resilience processes, Dreesbeimdiek et al. (2022) suggest identifying a set of existing indicators that can dynamically capture information on health, economic, environmental systems and their interfaces. An ambitious research goal in this sense is represented by the development of a composite Index of System-of-Systems Resilience, intended as a statistical tool using a range of relevant indicators across health, economic and environmental domains to support continuous resilience processes in an integrated fashion.
Ideally, the Index should fulfil a double purpose:

- A descriptive purpose, as it should provide a meaningful estimation of the overall construct of SoS resilience for a given community or geographic location at a given time. Specifically, the Index should be useful as a research instrument, and allow for a nuanced comparison between the resilience status of different communities, between the same communities at different points in times, and be applicable at different geographical scales.
- A prescriptive purpose, as it should inform resilience-promoting activities such as policymaking, strategic planning, risk management, or emergency preparedness and response. Specifically, the Index should be useful as a practical instrument, and aid complex design decision making through the enabling of context- and time-dependent comparisons between multiple possible courses of action, each with their own resilience trade-offs. Potentially, the Index could even develop to be applied for predictive resilience capabilities.

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Important conceptual and technical challenges involved in the construction of such an Index are apparent; in order to reflect a multidimensional construct such as SoS resilience in any meaningful way, the Index should possess considerable complexity and flexibility. Even then, the Index would not substitute complex decision-making within continuous resilience processes, but rather provide additional tools, perspectives and insights to involved stakeholders. Especially, the Index should offer a way to consider health and environmental indicators next to economic ones, which are often over-relied on as measures of societal development (Dreesbeimdiek et al., 2022). Yet, such an Index would in itself neither suggest resilience-enhancing interventions, nor provide a clear-cut identification of a 'best' course of action; decision-makers would still need to make deliberate (and possibly difficult) design choices while defining resilience strategies for different contexts and challenges.

1.3. Previous work and inspiration

Existing Indices can serve as precious references and inspirations for the development of the proposed composite Index of System-of-Systems Resilience. Within the community resilience domain, specifically, fundamental work has been conducted by Cutter et al. (2010), whose baseline resilience indicators for communities (BRIC) constitutes the most replicated quantitative method of measuring community resilience to date (Camacho et al., 2023). However, we observe that applications of the BRIC method thus far have mostly focused on its use as a research instrument, rather than as a support for continuous (design) decision making. Conversely, we suggest that investigating the possible value and use of a composite Index of System-of-Systems Resilience in design settings could uncover useful process insights, including in terms of best practices for Index results communication and visualization. For instance, it might be useful for the Index to be communicable both in a summarized and in an expanded overview, breaking down the different aspects contributing to the overall estimation of resilience for a given community. An inspiration in this sense is provided by the Health Index (Health index explorer, 2023), an open tool developed by the UK Office for National Statistics providing a systematic, multifaceted and dynamic overview of health-relevant indicators across different areas in England.

In terms of data sources, the Index might require a high degree of flexibility in the set of considered indicators, since data availability and characteristics vary considerably across different contexts and communities. A methodological inspiration in this sense is provided by the Frailty Index (Searle et al., 2008; Mousa et al.,2018), which supports a robust and reliable assessment of individual frailty (in terms of deficit accumulation to the individual risk of death) and can be applied to consider different kinds and numbers of deficits. Further elaborations on the relations and differences between the concepts of SoS resilience and frailty are provided in Pannunzio et al., 2024 (submitted).

1.4. Research focus and paper outline

Fulfilling the broad, ambitious vision of resilience as a continuous system design process informed by a composite Index of System-of-Systems Resilience appears to be a long-term research effort, involving both conceptual and technical challenges to be carefully disentangled. In the present study, we limit ourselves to initial, exploratory steps; not to validate a specific Framework or Index, but rather to examine key themes in this research domain while involving members of the design research community in an open dialogue. In doing this, we build on similar work done in the context of the Health Systems Design Special Interest Group within the worldwide Design Society, in which international meetings attended by a diverse group of researchers and practitioners supported a collective exploration and preliminary mapping of disciplinary landscapes and themes (Komashie et al., 2019; Ciccone et al., 2020).

More specifically, we here report on two exploratory research activities:

1. A rapid review, conducted to collect an initial set of indicators relevant to the Design Framework for System-of-Systems Resilience;
2. A design workshop, conducted to foster conversation on SoS resilience through the application of the Design Framework for System-of-Systems Resilience and the collected set of indicators on hypothetical application scenarios.

Next, we introduce the methods used for the rapid review and for the design workshop. Following, we provide a brief overview of the obtained results, including a general outline of the indicators collected through the review and two examples of SoS maps emerged from the workshop. Finally, we elaborate on a set of contextual reflections relevant to the broad research vision of resilience as a continuous process supported by an Index of System-of-Systems Resilience.

2. Methods

Our approach to the collection and exploration of indicators for the Index of System-of-Systems Resilience benefitted from an interdisciplinary perspective, drawing from complementary strengths of public health and design disciplines (Jung, 2023). On one side, we built on public health's tradition of development, application, and interpretation of a rich array of population-level measures (Turnock, 2012), performing a rapid review to identify and categorize relevant existing indicators. On the other side, we preliminarily explored the application of the Framework and of the collected set of indicators from a system design perspective through a workshop conducted at a major international design conference. More in general, we position our work within the growing body of resilience-relevant literature at the intersection of systems design, systems engineering, public health, and environmental and economic sciences, a convergence of perspectives which appears to be crucial for a broad variety of pressing societal challenges holding complex, multifarious implications (see e.g. Hou et al., 2022; Sarkodie & Owusu, 2021, Copeland et al., 2023; Nieuwborg et al., 2023; Pannunzio et al., 2023).

2.1. Rapid review

Using the Design Framework for System-of-Systems Resilience as a guide, we created a data capture template to identify existing indices of health, economic, or environmental performance of a geography. We defined each term broadly, and included indices spanning across more than one domain (e.g. health and environment). We used a snowballing technique to cascade this template through professional networks, asking relevant experts in each of the three fields to complete the template and then share onwards within their networks. We sought indices which were constructed from variables that are routinely available. The template additionally captured which geographical locations the indices had been designed for and validated in, and sources of empirical evidence. When we started to receive duplicate entries from new experts, we considered that we were approaching saturation. We then reviewed all captured indices to identify their constituent variables, and mapped these variables to whether they captured information on one of the domains, or an interaction between the domains.

2.2. Design workshop

The workshop was organised by the Health Systems Design Special Interest Group and was open to interested researchers and practitioners participating to the 24th International Conference on Engineering Design (ICED23). To facilitate conversations on SoS resilience, we employed causal loop diagramming (Tip, 2011), a traditional systems thinking technique (Richard, 1986) applied in a strong stream of research in systems dynamic modelling in the health domain (Darabi & Hosseinichimeh, 2020). In this domain, causal loop diagramming is often employed as a first way to map qualitative relations within a system before applying quantitative modelling through stock & flow simulations (Lin et al., 2020), and has been successfully applied to complex, multifarious public health phenomena such as childhood obesity (Butland et al., 2007) or the COVID-19 pandemic (Sahin et al., 2020).

The workshop lasted for a total of three hours and was structured as follows. First, a general presentation was provided on the concept of resilience, on the Design Framework for System-of-Systems Resilience, and on causal loop diagramming. Participants were then divided into groups of four or five. For the first activity, they were asked to select a future scenario involving a systemic stressor. Stressors could be chosen from a sample list (e.g. terrorist attack, extreme heatwave, major supply chain disruption, flood, solar storm, ageing population, antibiotic resistance, major internet shutdown), or new ones could be proposed by the group. Groups went through the provided list of indicators, chose the ones they expected to be impacted by the selected stressor, and mapped expected causal influences between indicators on the domains of the Framework for System-of-Systems Resilience, printed on large canvases. Upon completing the mapping of expected influences, participants were asked to identify causal loops between indicators, either balancing or self-reinforcing (Lannon, 2012), and given time to collectively reflect on the resulting overview.

For the second activity, groups went back to the causal loop diagram they had produced and brainstormed about interventions to make the system as a whole more resilient to the chosen stressor. These interventions could be of various kinds: policymaking, research and development initiatives, information campaigns, or more. Groups mapped the expected effects of the brainstormed interventions against the causal loop diagram they had previously built. Again, the groups were then given time to collectively reflect, before presenting their results and discussion to all other groups in a plenary closing conversation. The workshop setup was approved by the ethics review committee of [university omitted for review] and each participant was provided with an information sheet and asked to signed a consent form prior to the start of the session.

3. Results

3.1. Rapid review

The rapid review resulted in a list of 323 indicators. An overview of their distribution within the different domains of the Design Framework for System-of-Systems Resilience is provided in Table 1, together with examples of indicators pertaining to each domain.

Table 1. Overview of list of indicators

Framework Domain	Indicators N	Examples of indicators
Communities	39	"government and public services efficiency"; "social fragmentation"; "critical services spare capacity"
Health	55	"life expectancy"; "healthcare access"; "population growth"
Health & Economy	28	"workplace safety"; "poverty rate"; "health systems capacity"
Economy	101	"unemployment"; "productivity"; "gross domestic product"
Environment & Economy	31	"costs of environmental degradation"; "carbon pricing score"; "value of agricultural land and crop production"
Environment	41	"CO2 emissions"; "number of heatwaves"; "forest fires"
Environment& Health	28	"health impact of air pollution"; "antimicrobial resistance surveillance"; "access to safe water'

3.2. Design workshop

The workshop was attended by eighteen researchers, working in universities in eleven countries (Sweden, Germany, India, Singapore, United States, England, Scotland, Croatia, Denmark, Italy, and the Netherlands), ranging in seniority from research assistant to full professor roles, and belonging to a variety of research communities, including design, engineering, and health disciplines. The workshop resulted in four causal loop diagrams, respectively mapping the expected effects of extreme heatwaves, antibiotic resistance, and ageing populations (x2) across indicators categorized by domains of the Design Framework for System-of-Systems Resilience. In addition, the workshop resulted in a set of brainstormed ideas for resilience-promoting interventions, ranging from policymaking (e.g. targeted national immigration strategies to support resilience to ageing populations as a systemic stressor), to changes in clinical practice (e.g. stricter drug prescription protocols to support resilience to antibiotic resistance as a systemic stressor), to education and awareness initiatives (e.g. information campaigns to support resilience to extreme heatwaves as a systemic stressor). Two digitised examples of generated causal loop diagrams, completed with ideas for resilience-supporting interventions, are provided in Figure 2.

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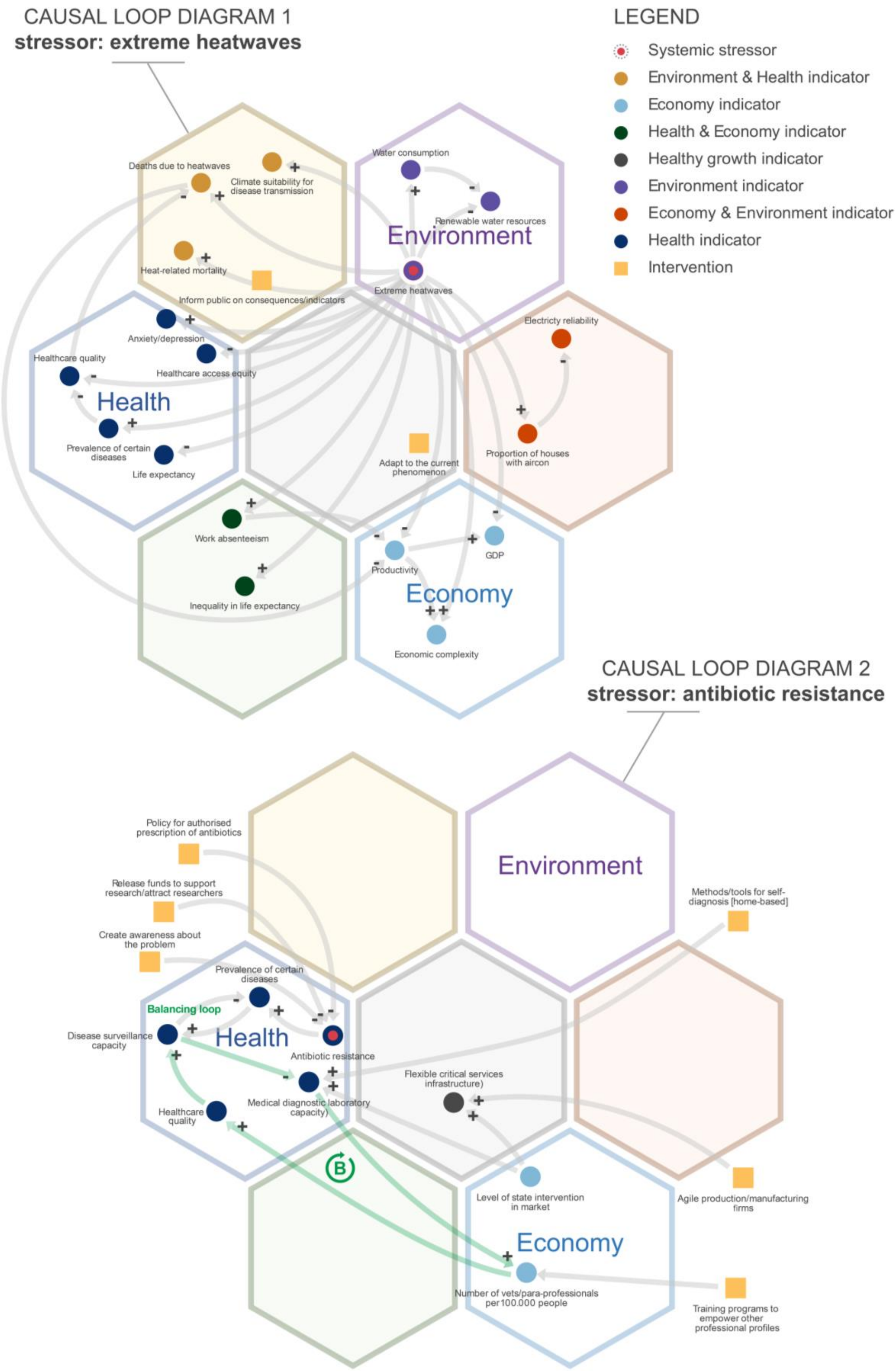

Figure 2. Examples of a causal loop diagram produced in the workshop (digitised)

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In addition, the workshop resulted in a set of reflections on the relations between health, economic and environmental indicators and on the complexity of defining, promoting and assessing SoS resilience, briefly summarised in the following section.

4. Reflections

4.1. System-of-Systems resilience across health, environment and economy

General observations on SoS resilience across the health, environmental and economic domains can be derived from an analysis of the causal loop diagrams produced in the workshop. In particular, we note that common mechanisms of influence can be recognized between groups of indicators pertaining to different domains, as forecasted in Dreesbeimdiek et al. (2022). Notably, demographic factors appeared in more than one map as pathways for causal connections between health and economic indicators, e.g. between 1) deaths due to heatwaves and 2) productivity, as shown in the first map in Figure 2. Indeed, the effects of population health on the economic performance of communities constitute a vast field of study in health economics modelling (Bhargava et al., 2001), which generally confirms the relations between population-level health outcomes and economic growth (e.g. Bloom & Canning, 2009; Alsan et al., 2007). Demographic factors can, also, constitute a common pathway for causal connections between health and environmental indicators (Cole & Neumayer, 2004), e.g. in the case of population growth determining an increase in water consumption.

Similar observations can be made for a number of mapped causal connection from economic to health indicators (e.g. between unemployment and life expectancy), which reflect common pathways of socioeconomic influences on the health of populations. These pathways of influence are examined in a wealth of public health research, which generally confirms the effects of specific economic factors on population health outcomes (Subramanian, 2002) - although empirical evidence on the aggregate effect of economic growth on population health is not yet conclusive (Lange & Vollmer, 2017).

Finally, common pathways of environmental influences on health are observed in terms of ecological and ecosystem-related health risks, including through air pollution (Brunekreef & Holgate, 2002), environmental contaminants (Pereira et al., 2015) or climate change (Haines & Patz, 2004).

Overall, the collected examples of common pathways of influence across domains paint a rich picture of the complex network of SoS interrelations within the Framework; and suggest a need to consider not only direct relations between individual indicators, but also aggregate mechanisms of influence between clusters of indicators when assessing and promoting resilience.

4.2. Using the framework and its indicators to collectively explore aspects of System-of-Systems resilience

Through the workshop exercise, it was noticed that the provided Framework and indicators seemed to contribute eliciting and structuring rich discussions among participants on the multiple factors contributing to SoS resilience and on their complex relations. Collectively, participants discussed on expected measurable phenomena at the interface between health, environment and economy, building overviews which then guided the ideation and exploration of contextual resilience-promoting interventions.

At the same time, the collective mapping process presented difficulties and ambiguities for participants. For instance, several attendees suggested the need for a clear upfront definition of systems (or sub-systems) boundaries, also in terms of time and space, before the indicators from the set could be used.

Indeed, it must be noted that some of the indicators in the set are mostly suitable for national-level measuring (e.g. "gross domestic product" or GDP), while others are mostly suitable for local-level measuring (e.g. "neighbourhood noise"). Similarly, some of the indicators are mostly suitable for describing long-term changes (e.g. "life expectancy", "housing affordability"), while others are mostly suitable for describing medium or short-term changes (e.g. "critical services spare capacity"). This suggests an upfront definition of precise system boundaries to be a desirable preliminary step within continuous resilience processes, and to facilitate the selection of appropriate contextual indicators down the line.

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4.3. Towards a composite Index of System-of-Systems Resilience

Some of the reflections emerged from the rapid review and workshop exercise could contribute informing future research efforts aimed at the development of a composite Index of System-of-Systems Resilience. One, in particular, concerned the issue of 'currencies' across the three domains of health, economy and environment. While mapping expected effects across the domains and their interconnections, participants reported noticing differences in underlying value structures across the Framework. Specifically, while all indicators within the economic domain can ultimately be translated into financial value, different health indicators point towards slightly different nuances of the 'health' construct (e.g. life expectancy vs healthy life expectancy), whereas environmental indicators cannot be collapsed into any single form of overall ecological value (as these rather describe a wide variety of environmentally-relevant phenomena, see e.g. water consumption, CO2 emissions, stability of marine biodiversity). We forecast that this distinction will need to be taken into careful consideration during the development of an Index of System-of-Systems Resilience; possibly, ad-hoc strategies will be required for reconciling the different characteristics of the set of indicators in the Framework domains, such as the establishment of (dynamic) weight factors.

In addition, we propose that the set of resilience-fostering interventions produced during the workshop, ranging from ranging from policymaking, to changes in clinical practice, to education and awareness initiatives could be used as a repository of potential decision-making scenarios supported by the Index of System-of-Systems Resilience, providing the opportunity for testing and iterating on future Index prototypes.

5. Conclusions and next steps

In this contribution, we focused on the collective exploration of the concept of SoS resilience and of a set of relevant indicators, through a rapid review and a design workshop involving an international group of design researchers. On the basis of these activities, reflections can be offered that are potentially relevant to the conceptualisation of the three domains and their relations, to the notion of SoS resilience as a continuous (re)design process, and to the development of a future Index of System-of-Systems Resilience.

On the basis of these preliminary explorations, we highlight a number of research opportunities:

- In terms of Framework principles, we point at the need to consider not only direct relations between individual indicators but also aggregate mechanisms of influence between clusters of indicators within the Index, possibly requiring the introduction of sub-system and new levels of hierarchy within the current Framework.
- In terms of SoS resilience as a continuous (re)design process, we observe a seemingly positive effect of the use of the Framework and related indicators as an initial way to guide and structure collective conversations in this complex domain; however, we point at the need for a clear definition of the considered systems boundaries before any collective mapping of expected effects across the Framework.
- In terms of future development of a composite Index of System-of-Systems Resilience, we note:
  - the potential need for ad-hoc strategies to reconcile the different characteristics of the set of indicators in the Framework domains, e.g. the establishment of (dynamic) weight factors;
  - the opportunity to consider a broad range of use cases as hypothetical decision-making scenarios for the testing of future Index prototypes.

Overall, we hope that the preliminary explorations presented in this contribution provide insights towards the goal of reaching a better understanding of the complexities involved with SoS resilience, and towards the complex but crucial challenge of meaningfully supporting this process using existing indicators. In this sense, we position our work within the growing body of literature at the intersection of systems design, systems engineering, public health, and environmental and economic sciences, a convergence of perspectives that appears to be crucial for a broad variety of pressing societal challenges.

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