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Designing for systems-of-systems resilience: from the individual to the planet

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Abstract

This contribution builds on the Design Framework for System-of-Systems Resilience to investigate the potential of a new systems resilience measuring approach inspired by the Frailty Index. To explore this research direction, we provide a brief overview of the evolution of the notion of resilience, offer a characterisation of systems resilience as an opposite of systems frailty, and perform a rapid review to identify and inspect existing multi-domain indices of community resilience. Finally, we suggest piloting the proposed system-of-systems resilience index in the Fens in the United Kingdom.

Keywords: resilience, complex systems, self-optimising systems

1. Introduction

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

The current global context is threatened by a range of crises and complex challenges, including pandemics, 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, growing research interest is dedicated to the concept of System-of-Systems (SoS) resilience, and to new resilience frameworks considering broad sets of systemic stressors and indicators (Cheng et al., 2022). Interest in systems resilience can also be observed in design literature: Taysom & Crilly (2017, 2018), in particular, offer a nuanced conceptualisation of resilience in socio-technical systems.

Within this broad research domain, Dreesbeimdiek et al. (2022) introduced the Design Framework for System-of-Systems Resilience. Building on complex adaptive systems theory (see e.g. Buckley, 2017), they provide the following characterisation 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 interfacing between health, economic and environmental systems, arguing that systemic disruptors ripple through these linked domains when producing their effects on communities (Figure 1).

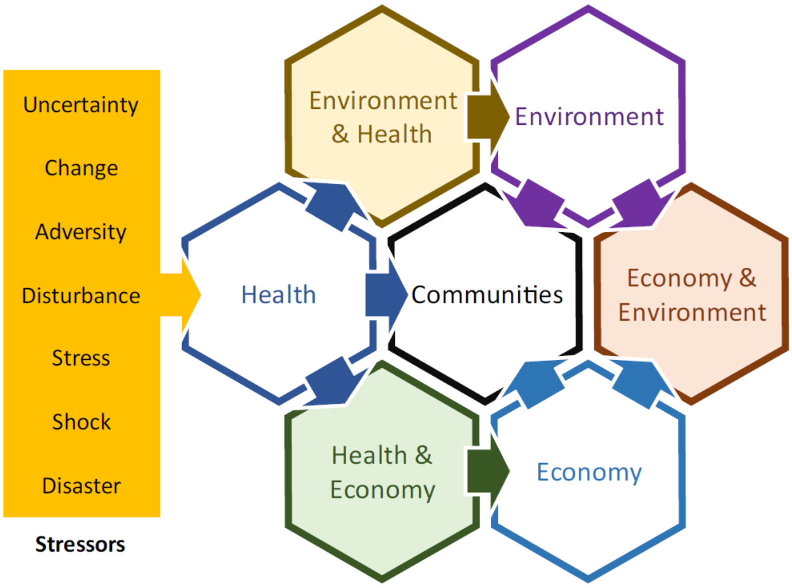

Figure 1. Stressors with exemplary rippling paths through the health, environment and economy sub-systems (from Dreesbeimdiek et al. 2022)

In the reported definition, the authors propose a notion of SoS resilience as a continuous *process*, rather than a system *property* or "intrinsic ability" (as defined e.g. in Hollnagel et al., 2006). They argue that, since complex adaptive systems are constantly evolving, efforts to improve community resilience (such as strategic planning or risk management) should not only be conceptualized as responses to specific disruptions; rather, these efforts should follow a continuous process, articulated across different resilience mechanisms (anticipating, accommodating, responding, learning and transforming). Within this continuous process, they characterise resilience-related decision-making as a *design* question, and advocate for the need to design resilience into contemporary systems.

1.2. Informing SoS resilience processes through a new composite index

To support continuous resilience processes, Dreesbeimdiek et al. (2022) propose the development of new indicators capable of capturing community resilience across health, economic, environmental systems and their interfaces. In this sense, an ambitious research objective is represented by the development of a new 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 community resilience processes. Ideally, the Index should fulfil a double purpose:

- A descriptive purpose, as it should provide an estimation of SoS resilience for a given community 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.
- A prescriptive purpose, as it should support resilience-promoting processes such as policymaking, strategic planning, risk management, or emergency preparedness and response. Ideally, the Index should 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 also develop to be applied for predictive resilience capabilities.

Pannunzio et al. (2024) worked towards the development of an index of System-of-Systems Resilience through collecting a set of relevant existing indicators and collaboratively exploring causal links among them. In this contribution, we add to this effort by elaborating on the conceptual links between SoS resilience and frailty, and by exploring a potential approach to the development of the index of System-of-Systems Resilience based on the Frailty Index (Searle et al., 2008).

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The contribution is structured as follows. First, we provide a brief overview of the evolution of the notion of resilience, and examine its nuances by contrasting it to a set of conceptual opposites (brittleness, vulnerability, and frailty). We then offer a characterisation of resilience as an opposite of frailty, finding sources of inspiration for our composite index in frailty measuring approaches. Furthermore, we perform a rapid review to identify existing, multi-domain indices of community resilience, which we compare to a potential, alternative measuring approach based on the Frailty Index. Finally, we suggest piloting a first version of the proposed measuring approach in the Cambridgeshire Fens in the United Kingdom.

1.3. Resilience: evolution of a concept

The concept of resilience has intertwined roots across many disciplines, and has evolved over the years into a multifaceted construct with different nuances and application domains (see e.g. McAslan, A., 2010).
Early appearances of the concept in scientific literature date back to the 19th century in the realm of material science and engineering, in which resilience was defined as a material's ability to withstand severe conditions. The construct of a "modulus of resilience", first originated through the pioneering contributions of Tredgold (1818), remains used to this day in engineering practices. More than a century later, the notion of resilience started being applied to the field of psychology, when groundbreaking studies by Garmezy (1971) paved the way for assessing how well individuals, particularly children, cope with traumatic situations.
A wider popularization of the concept was, however, only achieved when Holling (1973) introduced the notion of ecological resilience, extending the resilience discourse to the capacity of entire ecosystems to persist in the face of changes. His work emphasized resilience as the ability of an ecosystem to keep *existing* despite disturbances, distinguishing it from the ability to return to a predefined equilibrium state, which he identified as *stability*. The notion of resilience as 'keeping on existing' was later refined to specifically cover systems functionality: first by Klein et al. (2003), who write of preserving "actual and potential functions" under constantly changing circumstances, and later by Walker & Salt (2005), who describe resilience as the capacity of a system to "absorb disturbance and still retain its basic function and structure". Since then, the concept of resilience has since been applied to communities (e.g. in Berkes & Ross, 2013), nations (e.g. in Omand, 2005), and even the entire planet (e.g. in Priyadarshini & Bundela, 2023), embracing an increasing number of definitions, disciplines, scales, and types of interconnected systems.

1.4. Defining resilience by its opposites

The concept of resilience finds its richness not only in its many definitions, but also in its contrasts with opposing ideas. Hollnagel et al. (2013), for instance, indicates *brittleness* (intended as the "rapid fall off or collapse of performance") as the opposite of resilience in the context of health systems engineering. In these terms, systems resilience is intended in terms of "graceful extensibility", or the ability of a system to extend its capacity to adapt when unforeseen events challenge its boundaries (Woods, 2015). Brittle systems are, in this sense, the ones that are least likely to gracefully extend, but rather break and rapidly collapse in performance.
Other scholars intend resilience as the opposite of *vulnerability*. In ecology and in the social sciences, for instance, vulnerability is often defined in terms of susceptibility of groups or individuals to harm, e.g. from social or environmental change (McCarthy et al., 2001; Adger, 2006). In medical ethics, vulnerability is described as a significant probability of incurring in harm while substantially lacking the ability or means to protect oneself (Schroeder & Gefenas, 2009). Vulnerable systems are, in this sense, identified as the ones that are more exposed to harm, and as such at increased risk of damage and disruption.
In the medical domain, scholars such as Whitson et al. (2018) use the concept of *frailty* as a health-relevant dimension contrasted to physical resilience. Frailty, usually associated with aging, can be measured in relation to the accumulation of health deficits in the individual, for instance in terms of symptoms, diseases, disabilities, or other diagnosed abnormalities. Together, these deficits contribute to

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a reduction of adaptive capacities and correlate to negative outcomes such as mortality (Mousa et al., 2018).
Frail individuals are in this sense the ones who present several accumulated health deficits, and as such face the double challenge of being more at risk of harm while less likely to adapt to changes. From this perspective, the concept of frailty may be seen as a combination of:

- inability to adapt and extend described by *brittleness*, and;
- increased exposure to harm described by *vulnerability*.

In these terms, frailty can represent a particularly useful conceptual opposite of resilience, which thus becomes a descriptor of systems that enjoy both low risk of harm and good adaptive capacities.

1.5. The Frailty Index: inspiration for a measuring approach

The concept of frailty can also provide inspiration in terms of approaches to resilience measuring. Mitnitsky et al. (2007), particularly, developed a Frailty Index in which health status was defined by a deficit count, using a combination of 33 health-related variables. For each time interval, the chance of accumulating deficits increased linearly with the number of deficits. Later, Searle et al. (2008) presented and validated a procedure to create a Frailty Index based on any sufficiently large set of deficits available for a given individual. More specifically, they express Frailty as a ratio of recorded deficits over the total of considered deficits. For instance, if out of 40 considered deficits, 10 were present in a given individual, the resulting Frailty Index would be 0.25. Using this simple and flexible approach, the authors found the Frailty Index to be a consistent instrument even when not considering the same deficits or the same number of deficits. Most importantly, the authors reported strong correlations between the Frailty Index and risk of death, institutionalization, and worsening health status, especially when including at least 30 variables (Rockwood & Mitnitski, 2007). From these findings, the authors draw the suggestion that "frailty is a real phenomenon, which is a property of a biologically complex system", and invite other researchers to operate more widespread evaluations of frailty, including through the use of datasets "that might not have set out to measure frailty per se".

1.6. Frailty across health, economy and environment

Drawing inspiration from the Frailty Index, which considers the accumulation of frailties to assess an individual's resilience in terms of physical health, we hypothesise the application of a similar approach in evaluating SoS resilience across the health, environment and economic domains.
System-level frailties in community health, for instance, could manifest themselves in terms of structural funding issues, inefficient allocations or resources, care fragmentation, or even loss of trust of the patient population (see e.g. Kruk et al., 2017 for an overview of cases). Just as in individuals, frailties in health-relevant systems could accumulate and compound. An example is provided by Armocida et al. (2020), who show how the violent shock received by the Italian national healthcare service and the affected patient population during the COVID-19 pandemic was exacerbated by previous years of systemic fragmentation, defunding, privatisation, and deprivation of human and technical resources.
Similarly, environmental systems frailties could manifest themselves in terms of lack of biodiversity, uncertain or unpredictable food chains, or extreme weather conditions. An example is the Antarctic, which was identified in the 90's as a fragile ecosystem because of its vulnerability to environmental degradation due to human activities (Joyner, 1994).
In economic systems, frailty could manifest itself in terms of regions' low diversification in economic structures, or in terms of structural deficiencies in the availability and valorisation of human and knowledge capital (see e.g. Simmie & Martin, 2010). On a global scale, economic fragility has been described as a result of successive financial crises, worsening international coordination and increasing government debt (Fidler & Nicoll, 2010).
Importantly, frailty may not only be situated within the three domains, but also at their interfaces. Countries whose economies are predominantly reliant on agriculture, for instance, are currently more exposed to negative economic consequences of climate change (Molua & Lambi, 2007).

Overall, the notion of system resilience as an opposite to system frailty, defined on the basis of accumulated system deficits, appears to be potentially applicable to the diverse domains covered in the Design Framework of Systems-of-Systems Resilience.

To this end, we note that the application of a health-relevant construct such as frailty to large-scale complex systems appears to be in line with the principles underpinning the nascent field of planetary health. This field emerged in response to the increasing recognition of the intricate connections between human health and the health of broader ecosystems (Horton et al., 2014), and aims at transcending individual-focused models of care and acknowledging the dependence of human welfare on natural ecosystems. An example in this sense is again offered by the COVID-19 pandemic, which has been linked to biodiversity loss and ecosystem damage (Everard et al., 2020). The paradigm shift implied in the planetary health perspective recognizes that the health of populations is inseparable from the health of the planet, and underscores the urgent need for a more integrative approach to collective health promotion and preservation. Next, we will further explore the potential of a Frailty Index-inspired measure of Systems-of-Systems Resilience through a comparison with existing multidomain community resilience measures, identified through a rapid literature review.

2. Methods

2.1. Rapid review

To identify multi-domain community resilience indices described in academic literature, we built search queries using sets of different keywords covering the concepts of 1) community resilience; 2) measuring; and 3) health, economy or environment. We run the resulting search queries in Scopus and Web of Science, obtaining respectively 383 and 628 results. After importing the contributions in Rayyan, an online tool for literature reviews, we excluded 251 duplicates. We then screened the titles and abstracts of the collected sources to exclude a total of 716 irrelevant contributions, including 357 results not covering any specific community resilience measure (e.g. presenting exclusively qualitative results), 135 results covering measures focused on sub-groups rather than whole populations (e.g. specifically measuring the resilience of healthcare workers), 125 results covering community resilience measures to specific stressors only (e.g. specifically measuring the resilience of communities to floods), 52 contributions focusing on the resilience of non-human communities (e.g. flora or fauna), 32 contributions covering mono-dimensional measures of resilience (e.g. measuring economic resilience only), 12 contributions covering measures of individual rather than community resilience, and 2 contributions in languages other than English. We then analysed the full text of the remaining 44 included contributions to extract information on multi-domain community resilience indices names, covered resilience domains, intended data source, and aggregation methods (when specified).

3. Results

Out of the 44 included contributions, we identified 13 unique multi-domain community resilience indices. These follow a conceptualization of community resilience influenced by a broad set of disciplines, including disaster preparedness, sustainability, social sciences, and infrastructure engineering. Only one (ARC-D) explicitly integrated health, environmental and economic indicators. Among the components of the Design Framework for Systems-of-Systems Resilience, health seems to be least covered in existing multi-domain indices; this is, partly, because population health measures are sometimes identified as community resilience *outcomes* rather than resilience *capacities*, and are as such excluded from composite indices (see e.g. Sherrieb et al., 2010). Finally, the identified community resilience indices rely on different statistical approaches to aggregate indicators into a composite measure of overall community resilience, including weighted averaging and z-score standardization.

Table 1. shows an overview of the results of the rapid review.

Table 1. Multi-domain community resilience indices

Index name	Resilience domains	Data source	Aggregation method	Main reference
Community Resilience Measure	Electric power network, water supply network, education, healthcare, business	Simulation model	Weighted geometric average	Aghababaei & Koliou (2023)
Conjoint Community Resiliency Assessment Measure (CCRAM)	Leadership, collective efficacy, place attachment, emergency preparedness, social trust	Survey	Average of equally weighted survey items scores	Leykin et al. (2013)
Resilience Framework for Structural Change	Resource access, diversification, collaboration, planning and communication	Survey	n/s	Bec et al. (2019)
Community Resilience to Natural Hazards and Disasters	Social, economic, infrastructural, institutional, community, and environmental	Secondary data	Summation of equally weighted average subcomponent scores	Burton (2015)
Baseline Resilience Indicator for Communities (BRIC)	Social, economic, infrastructural, institutional, community capital	Secondary data	Equal weightings of variables and sub-domains	Cutter et al. (2010)
Analysis of Resilience of Communities to Disasters (ARC-D)	Education, economic, environment, political/governance, health, infrastructure, social and cultural, disaster risk management	Survey	n/s	Clark-Ginsberg et al. (2020)
PEOPLES framework	Population, environment, organized government services, physical infrastructure, lifestyle, economic, social capital	Secondary data	Two possible methods: 1) Indicators weighting and serviceability function; 2) Aggregation through fuzzy rules	Renschler et al. (2011)
Communities Advancing Resilience Toolkit (CART)	Connection and caring, resources, transformative potential, disaster management, information and communication	Survey	n/s	Pfefferbaum et al. (2013)
Community Resilience	Visionary leadership, social network, social support, trust, place attachment and collective efficacy	Survey	n/s	Haas et al. (2021)
Reflective Thrive-Oriented Community Resilience Scale	Emergencies, climate change, flooding, earthquake/tsunami, deal with problems, economy bounce back	Survey	n/s	Lindberg & Swearingen (2020)
Community Resilience Index	Economic development, social capital	Secondary data	Z-score standardization, average of both concepts	Sherrieb et al. (2010)
FEMA's Community Resilience Indicator	n/a	Secondary data	Z-score standardization, average of scores	Tan (2021)
Resilience Community Index	Social, economic, infrastructural, environmental, institutional	n/a	Weighting, consistency and correlation evaluation	Toseroni et al. (2016)

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4. Discussion

4.1. Towards a Frailty Index approach to measuring System-of-Systems Resilience

The identified community resilience indices represent useful, carefully curated instruments, covering a variety of use cases and application domains. Yet, none follows an approach similar to the one adopted in the Frailty Index as outlined in 1.5. Particularly, we note that no existing community resilience index is built from a perspective of compounding deficits; and that none is (directly) applicable to diverse ranges of datasets, different in content and in number of indicators. In contrast, a composite index of System-of-Systems Resilience including Frailty Index principles could be derived from a wide variety of publicly available data, and as such be easily applicable to different contexts, datasets, and time dimensions. Such an Index could even be applied to domains other than health, economy and environment; for instance, additional domains such as education could be added to the framework.

A major challenge, however, is identified in the validation of such an index. While the Frailty Index can be validated by observing its consistent association with mortality, no comparable metric exists for overall SoS resilience. Yet, viable alternatives could be found in each of the domains of the Design Framework for System-of-Systems Resilience; particularly, gross domestic product (GDP) could be used as an overall dimension of performance in the economic domain and health-adjusted life years (HALYs) could be used as an overall dimension of performance in the health domain. As already observed in Pannunzio et al. (2024), it is harder to find a meaningful overall dimension of environmental performance; however, CO_2 levels or biodiversity measures could possibly be employed for this purpose.

4.2. Proposed application case: the Fens, UK

The Fens, in the East of England, were formerly a large wetland that has been extensively drained for agriculture. Its value for arable agricultural use is a consequences of its fertile, peat-rich soil. Currently, the area supports around a third of England's fresh vegetable and salad production, contributing about £3bn annually to the UK economy and representing an important sources of employment (NFU East Anglia, 2019). However, a range of interconnected issues now pose serious challenges to the Fens in terms of environment, economy, and health.

First, peat draining causes land subsidence, damaging roads and other infrastructure and creating a flood risk as the farmland is now up to 4m below the level of the river system (Great Fen, 2023). Paradoxically, the Fens also face water shortages, due to low rainfall, increased water demand from housing development, and changing climate patterns, increasing the risk of agricultural drought. Furthermore, as the exposed peat oxidises, it reduces the soil carbon stock, producing one of the largest sources of CO2 emissions associated with land use in lowland Britain (BEIS, 2022). Centuries of drainage and farming have also deeply impacted biodiversity in the Fens, marginalizing undrained wetland habitat to four nature reserves covering less than 1% of the original area (Natural Cambridgeshire, 2021). Finally, Fenland communities face economic and public health challenges, as they experience poorer outcomes than the rest of Cambridgeshire on a number of health and wellbeing factors (Fenland District Council, 2018), on social mobility, and on other educational and wealth factors.

In these terms, the Fens can be seen as a SoS affected by accumulated and interconnected sources of frailty, including hydrological, environmental, socioeconomic, and public health deficits.

Therefore, the search of strategies and interventions for the safeguarding of the Fens should include an attention to minimising overall SoS frailty in the pursuit of increased community resilience. Trade-offs across domains would need to be considered, for instance between environmentally desirable options and their possible negative impact on local economies. In this context, a preliminary composite Index of System-of-Systems Resilience could be built by using publicly available indicators, including those collected by Pannunzio et al. (2024), and applying methodological principles underpinning the construction of the Frailty Index. The resulting composite Index and its variation over time could then be explored in its statistical properties and in its capacity to operationalise the Design Framework for System-of-Systems Resilience (Dreesbeimdiek et al., 2022) for the Fens context. Of course, as pointed out in Pannunzio et al. (2024), even a well-working Index would need to be a part of a broader resilience

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process in order to bring about the desired results; in the specific case of the Fens, stakeholders engagement and involvement would be particularly crucial, considering the complexity of the local organisational landscape (Pannunzio et al., 2023; Lloyd et al., 2023).

5. Conclusion

In this contribution, we explored methodological opportunities related to the construction of a new composite index based on the Design Framework for System-of-Systems Resilience (Dreesbeimdiek et al., 2022). To do so, we provided a brief overview of the evolution of the concept of resilience, we elaborated on a characterisation of SoS resilience as an opposite of systems-of-systems frailty, and found sources of inspiration in frailty measuring approaches. We then performed a rapid literature review to identify existing measuring approaches to community resilience, and compared them to a potential, Frailty Index-inspired resilience measuring approach. Finally, we proposed the preliminary application of a first version of such Index in the Cambridgeshire Fens in the United Kingdom.

Overall, our contribution constitutes an early attempt to operationalise and quantify the Design Framework for System-of-Systems Resilience, as presented in Dreesbeimdiek et al. (2022) and detailed in Pannunzio et al. (2024). While a considerable amount of further research is necessary in this sense, we hope to have offered a few additional, exploratory insights relevant to this goal. With this, we hope to have inspired systems designers and engineers interested in novel approaches to measuring SoS resilience, an area of research of particular relevance in the current global context.

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