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Towards a Contemporary Design Framework for Systems-of-Systems Resilience

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Abstract

In an increasingly interconnected world, changes of uncertain nature and impact affect the functioning of human societies that depend on health, ecological, and economic systems. The proposed framework for systems-of-systems resilience explains ways of accommodating and responding to these challenges while encompassing the interfaces of the health, environment, and economy domains and their effect on communities. Resilience is defined as a continuous process and we distinguish between four system properties, five resilience capacities, and a variety of system activities.

Keywords: resilience, systems engineering (SE), complex systems, socio-technical systems, characteristics and properties

1. Introduction

In the increasingly interconnected and interdependent world, changes with varied characteristics and impacts affect the functioning of human societies from health, economic, and ecological perspectives. To explain ways of accommodating and responding to these challenges to minimise negative impacts, the ***resilience*** concept has been gaining interest which was particularly driven by major crises such as the financial crisis 2007/08 or the COVID-19 pandemic. However, the term had been used in various areas before Holling (1973) used it to describe dynamic ecological system equilibria (Alexander, 2013). Consequently, questions of conceptual foundation and terminological clarity have arisen.

From 1973 onwards, resilience was adopted in various disciplines focused on complex adaptive systems (CAS), such as engineering and sustainability science. CAS theory attempts to "explain how complex structures and patterns of interaction can arise from disorder through simple but powerful rules that guide change" (Folke, 2006). Due to multi-disciplinary conceptual developments, varying definitions have emerged, which primarily differ in the process of reaching positive outcomes when facing adverse events. In **ecological resilience**, systems respond to challenges through adaptation allowing for many possible desirable, emerging states (Zhong et al., 2014). In **resilience engineering**, systems absorb the shock and recover quickly to return to the original functional status (Gunderson, 2000).

In recent decades, transdisciplinary and multi-level studies have highlighted that the dynamic aspect of resilience arises from the interaction across multiple levels of functioning, i.e., people, processes and organisational structures (Boon et al., 2012; Wiig et al., 2020). The expanding use of multi-level systems thinking for the resilience concept motivated the authors to develop a systems-of-systems framework, integrating resilience views from various disciplines for applicability across a variety of systems.

1.1. Focus on economic performance negatively impacts health & environment

Similar to resilience, the concept of sustainability or sustainable development has suffered from a lack of terminological and conceptual clarity (Purvis et al., 2019). Early sustainability efforts (Meadows et al., 1972; Schumacher, 1973) questioned economic growth, since "the modern growth-based economy was unsustainable on a finite planet" (Purvis et al., 2019, p. 683). Nevertheless, five decades later, **economic growth** is still regarded as a major **indicator to measure countries' societal development**, as decision-makers and academics alike often use Gross Domestic Product (GDP) to compare countries' development state. Although a rising GDP per capita can help to raise living standards, it does not account for social and environmental conditions as well the physical and mental health of communities. For example, the two current major crisis, COVID-19 and climate change, have many underlying causes a significant proportion of which can be explained through the focus on economic growth in many countries. For example, "COVID-19 death rates are 10 times higher in countries where more than half of the adult population is classified as overweight" (Wise, 2021). Due to the prevalence of **higher obesity in countries with higher GPD per capita** (WHO, 2018), many rich countries experienced high levels of COVID-19 deaths, which "prioritised public health across a range of measures, including population weight" (Wise, 2021) thereby managing to minimise the COVID-19 impacts. In addition, a **higher GDP per capita** generally indicates a **higher rate of per capita CO2 emissions** (Andrew and Peters, 2021), with most high-income countries (e.g. US, Australia) having very low Climate Change Performance (CCP) indices (Burck et al., 2020). These examples highlight the weaknesses of an economic focus and emphasise the importance of a balanced set of policies accounting for social, environmental, and economic goals as well as public health factors.

In a changing global environment, sustainability and resilience are needed at all system levels including communities and economic enterprises. This work builds on the notion that sustainability and resilience are distinct conceptual paradigms and should not be fused into new conceptual domain. Rather, a careful alignment of existing ideas for use in practice is desirable (Anderies et al., 2013). Both concepts include the need to make choices in decision-making processes. While the sustainability concept guides action through normative choices, resilience as a system-level concept is more difficult to use in practice (Anderies et al., 2013). Linear conceptualisations – viewing these concepts as end goals or states to be reached – do not account for the required continuous adjustments in CAS, so that recent studies utilising a systems approach regard them as concurrent processes which are continuously influenced and adapted (Lennox et al., 2018; Nelson et al., 2020). In this conceptual paper, we propose an integrative resilience framework which moves beyond simplistic linear models towards adaptive and collaborative strategies to enable social and economic institutions to effectively deal with expected and unexpected changes.

1.2. The need for a systems approach

The interconnected global economic system - combined with high rates of resource utilisation and the degradation of natural capital - is eroding the resilience of human societies across the globe - involving economies, societies and the environment to the point where, as illustrated by COVID-19, these trends have become a severe risk to the wellbeing of people, the economy and indeed the very survival of humanity on earth. In such an environment with challenges, threats and uncertainties of unknown types and impact, a systems approach to resilience offers ways of conceptualising complex systems characterised by alternative states and non-linear transitions. General Systems Theory, formulated by Ludwig von Bertalanffy, provides a common taxonomy of systems across disciplines which can be expressed in universal terms. Systems are described as "the combination of interacting elements organised to achieve one or more stated goals" conceiving the world as a system of interconnected parts which exhibit behaviour not attributable to the sum of its individual components (Sillitto et al., 2017). One type of system is a system of systems (SoS) which is comprised of multiple systems independently developed but working together for a common purpose. With SoS evolving into larger networks, the increasing number of sub-systems, owners, and stakeholders lead to higher uncertainty and complexity (Gorod et al., 2008). Notably, these SoS constituents can be of very different nature or purpose as reflected in the wide range of systems that have been described by scholars, e.g. organisational (Jackson et al., 2021), social (Palmer et al., 2021), engineered (Jackson et al., 2021), governance (Wang and Mansouri, 2021), or ecological (Bousquet et al., 2021). To describe and explain the properties and

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mechanisms required in resilient systems facing the complexities of the real world, many previous studies have adopted the CAS theory (Coetzee et al., 2016; Nelson et al., 2020). Complex systems are systems that can produce unexpected dynamics because of nonlinear interactions among components. Compared to these complex-only systems, the concept of "adaptability" explicitly focuses on the capacity of systems to change in response to self-organisation, emergence, co-evolution, and path dependency. A consequence of such systems behaviour can be change propagation, which is the "process by which a change to one part or element of an existing system configuration or design results in one or more additional changes to the system, when those changes would not have otherwise been required" (Clarkson et al., 2004; Eckert et al., 2004). Hence, the interfaces between constituent systems are critical areas of concern in an SoS environment (Watson et al., 2021).

This paper links resilience thinking with a systems approach building on three key assumptions:

a) Humans are embedded in systems that can be individually labelled but have non-negligible links through which change can propagate. These systems are made up of social (e.g. community building, health and wellbeing, economic viability), ecological (e.g. nutrient cycling, biodiversity), and technical components and processes which exhibit CAS characteristics.
b) Systems do not exist and operate for their own sake. They underlie various - sometimes conflicting - goals. Various attempts have been made to unify those goals as exemplified by concepts such as "people-profit-planet" or "Environmental, Social and Governance" (ESG). Ultimately, systems should continuously provide humans with means for their long-term survival. As a result, SoS are typically never fully complete and rather behave evolutionary.
c) Resilience is a secondary system property, as efforts on system-level resilience may paradoxically work against the removal of undesirable conditions such as poverty (Olsson et al., 2015). As such, poorly performing systems can be highly resilient and resistant against change. Our resilience perspective aims to describe how systems cope with change and disturbance. As Wiig et al. (2020) emphasise: "The overall purpose and goal of a system is, therefore, different from how resilient that system is." Hence, the primary system property (purpose, e.g. equity, liveability and well-being) is separate from its resilience.

With the presented framework we do not aim to identify the link or least common denominator between research areas or impose yet another resilience model to address sustainable development. We rather provide an integrative framework that allows for the choice of stressors, metrics and methods to be tailored to a given perspective (i.e. an individual organisation, a geographic region, a global policy) while putting emphasis on the important links and aspects between systems.

2. A contemporary systems framework for resilience

The proposed systems-of-systems framework assumes that resilience should be understood in terms of domains that are composed of complex adaptive systems. As visible in Figure 1, the system of interest can be characterised by the interplay between the main domains health, economic and environmental systems, and their effect on communities.

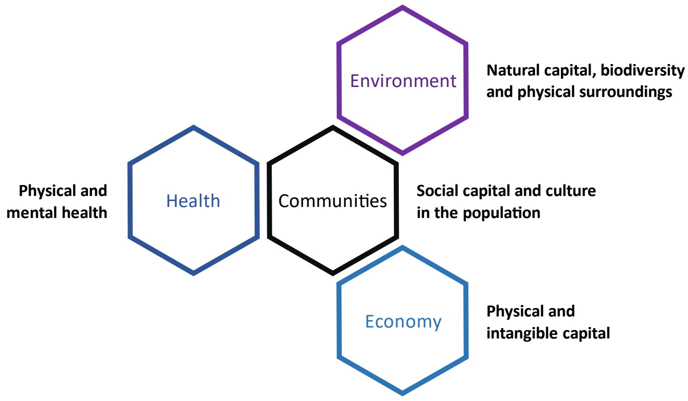

Figure 1. Systems-of-systems framework to illustrate the interplay among health, economic and environmental systems on communities

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2.1. Main domains: Economy, Health, Environment, Communities

The **economic domain** traditionally spans production and financing but other aspects such as work, knowledge, and welfare are gaining importance (Lamberton, 2005). While traditional perspectives on the economy tend to be heavily skewed towards short-term interests, we expand this view and define it as *encompassing tangible and intangible capital, which incorporates production and consumption, social considerations, as well as global economic governance and regulation*.

The **health domain** *encompasses the physical and mental health of the population as individuals and as a collective*. In that sense, health shall not be understood as the non-presence of diseases but rather as part of the dynamics of social organisation, lifestyles, and patterns of consumption behaviour (Kjærgård et al., 2014). Therefore, health should be understood, rather, socio-ecologically with focusing on strength and assets and the role of culture to health (Hancock, 1999).

In systems frameworks for sustainability, the **environmental domain** is often too narrowly defined as outside of human practices, ignoring aspects such as the ecology of the human body (James and Magee, 2017). Hence, we describe the environment as *encompassing natural capital, biodiversity and physical surroundings* and as an outcome of natural processes and human impact whilst appreciating that the environmental boundaries can vary for every collective that may be in focus of a systems analysis.

The systems we inherit today are highly developed with globalisation and digitalisation as examples for the striking speed at which change can occur. Paradoxically, we are also more than ever aware of the threats to the systems undergoing this rapid transition. As noted above, it is clear that systems do not behave in linear ways but are rather as a result of social (i.e. relationships among people facilitating action), human (i.e. skills and information) and moral (i.e. investment of personal and collective resources toward justice and virtue) dynamics interacting with system structures (Stokols et al., 2013). Therefore, the **communities** that engage within and across the domains of environment, economy and health are at the very centre of these domains and *encompass groups of people with spatial, temporal, cultural and organisational ties*, who may well have competing worldviews, beliefs and interests but are all driven by the instinct of survival. This long-term survival of communities on a local, regional or national level is directly impacted by the interconnected environmental, health and economic systems.

2.2. Domain Interfaces

There are fundamental links between the described domains. Apart from impacting the seamless integration of different systems, a direct consequence of interfaces is the creation of interdependencies. As systems themselves evolve into even more complex networks, the links between systems are increasingly important (Zio and Ferrario, 2013). The greater the connectivity between sub-systems, the greater the probability that a change in one sub-system will lead to changes in other sub-systems. The reaction of systems to internal or external changes depends on a variety of factors, described as changeability, which "is determined by the number of acceptable change paths that can be taken by a system" (Ross et al., 2008). Depending on the design and delivery of a system, shocks or changes affect the intended performance of the system in various ways. The intended system functionality may respond to a shock (a-c) or change (d-f) as illustrated in Figure 2. How systems respond to shocks or changes depends on the characteristics of the individual sub-systems and the system as a whole.

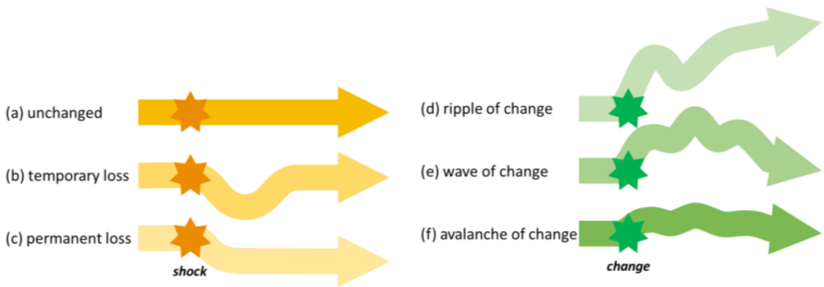

Figure 2. Response to shocks and change

The **economy** can create conducive conditions for the **health** of communities by providing healthcare systems and services. The quality of these systems and services are decisive factors but are themselves

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driven by the economic performance given finite resources. This intersection is similar to the "global health" concept that refers to the activities which seek to improve healthcare in poorer regions with the assistance of richer ones and regional, national and local actors seeking to improve healthcare within their immediate sphere. From a sustainability perspective, **economy** and **environment** are often perceived as domains with largely counteracting activities. On a high level, the environment provides natural resources that serve as inputs for the economy. For the world to become more sustainable, the impact of economic activity must be understood in relation to its impact on the environment, and vice versa. Additionally, it is clear that a communities' health impacts on economic activity, and influences and is influenced by the environment. Yet, there is also destructive potential in the environmental domain with climatological events heavily impairing economic activity and causing major costs at the expense of other domains, e.g. health. The intersection of **environment** and **health** represents the question on the number of resources required by the population for health and longevity. At the same time, with every unit of survival, the overall resource requirements increase. Environmental risk factors (e.g. nitrates in groundwater) further complicate this relationship.

3. Designing resilience into contemporary systems

Developed as an idea on how systems can handle endogenous disturbances (Walker and Salt, 2012), resilience has become an umbrella term for various complex ideas (Joseph, 2013). Difficulties arise from the scope of analysis, the disruptive events considered, the activities suggested for coping with the disruption, and the system qualities that should be preserved (Sheard and Mostashari, 2009). Our understanding of resilience broadly aligns with that of Wiig et al. (2020) who provide a comprehensive conceptualisation of resilience in the healthcare context and ask four essential questions. The first question **(Resilience for what?)** refers to the purpose, often encapsulated by a performance metric of the system to assess the system's ability to survive and to recover (Uday and Marais, 2015). This notion has caused a debate about the usefulness of drilling down the scope of complex systems to a single metric. Systems behave in an evolutionary manner, thus, resilience shall not be considered the ultimate goal of a system but rather as an enabler to system outcome (Béné et al., 2014). This supports the view that resilience shall be described as a process rather than a property. The second question **(Resilience of what?)** is associated with the elements, structures, and actors we seek to design to act resiliently. The complexity of this question arises from the characteristics and behaviour of modern systems as previously described. The next question (**Resilience to what?)** addresses the vast number of uncertainties and challenges contemporary systems face (Figure 3) which complicates the identification of what systems need to be resilient against. Various considerations can be made to understand uncertainty, including the frequency, likelihood, and predictability of an event or development. Finally, the fourth question **(Resilience through what?)** is concerned with the human and organisational resources or activities by which resilience is delivered and hence, pertains to a design question.

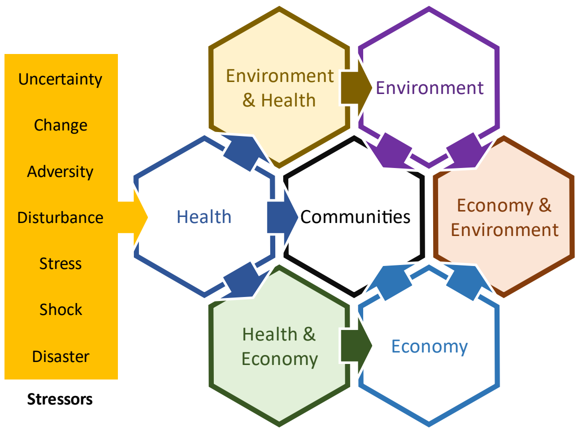

Figure 3. Stressors with exemplary rippling paths through the sub-systems

This work primarily contributes to the second and fourth question. The four domains and their intersections represent how we conceptualise systems to organise our collective efforts towards

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resilience. With the fourth question, we ask about the specific links mediating the uncertain conditions, the system, and its purpose or value. To understand these links, it is important to distinguish three components: (i) properties, (ii) mechanisms and (iii) activities and how they relate to design processes. The resilience literature suggests a vast number of properties, e.g. modularity, survivability, scalability, systems can exhibit generating a certain behaviour. We consider that the key properties boil down to **flexibility, agility, robustness, and adaptability** as proposed by Fricke and Schulz (2005). These paradigms are defined based on how a system can possibly behave in face of a stressor and can only be observed over time and whether a conscious actuation is required within or outside of the system (Figure 4). Resilience mechanisms refer to how a system deals with a change or shock and depend on the stage of a disruptive event. Prior to an event, a system can **anticipate** the potential disruption. When the system experiences the change or disruption, it needs to **accommodate** and **respond** to it. During and after the event, the system ideally **learns** from the experiences and arranges for **transformation**, hence, optimising the system towards an improved steady-state operation. Finally, the system activities refer to the set of actions that take place within the systems and enact the effort to deliver resilience. In this paper, we argue that the alignment and combination of adequate resilience properties, mechanisms, and activities resembles the mapping exercise of design domains in systems design (Pahl and Beitz, 1996; Suh, 1990). The "input" is the need for preservation of certain qualities of the system during disruption or simply, the need for resilience. The "output" refers to the means by which to produce the behaviours required by the needs. The design decisions for resilience happen "in between" which is often described as the "functional" domain representing the performances or behaviours that are instrumental to meet what was determined in the needs domain (Hubka and Eder, 1988).

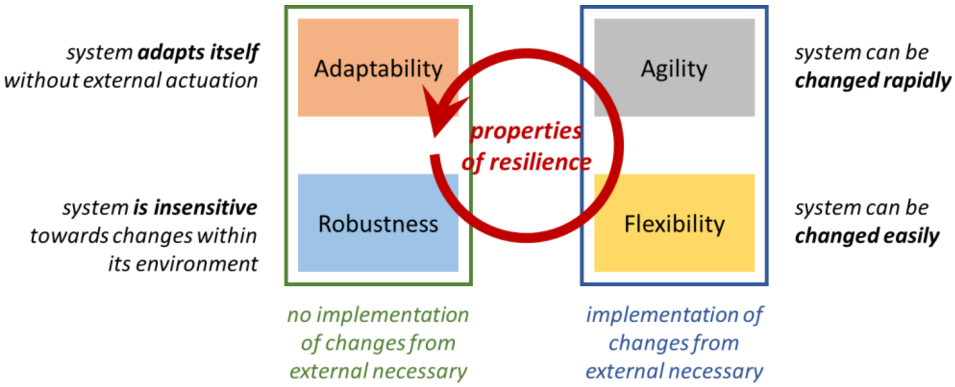

Figure 4. Properties of resilience (Fricke and Schulz, 2005)

4. A systems-of-systems approach to resilience

Today's systems face high uncertainty with multiple plausible futures possible (Maier et al., 2016). Consequently, when dealing with such uncertainty, a conceptual approach to resilience is needed that can accommodate the wide range of possible change patterns and disruptions a system may experience. Therefore, we define resilience as a process rather than a property. Specifically, we argue:

> *"Resilience is the process by which systems can face change and challenges in such a way that they evolve and innovate to* drive *and maintain socially agreed positive outcomes."*

This resilience definition describes a process by which **a system (A)** - which is situated in a context of different domains - is able to **behave in a certain way (B) in the face of change or challenges (C).** In an attempt to contribute to increased coherence in resilience literature (Sheard and Mostashari, 2009), our definition provides a natural language pattern so that it can be flexibly tailored to the system of interest, the nature of the expected challenges, the present targets for acceptable performance and the means to deliver such performance. We take a flexible yet proactive approach to the system architecture and maintenance to deliver resilience in the context of the available resources, expected performance, and change appetite. It can be applied to a variety of systems and levels of scale, e.g. organisations, cities, countries or regions:

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"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."

We conceptualise this process by means of the proposed framework and start at its core (Figure 5). Our four previously described domains and their respective interfaces are located at the centre as the focal SoS undergoing a resilience process. Again, we note that the principles that describe a resilient system's behaviour boil down to four **properties**: **flexibility, robustness, adaptability, and agility**. Note that the four described paradigms should not be understood as complementary or desirable for all systems under all circumstances. In fact, these paradigms can individually be rather conflicting and impairing benevolent developments. For example, a robust system might be able to withstand an adversity but also hamper novel system improvements. Additionally, given possible idiosyncratic characteristics of individual SoS components, the overall SoS resilience may be achieved by the application of one or more of the four properties to each of the different components. The system, thus, needs to continuously compose a portfolio of complementary system properties for different elements of the SoS so that they can tackle disruptions irrespective of their type or stage. This composition exercise depends on the **mechanisms** describing how the system addresses the stressor or change, forming the second framework layer. Stressors or change can be emerging, materialising, or abating; and their impact on the system can be perceived as good or bad. Ultimately, it matters how the resilience principles and mechanisms are realised in the system, hence, linking them to suitable **activities**. In terms of resilience, we consider that the orchestration or mapping of principles, mechanisms and activities over time enable systems to explore a design solution space to deliver and maintain resilience.

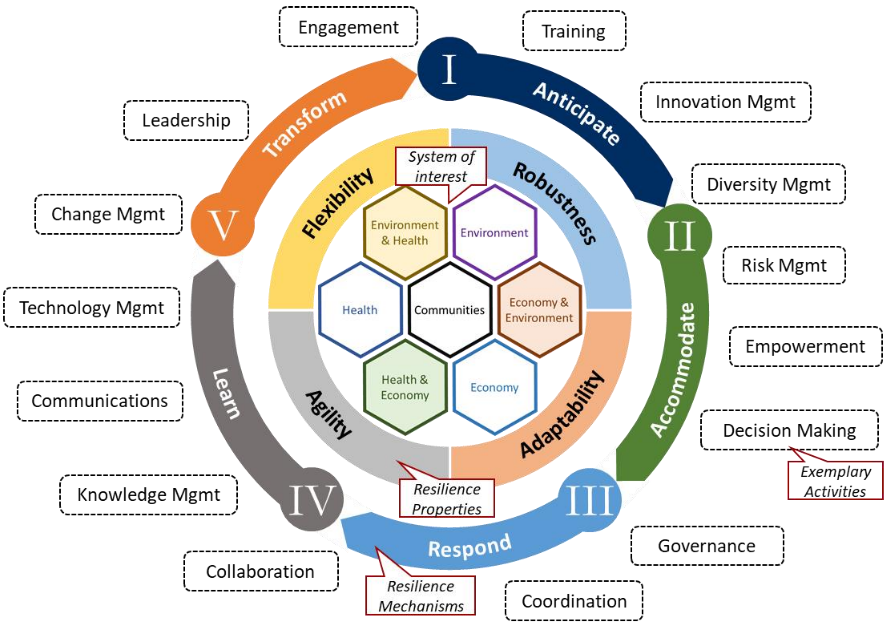

Figure 5. Process framework for resilient systems

5. Designing resilient technical systems: the case of hospital oxygen systems during COVID-19

To showcase how the proposed concepts may contribute to more resilient systems and the usefulness to different types of systems, we apply our framework to the case of a technical system - namely hospital oxygen systems during COVID-19. Given the respiratory characteristic of the virus, medical oxygen has been key to survival for critically ill patients, yet the pandemic-driven spike in oxygen demand has highlighted deficiencies in existing technical systems (Kumar et al., 2021). In that sense, it is intuitive to think of COVID-19 as a disruptor of the **health** domain and extensive public discourse has been taking place over the last two years on the rippling effects to other domains of our life. In the specific case of hospital oxygen systems, a similar exercise is possible: The **economic** domain concerns

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questions such as the delivery of oxygen (e.g. liquid oxygen, cylinders, and on-site oxygen production) or the general market structures that are subject to oligopolistic dynamics. Hospital oxygen supply is also concerned with an **environmental** domain as the selection of a delivery scenario entails different environmental consequences. For example, on-site production of oxygen requires higher investment yet has a smaller ecological footprint as this option has fewer transportation requirements as compared to cylinders and tanks. Finally, COVID-19 and its knock-on effects impact different **communities** in different ways given their level of economic development, geographical and urban conditions as well as other local conditions (energy, working time), especially in terms of oxygen systems. Several scholars have recently published on the national and regional conditions affecting the access to oxygen therapy during COVID-19 (Bałys et al., 2021; Graham et al., 2020). Following our previously described definition, the specific resilience challenge for hospital oxygen pipeline systems can, thus, be formulated as follows: *Resilience is the process by which hospital oxygen pipeline systems can face change and shocks in such a way that they are able to adequately support the delivery of high-quality oxygen therapy to patients.* This process now involves the alignment and combination of resilience properties, mechanisms, and activities aiming to answer the *Resilience through what?* question. Exemplary considerations that this process entails are displayed in Figure 6.

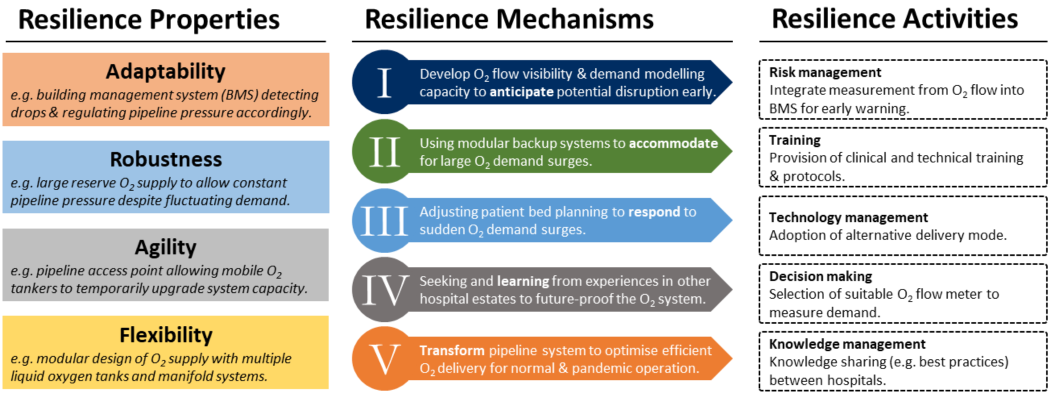

Figure 6. Illustration of the application of the framework for systems-of-systems resilience

We acknowledge the wider complexity of oxygen systems that have not been represented in the foregoing example. Yet, it shows the powerful way of thinking to connect a systems approach with the concept of resilience and a design process for the case of a specific technical system.

6. Discussion and Conclusion

The recent COVID-19 pandemic and the climate emergency have raised the need for resilient systems. Considering an increasingly uncertain future due to changes in socio-economic conditions, technology, politics, and climate, the resilience concept is believed to support systems by anticipating and mitigating forthcoming disruption and change. Yet, the operationalisation of resilience is still in its infancy. Based on a reflective analysis of the key terminology, questions, and issues, this paper provides a versatile framework that captures the essential elements of resilience whilst remaining flexible to different system interpretations, contexts, and requirements. A key element of the proposed framework is the emphasis on interfaces and linkages whereby we hope to create increased understanding of complex SoS phenomena. To that extent, this paper provides perspectives in three aspects: **First**, the suggested framework highlights how core domains of our everyday life and their very interfaces can describe CAS on a high-level. The complexity inherent to the interactions of the modern world creates an opportunity to understand, evaluate, and improve these systems in a holistic, systematic manner. Therefore, we put emphasis on the interfaces between individual systems through which change - good and bad alike - can propagate in multiple directions and with often unpredictable impact. **Second**, due to the evolutionary behaviour of CAS, we extend the understanding of resilience as a continuous lifecycle process rather than a system property. CAS are subject to often simultaneous internal and external pressures for change and are, thus, constantly evolving and reconfiguring in response to new conditions. Hence, resilience is not only relevant in the immediate aftermath of disruptions but requires a process-view and

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consideration of multiple plausible futures. **Third**, the design of the strategies that deliver and maintain systems resilience can be thought of as the combination of resilience mechanisms and certain activities enacted among communities. We hope that with the articulation of the linkages and issues between stressor, systems, and resilience approaches, we can disentangle some of the key conceptual elements around resilience providing a useful tool that shows how a system of interest might address a single or multiple stressors in a resilient fashion. In its current form, the framework aims to align the resilience language created by previous academic discourse. Several enhancements can be made in future research. In particular, it may well be necessary to adjust the selection of the domains or their number to represent the specific context of a system and/or to appropriately capture the relevant interfaces. As a next step, we propose the identification of metrics that capture not only the performance of the individual sub-systems but also of its interfaces. We hope that the reductive approach presented in this paper will be useful for researchers and practitioners in developing resilient strategies for complex adaptive systems.

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