Resilience and Systems

Subjects: Engineering, Civil

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Resilience is a growing area of interest and study, but it has a variety of origins and apparent inconsistencies across disciplines.

Keywords: resilience ; resilience definitions ; engineering resilience

1. Resilience—Roots and Evolution

The word resilience originates from the Latin word ‘resiliere’, which translates as ‘bounce back’. The first usage of the term was possibly made by the physicist Thomas Young in 1807 to describe elastic deformation in the context of material sciences [1][2]. As a natural environment concept within the sustainability science research [3], the term is said to have first appeared in the work of Holling [4], where resilience is interpreted as ‘the persistence of relationships within a system and is a measure of the ability of those systems to absorb changes of state variables, driving variables, and parameters, and still persist’ (p. 17, [4]), [3]. Subsequent multidisciplinary development and evolution of the concept of resilience, however, remains fragmented [5][6]. Anderies et al. [7] argue that the reason the term resilience can be ambiguous is because of its broad usage in serving different discipline-specific goals and, as such, makes resilience more of a way of thinking rather than a fixed concept. Accordingly, discussion of resilience can create confusion [8] and there is a lack of consensus on what constitutes resilience.

Carpenter et al. [9] argue that for every resilience scenario, a guiding question must be the qualification ‘of what, to what’. Systems thinking can help in this regard. The first question, ‘of what’, has relevance to system definition, system boundaries, system external environment, and the interaction between the system and the external environment. Here ‘environment’ is distinguished from its usage with reference to the natural or green environment. The second question, ‘to what’, has relevance to system inputs, outputs, and behavior but is expressed as change. All the definitions provided for resilience in the literature include some aspect of dealing with change, whether it is resistance to change, adaption to change, or recovering from change [10].

At a global level, thinking is directed towards an ever-changing world due to a growing set of major changes such as global economic competition, demographic shifts, rapid urbanization, the rise of technology, increased level of interconnectedness and complexity, climate, resource scarcity, and global pandemics [11][12][13][14][15]. Change is a major driver behind the growth in resilience interest and the evolution in resilience thinking while managing change presents its own challenges in all disciplines. **Figure 1** shows a growing trend in publications on resilience; a total of more than 42,000 publications have surfaced between November 1973 and June 2022 covering 27 different disciplines, with social sciences, medicine, engineering, environmental sciences, and psychology at the top of the list, while veterinary and dentistry are at the bottom of the list. Multidisciplinary research only comprises about 1% of the total number of publications (**Figure 2**). The start date chosen is 1973, the year of the Holling seminal paper. The resilience literature, published between November 1973 and June 2022, is scattered among 159 different journals/sources (**Table 1**), with some authors quite prolific (**Table 2**). Some publications attract citations more than others (**Table 3**), but it is generally acknowledged that number of publications and number of citations are not correlated with the originality in the publications or the advancement of knowledge presented in the publications—quantity is not a good measure of quality.

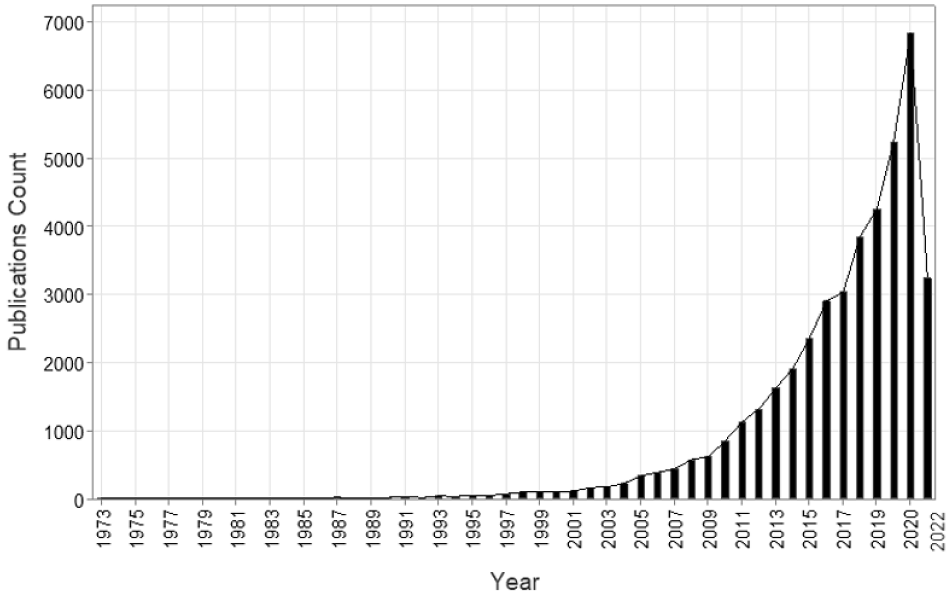

Figure 1. Number of publications with resilience in their titles—November 1973 to June 2022.

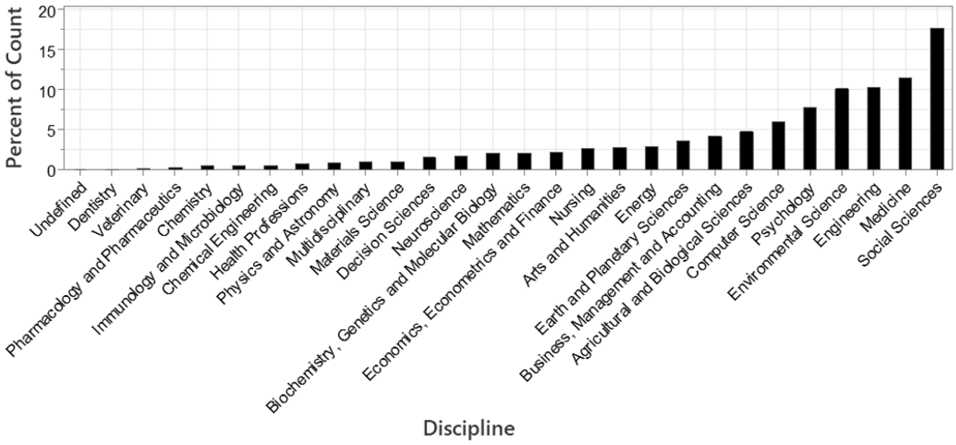

Figure 2. Number of publications with resilience in their title, by discipline—November 1973 to June 2022.

Table 1. Resilience journals/sources listing (highest to lowest) as per publications count—November 1973 to June 2022.

Journal/Source	Publications Count
Sustainability Switzerland	**539**
Ecology and Society	**297**
PLoS ONE	**289**
International Journal of Disaster Risk Reduction	**288**
Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)	**278**
International Journal of Environmental Research and Public Health	**277**
Frontiers in Psychology	**208**
IOP Conference Series: Earth and Environmental Science	**181**
Reliability Engineering and System Safety	**147**
Natural Hazards	**138**
The rest of the 149 journals (including undefined journals) publishing fewer than a total of 135 publications per source	**6959**

Table 2. Resilience authors listing (highest to lowest) as per publications count—November 1973 to June 2022.

Author	Main Area(s) of Expertise	Publications Count
Ungar, M.	Social Works	116
Pietrzak, R.H.	Clinical Psychology	90
Linkov, I.	Risk and Decision Science	85
Cimellaro, G.P.	Earthquake Engineering	78
Southwick, S.M.	Psychiatry	69
Masten, A.S.	Competence, Risk and Resilience	59
Shaw, R.	Disaster risk and Climate Change	58
Allen, C.R.	Ecological and Social-ecological Resilience	53
Bonanno, G.A.	Psychology and Resilience	51
Theron, L.	Educational Psychology	50
Folke, C.	Social–ecological systems, Sustainability and Global Change	46
Others	Various disciplines	<46

Table 3. Listing of publications with resilience in their titles by citation count—November 1973 to June 2022.

Author(s)	Publication Title	Citations Count
Holling [4]	Resilience and Stability of Ecological Systems	19,670
Luthar et al. [18]	The Construct of Resilience: A Critical Evaluation and Guidelines for Future Work	4284
Connor and Davidson [19]	Development of a New Resilience Scale: The Connor–Davidson Resilience Scale (CD-RISC)	4043
Folke [20]	Resilience: The Emergence of a Perspective for Social–Ecological Systems Analyses	3952
Masten [21]	Ordinary Magic: Resilience Processes in Development	3817
Walker et al. [8]	Resilience, Adaptability and Transformability in Social–Ecological Systems	3652
Bonanno [22]	Loss, Trauma, and Human Resilience: Have We Underestimated the Human Capacity to Thrive after Extremely Aversive Events?	3483
Rutter [23]	Psychosocial Resilience and Protective Mechanisms	2806
Lozupone et al. [24]	Diversity, Stability and Resilience of the Human Gut Microbiota	2724
Hughes et al. [25]	Climate Change, Human Impacts, and the Resilience of Coral Reefs	2648
Bruneau et al. [26]	A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities	2401
Norris et al. [27]	Community Resilience as a Metaphor, Theory, Set of Capacities, and Strategy for Disaster Readiness	2378
Others		<2370

Within existing publications, change or change implication might be described under different names, including disruption, disturbance, perturbation, stressor, accident, and disaster. Based on their root causes, disasters are commonly grouped under natural disasters (earthquakes, floods, …), human/man-made disasters (technological or human error-related, deliberate terrorist or cyber-attacks, …) and complex disasters (famine, …) [28]. Disasters, of course, can lead to damaged physical infrastructure and a damaged natural environment and they can endanger people's safety [29][30]. **Figure 3** shows a generally increasing trend in the number of disasters from 1900 onwards, and particularly 1950 onwards, with many climate change-related. Falling under the broad category of natural disasters, global pandemics—particularly the current COVID-19 pandemic—have caused major disruptions to various systems, from mental health [31][32][33] and healthcare to supply chain [34], global trade [35], and economic systems [36], with cascading impacts across the scales.

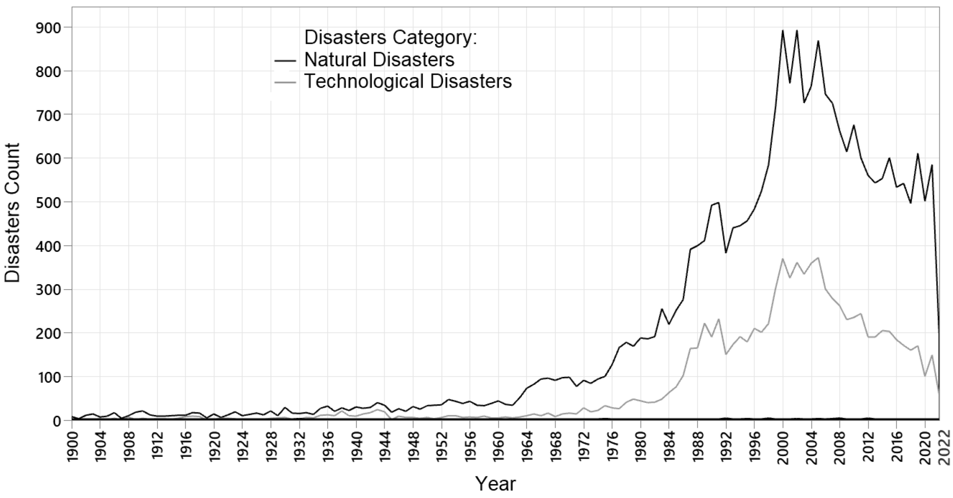

Figure 3. World disasters count for natural and technological categories from 1900. The complex disasters category would not be visible on the scale of **Figure 3** because the numbers are very small.

2. Resilience Variants and Extensions

This section looks at a range of variants and extensions of resilience and related ideas, including management, adaptability, and transformability.

2.1. Socio-Ecological and Engineering Resilience

The work of Holling [4][37] with respect to ecological resilience and engineering resilience has attracted much attention. The extension, socio-ecological resilience, and engineering resilience are seen as overarching.

Socio-ecological and engineering resilience use ideas also found in the systems optimization literature, and in particular in the calculus of extrema and nonlinear programming related to local and global optima and starting points for searches, while engineering resilience also borrows from the systems stability literature. Engineering resilience:

> *… concentrates on stability near an equilibrium steady state, where resistance to disturbance and speed of return to the equilibrium are used to measure [resilience] …*
>
> [37] (p. 33)

Socio-ecological resilience:

> *… emphasizes conditions far from any equilibrium steady state, where instabilities can flip a system into another regime of behavior—that is, to another stability domain. In this case, the measurement of resilience is the magnitude of disturbance that can be absorbed before the system changes its structure …*
>
> [37] (p. 33)

> *… the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks …*
>
> [8] (p. 1)

Engineering resilience is seen to be more narrowly defined. The different units of measurement for resilience expressed in these definitions are not satisfying. Terminology, generally, is something that is holding back the development of a unified resilience framework.

Resilience as described here can be visualized, as with global and local minima in systems optimization, in terms of a landscape with a single valley (engineering resilience) or multiple valleys (socio-ecological resilience), and movement between states, equivalently locations on the topography. The multiple valleys are domains of attraction [38]. Some publications describe a ball moving over the topography, where the ball location corresponds to the system state [8]. Social resilience is seen as a natural extension of ecological resilience, where social systems involving humans exhibit equivalently shaped topographies with multiple domains of attraction [39][40][41][42]. Terms introduced such as latitude, resistance, precariousness, and panarchy [8], in attempting to understand resilience, would generally not be able to be determined or would be very difficult to determine for actual systems.

The terms ‘specified resilience’ and ‘general resilience’ can be found in the literature. The former is close to the concept of resistance and focuses on maintaining a certain level of system behavior for a known and likely set of perturbations, while the latter refers to wider system-level features such as the capacity for learning and adaptation; and coping with perturbations in all forms [43][44][45]. For a range of perturbations described as narrow and predictable for engineering resilience, and broad and unpredictable for socio-ecological resilience [4][37], specified resilience and general resilience might be considered alternative terms for engineering resilience and socio-ecological resilience, respectively.

2.2. Introduced Terminology

Resilience is a fruitful source of new terminology, introduced as part of verbal modeling and in an attempt to explain all the variants possible. For example: socio-ecological resilience [8][46]—resistance, latitude, panarchy, precariousness, adaptability, and transformability; resilience of engineered and infrastructure systems [47][48]—absorptive capacity, restorative capacity, and adaptive capacity; seismic resilience of communities [26]—robustness, redundancy, resourcefulness, and rapidity; engineering resilience [37]—resistance, rate of return to equilibrium, and single domain of attraction; general resilience [49]—response diversity, modular, thinking, planning and managing across scales, exposure to disturbances, quick response, guiding not steering, and transformable; ecological resilience (quantitative) [50]—alternative regimes, scale, thresholds, and adaptive capacity; general resilience [51]—diversity, modularity, openness, nestedness, trust, monitoring, feedbacks, reserves, and leadership; ecological resilience [52]—diversity, modularity, openness, cross-scale interactions, slow variables, reserves, polycentric governance, social capital, adaptability, tight feedbacks, and innovations; ecological resilience [53]—diversity and redundancy, connectivity, slow variables and feedbacks, complex adaptive systems, learning and experimentation, polycentric governance, and inclusive participation; and ecological resilience [4][37]—system identity, functional diversity, multiple domains of attraction and nonlinearity, spatial and temporal heterogeneity, cross-scale interactions, critical thresholds, qualitative behavior, redundant regulations, broad and unpredictable perturbations, adaptive feedbacks, and transformation (extinction).

Of interest among the above terms from a systems viewpoint are the notions of adaptation, learning, and feedback, though there is not a consensus in the resilience literature on tight definitions for these terms.

Although different terminology is used to describe perturbations throughout the resilience literature, perturbations are related to where the system boundary is drawn. Perturbations are external/exogenous to the system and reflect the system–environment interaction. Perturbations are also referred to as accidents and stressors [27] and when a serious disruption/disturbance occurs to a system, it is called a disaster [54]. Perturbations are sometimes inappropriately referred to as changes. Change may come about through system parameter changes or through system structure changes [43][55][56][57].

2.3. Resilience-Inherent or Managed

Resilience may be obtained through the inherent system characteristics or through management. The former might be thought of as preset or internal control, while the latter might be thought of as controls applied external to the system, along with modifying the system itself.

Terminology such as ‘absorb changes of state variables and driving variables’ [4] (p. 17), elastic resilience [58], self-organization [59], static resilience [60], system internal resistance [61], and built-in adaptability [62][63] are some of the terms used in the literature to describe resilience through the inherent system characteristics. Similarly, ‘absorb changes of parameters’ [4] (p. 17), ductile resilience [58], and dynamic resilience [64] are some of the terms used for resilience through management.

However, some researchers [44][65] acknowledge a conceptual tension between resilience being inherent or managed; both of the two notions can obtain resilience [66][67][68]—though in different forms and combinations depending on the system type (**Figure 4**). For the engineering resilience category, as the system dynamics are known and the perturbations are of a limited and known range, the resilience focus is on the perturbed system state rate of return to the equilibrium which is mostly achieved through the inherent system characteristics and any anticipated degradation in the system structure is countered by the management of a fixed and known nature. A vital consideration for engineering resilience must be a careful examination of the relationship between the inherent system characteristics versus the system state rate of return to equilibrium and seeking an optimum solution. An over-passive system might work as a double-edged sword and negatively affect the system state rate of return to the equilibrium, as well as creating unwanted rigidity and inertia along with any associated additional lifecycle costs [61][69].

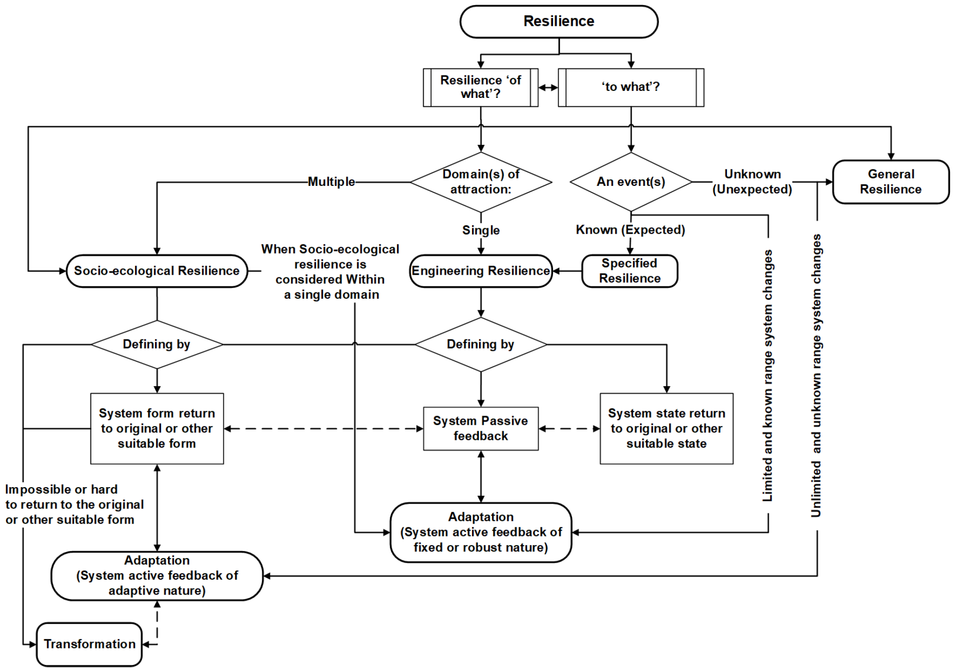

Figure 4. Resilience interpretation in terms of adaptation: a big picture.

For socio-ecological resilience, because the system dynamics are not well known and the perturbations are also not well known and wide-ranging, the resilience focus shifts toward management that is not fixed but rather of a broader and adaptive nature [70][71]. With an increasing trend of complexity and uncertainty involved in infrastructure systems, there is a growing tendency for engineering/specified resilience to trend toward general/socio-ecological resilience in the resilience literature [66][72] (**Figure 4**).

2.4. Resilience Engineering-Designing Resilience

Resilience engineering appears to have a stronger academic rather than industry focus [73]. It initially appeared in a resilience engineering symposium held in Söderköping, Sweden, on 25–29 October 2004 [74][75]. A distinction is made with engineering resilience. Resilience engineering focuses on addressing risks, improving safety, and operational management in complex socio-technical and human services delivery systems such as infrastructure—through mainly system organization [76][77][78]. Hollnagel defines resilience engineering as:

> *… the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions…*
>
> [79] (p. 36)

Some of the terminology as part of the verbal modeling available in the literature for characterizing resilience engineering are: cross-disciplinary [80]—anticipate, respond, learn, and monitor. Organizational domain [75]—avoid, withstand, adapt, and recover. Organizational domain [81]—awareness, preparedness, learning, flexibility, management commitment, and reporting culture. Most of the terminology used here is not consistent with system terms.

Cimellaro [82] and Cimellaro et al. [83] introduce the concept of resilience-based design (RBD)—an extended version of performance-based design (PBD), which is a holistic framework to define and measure resilience at various scales. Similarly, Forcellini proposes a resilience-based (RB) methodology that underpins resilience's holistic and dynamic nature and the relevant perturbations. He demonstrates the RB methodology application to two sample systems of civil infrastructure [84] and health system infrastructure [85] exposed to climate change (temperature as the dynamic environmental variable) and the COVID-19 pandemic crisis, respectively. Both RBD and RB methodology are closely related concepts to resilience engineering.

Resilience engineering might be considered as an approach to design in resilience for a dynamic system, looking at the trade-offs between obtaining resilience through the inherent system characteristics and resilience through management centered on certain objective functions such as system-required functionality and behavior.

2.5. Resilience and Sustainability-Related or Distinct Concepts

The concept of resilience and its relationship with sustainability has received enormous attention from academia, industry, government, and other stakeholders over the past decade [86]. Despite the two concepts' contextual differences and their independent theoretical evolutions, sustainability—in the context of sustainable development—defined as 'meeting the needs of the present without compromising the ability of future generations to meet their own needs' [87] (p. 12), with a triple bottom line of social, environmental, and economic pillars, shares a vast number of similarities with resilience. While scholars may hold a different opinion on the notion of resilience as a component of sustainability or vice versa, there is an overwhelming consensus among researchers that the two concepts are mutually complementary and need a holistic and systematic treatment [88].

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