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Review

Resilience and Systems—A Review

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Abstract: This paper presents, from a systems orientation, a review of the resilience literature since its emergence as an ecological concept in academic parlance in 1973. It argues that much of the resilience literature covers existing ground in that existing engineering systems stability ideas are being reinvented. The review follows modern control systems theory as the comparison framework, where each system, irrespective of its disciplinary association, is represented in terms of inputs, state, and outputs. Modern control systems theory is adopted because of its cohesiveness and universality. The review reveals that resilience can be thought of in terms of adaptive systems and adaptation, where the system has the ability to respond to perturbations and changes through passive and active feedback mechanisms—returning the system state or system form to a starting position or transitioning to another suitable state or form. This systematic and cross-disciplinary review offers the potential for a greater understanding of resilience and the elimination of overlap in the literature, particularly related to terminology.

Keywords: resilience; resilience definitions; engineering resilience; socio-ecological resilience; resilience engineering; system thinking; adaptive control systems; state-space approach

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1. Introduction

Resilience is a growing area of interest and study, but it has a variety of origins and apparent inconsistencies across disciplines. This paper first reviews the existing resilience literature and attempts a categorization and integration across various disciplines, including the seminal work of Holling [1]—as a starting point of resilience in academic parlance and subsequent developments on this. The paper then discusses this in the context of Civil Engineering Systems viewpoints and, in particular, adaptive control systems thinking, as an attempt to unify much of the literature.

The data collection and analysis process for this review was carried out during the COVID-19 pandemic between January 2020 and June 2022. Because of the desk-study nature of the review papers, the pandemic impact on the study was minimal. The data used in the review were obtained through a comprehensive bibliographic search based on the keywords: resilience, resilience elements, resilience capacities, resilience capabilities, resilience features, resilience defining measures, resilience definition, general resilience, specified resilience, resilience engineering, engineering resilience, ecological resilience, and social-ecological resilience; in various combinations in the publication title, abstract, and keywords. Multidisciplinary search databases used included Scopus, Web of Science, Dimensions, and Google Scholar. Within these databases, a total of 3701 documents published between November 1973 to June 2022 were located. These included articles, conference papers, book chapters, reviews, books, editorials, conference reviews, notes, erratum, letters, and short surveys. Authors of seminal papers on resilience conceptual foundation and its constituent elements included C. S. Holling, B. Walker, S. Carpenter, C. Folke, L. Gunderson, N. Adger, J. Anderies, R. Biggs, M. Bruneau, D. Salt, E. Hollnagel, and E. D. Vugrin (A summary of the papers is given in Sections 3.2 and 3.4).

Publications that mesh systems thinking with resilience include those of Hsu and Stallins [2], Pham [3], Ge et al. [4], Tian and Dai [5], Andersson et al. [6], Taranu et al. [7], Froese et al. [8], Cámara et al. [9], Carmichael [10], Goerigk and Hamacher [11], Jowitt and Milke [12], and Porse and Lund [13]. However, these do not present a complete systems picture or attempt to unify the various schools of thought on resilience. This paper is directed toward that gap.

Over recent years, a number of reviews covering aspects of resilience in different disciplines have been conducted. These include, with reference to the respective discipline mentioned: psychology [14–17], urban planning [18], built environment [19], critical infrastructure [20], water [21,22], transportation [23], energy [24,25], community [26], society [27], ecology [28], social-ecological systems [29,30], organization [31], resilience engineering [32,33], resilience quantification and measurement [30,34,35], and system approaches toward resilience [36]. Yet, there is a lack of any comprehensive, cross-disciplinary conceptual treatment of resilience or treatments that address conflicts in terminology and treatments across disciplines. This paper attempts an integration of these different viewpoints advanced by exploring commonalities and using system thinking, in particular through a modern control systems theory framework, using ideas associated with inputs/controls, state, and outputs. By doing this, the paper fills a knowledge gap and represents an original contribution to the field of resilience. The paper will be of interest to people attempting a systematic understanding of resilience and its conceptual unification for a cross-disciplinary operationalization, as well as people generally interested in resilience and systematic thinking.

The paper is structured as follows. The following section presents the state of the art on the roots of resilience and its evolution over time. Section 3 looks at a range of variants and extensions of resilience across disciplines, including terminology and resilience conceptual analysis. Section 4 defines general terminology on control system theory and system state-space representation. Subsequently, Section 5 presents resilience as an alternative to adaptation in system terms. The conclusions and future research directions follow.

2. 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 [37,38]. As a natural environment concept within the sustainability science research [39], the term is said to have first appeared in the work of Holling [1], 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, [1]), [39]. Subsequent multidisciplinary development and evolution of the concept of resilience, however, remains fragmented [31,40]. Anderies et al. [41] 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 [42] and there is a lack of consensus on what constitutes resilience.

Carpenter et al. [43] 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 [44].

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 [45–49]. 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.

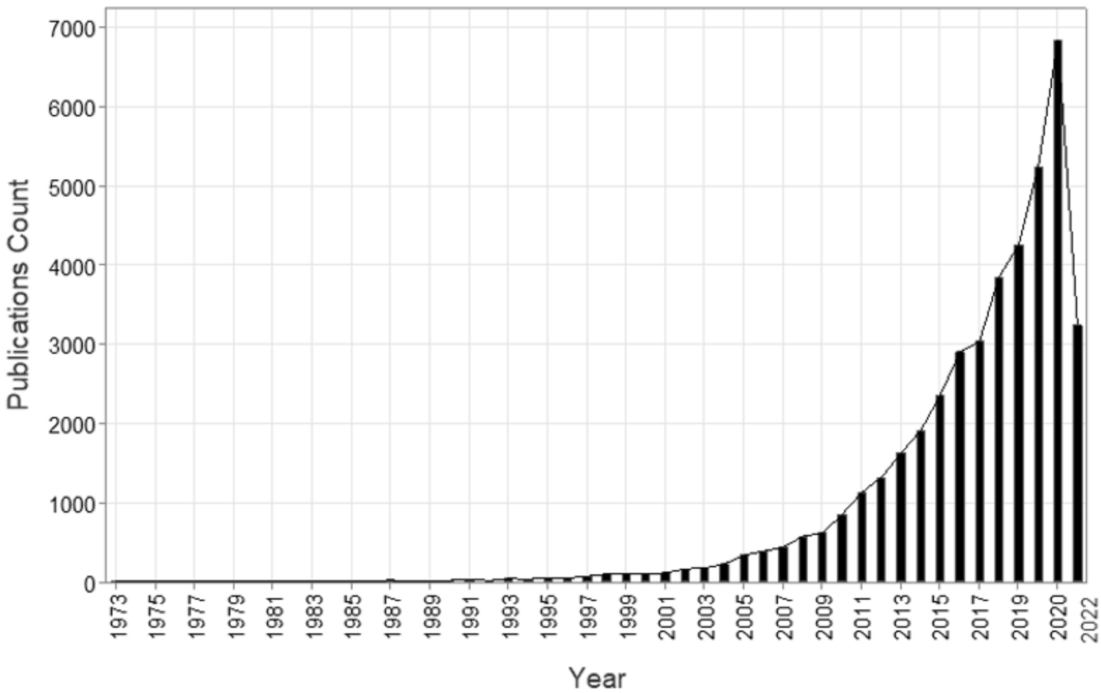

Figure 1. Number of publications with resilience in their titles—November 1973 to June 2022. Data source: Scopus [50].

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, . . .) [62]. Disasters, of course, can lead to damaged physical infrastructure and a damaged natural environment and they can endanger people's safety [63,64]. 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 [65–67] and healthcare to supply chain [68], global trade [69], and economic systems [70], with cascading impacts across the scales.

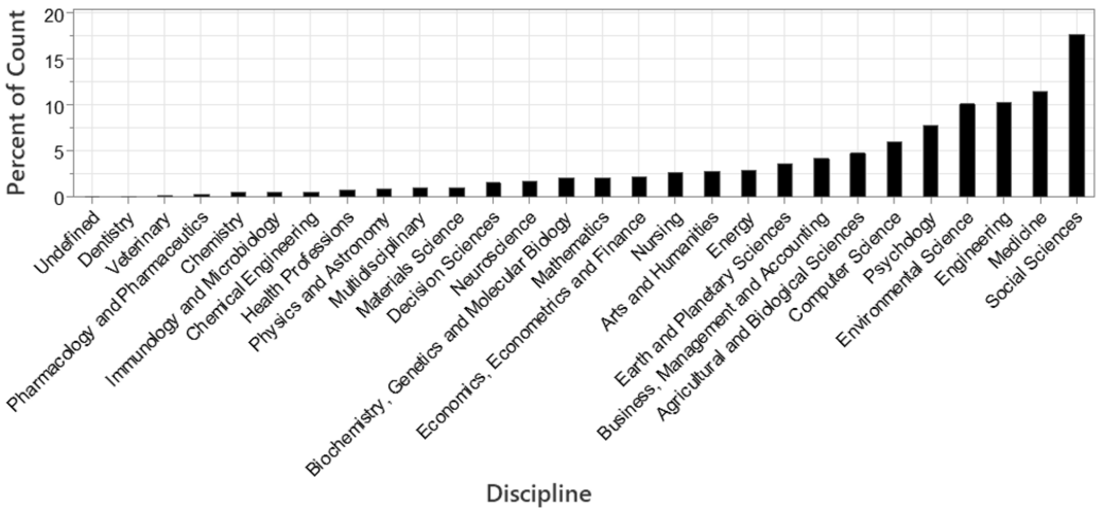

Figure 2. Number of publications with resilience in their title, by discipline—November 1973 to June 2022. Data source: Scopus [50].

Table 1. Resilience journals/sources listing (highest to lowest) as per publications count—November 1973 to June 2022. Data source: Scopus [50].

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. Data source: Scopus [50].

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

Table 2. *Cont.*

Author	Main Area(s) of Expertise	Publications Count
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. Data source: Scopus and Google Scholar [50,51].

Author(s)	Publication Title	Citations Count
Holling [1]	Resilience and Stability of Ecological Systems	19,670
Luthar et al. [52]	The Construct of Resilience: A Critical Evaluation and Guidelines for Future Work	4284
Connor and Davidson [53]	Development of a New Resilience Scale: The Connor–Davidson Resilience Scale (CD-RISC)	4043
Folke [54]	Resilience: The Emergence of a Perspective for Social–Ecological Systems Analyses	3952
Masten [55]	Ordinary Magic: Resilience Processes in Development	3817
Walker et al. [42]	Resilience, Adaptability and Transformability in Social–Ecological Systems	3652
Bonanno [56]	Loss, Trauma, and Human Resilience: Have We Underestimated the Human Capacity to Thrive after Extremely Aversive Events?	3483
Rutter [57]	Psychosocial Resilience and Protective Mechanisms	2806
Lozupone et al. [58]	Diversity, Stability and Resilience of the Human Gut Microbiota	2724
Hughes et al. [59]	Climate Change, Human Impacts, and the Resilience of Coral Reefs	2648
Bruneau et al. [60]	A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities	2401
Norris et al. [61]	Community Resilience as a Metaphor, Theory, Set of Capacities, and Strategy for Disaster Readiness	2378
Others		<2370

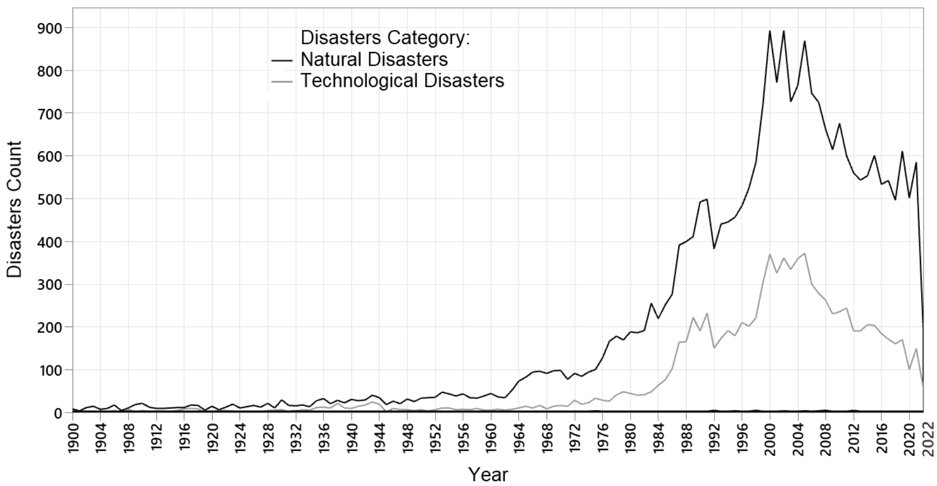

Figure 3. World disasters count for natural and technological categories from 1900. Data source: EM-DAT [62]. The complex disasters category would not be visible on the scale of Figure 3 because the numbers are very small.

3. Resilience Variants and Extensions

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

3.1. Socio-Ecological and Engineering Resilience

The work of Holling [1,71] 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] . . .* [71] (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 . . .* [71] (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 . . .* [42] (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 [72]. Some publications describe a ball moving over the topography, where the ball location corresponds to the system state [42]. 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 [73–76]. Terms introduced such as latitude, resistance, precariousness, and panarchy [42], 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 [77–79]. For a range of perturbations described as narrow and predictable for engineering resilience, and broad and unpredictable for socio-ecological resilience [1,71], specified resilience and general resilience might be considered alternative terms for engineering resilience and socio-ecological resilience, respectively.

3.2. 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 [42,80]—resistance, latitude, panarchy, precariousness, adaptability, and transformability; resilience of engineered and infrastructure systems [81,82]—absorptive capacity, restorative capacity, and adaptive capacity; seismic resilience of communities [60]—robustness, redundancy, resourcefulness, and rapidity; engineering resilience [71]—resistance, rate of return to equilibrium, and single domain of attraction; general resilience [83]—response diversity, modular, thinking, planning and managing across scales, exposure to disturbances, quick response, guiding not steering, and transformable; ecological resilience (quantitative) [84]—alternative regimes, scale, thresholds, and adaptive capacity; general resilience [85]—diversity, modularity, openness, nestedness, trust, monitoring, feedbacks, reserves, and leadership; ecological resilience [86]—diversity, modularity, openness, cross-scale interactions, slow variables, reserves, polycentric governance, social capital, adaptability, tight feedbacks, and innovations; ecological resilience [87]—diversity and redundancy, connectivity, slow variables and feedbacks, complex adaptive systems, learning and experimentation, polycentric governance, and inclusive participation; and ecological resilience [1,71]—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 [61] and when a serious disruption/disturbance occurs to a system, it is called a disaster [88]. Perturbations are sometimes inappropriately referred to as changes. Change may come about through system parameter changes or through system structure changes [28,77,89,90].

3.3. 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' [1] (p. 17), elastic resilience [91], self-organization [92], static resilience [93], system internal resistance [94], and built-in adaptability [95,96] are some of the terms used in the literature to describe resilience through the inherent system characteristics. Similarly, 'absorb changes of parameters' [1] (p. 17), ductile resilience [91], and dynamic resilience [97] are some of the terms used for resilience through management.

However, some researchers [78,98] acknowledge a conceptual tension between resilience being inherent or managed; both of the two notions can obtain resilience [30,99,100]—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 [94,101].

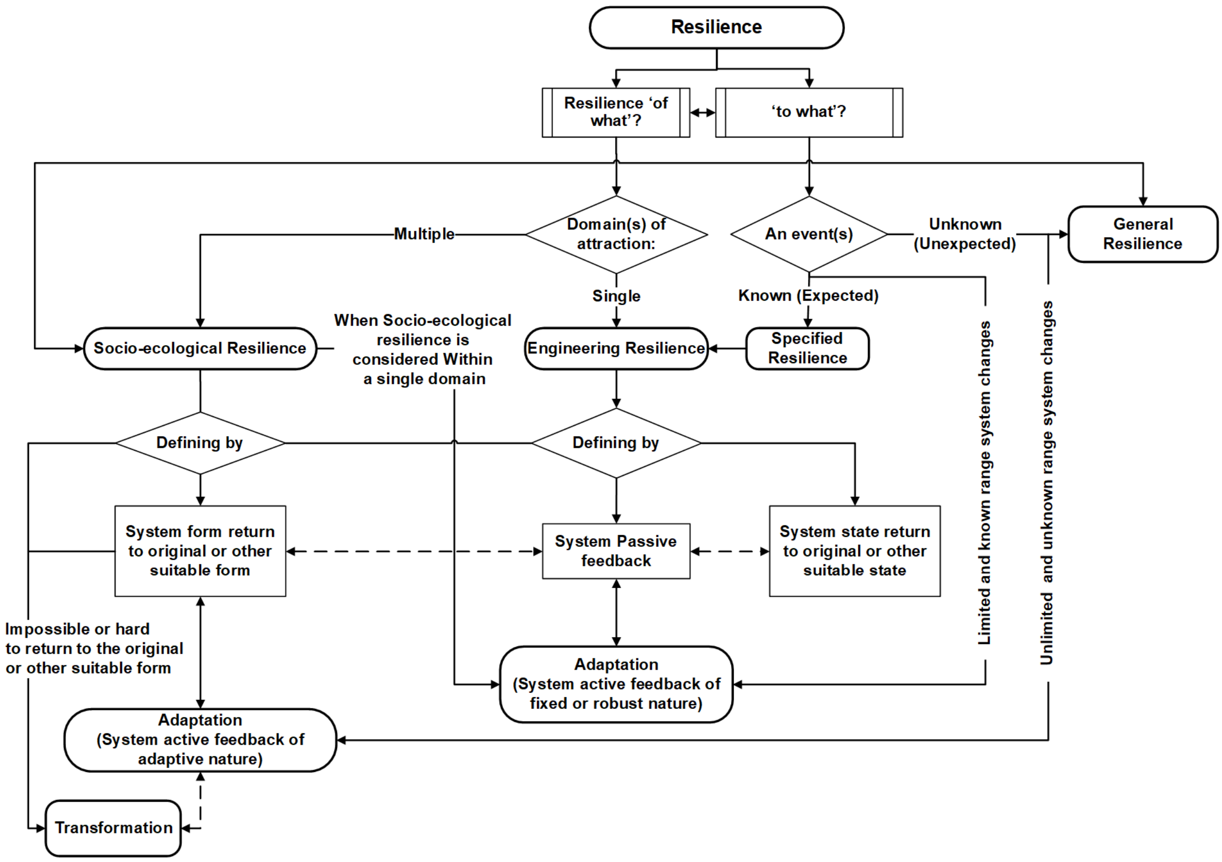

Figure 4. Resilience interpretation in terms of adaptation: a big picture.

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 [102,103]. 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 [30,104] (Figure 4).

3.4. Resilience Engineering-Designing Resilience

Resilience engineering appears to have a stronger academic rather than industry focus [105]. It initially appeared in a resilience engineering symposium held in Söderköping, Sweden, on 25–29 October 2004 [106,107]. 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 [108–110]. 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* . . . [111] (p. 36)

Some of the terminology as part of the verbal modeling available in the literature for characterizing resilience engineering are: cross-disciplinary [112]—anticipate, respond, learn, and monitor. Organizational domain [107]—avoid, withstand, adapt, and recover. Organizational domain [113]—awareness, preparedness, learning, flexibility, management commitment, and reporting culture. Most of the terminology used here is not consistent with system terms.

Cimellaro [114] and Cimellaro et al. [115] 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 [116] and health system infrastructure [117] 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.

3.5. 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 [118]. 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' [119] (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 [120].

4. Systems Terminology

This section introduces much of the necessary terminology of dynamic systems, with a particular emphasis on modern control systems (Table 4), which is subsequently utilized in Section 6 to describe resilience in terms of adaptive systems and adaptation. The terminology is also used to regroup most of the inconsistent verbal modeling in the resilience literature around the system terms.

Table 4. Control systems terminology.

Terminology	Definitions
System	An assemblage of functionally related components forming a unity whole to fulfill a certain purpose [121–124]. A system can be described by the fundamental variables of state, input, and output.
• Subsystem	Components or layers of a system that collectively affect its behavior [121].
• Environment	That which is not part of a system is referred to as the environment and is separated from the system itself by its boundary, which is normally chosen as per the intent of the study [122].
• State $(x(t))$	A descriptor of the system's internal behavior and the minimum number of variables (equal to the order of the system)-known as the state variables (also referred to as states) $(x_i(t),\ i = 1, \ldots, n)$ that can completely represent the system and its behavior to a certain set of inputs $(u_j(t),\ i = 1, \ldots, m)$. The system state variables are not always directly measurable and observable. The state variables collectively constitute the state vector $[x_i(t)]^T$ in the form of a unique point within the state space (also known as phase space) (Figure 5), where its evolution/trace over time is called the state trajectory and its graphical representation is labeled as the phase portrait [125,126].

Table 4. *Cont.*

Terminology	Definitions
• Input	The external forces acting upon the system are introduced in the form of inputs which are classified under two categories—those that are influenced by the engineer (referred to as controls) and those that cannot be influenced by the engineer [122].
• Output	Contrary to the system state, system output indicates the system's external behavior, such as performance or response, and is normally a measure of direct interest to the engineer and is directly measurable and observable [122].
• Perturbation	A fundamental variable of the system which is related to the uncertainty in the system environment [90].
State-space models	State-space models are formed by the interaction of the system's fundamental variables (i.e., input, state, and output) and are generally given by the dual state and output equations. The coefficients used in the state equations to link the system fundamental variables are referred to as the system parameters [122]. State-space models are at the core of time-domain or state-space approaches—also known as the modern control theory and overcomes the apparent limitations of classical control theory (input-output transformations) by including the system state [125,127].
• Linear models	Linear models follow the supervision principle of linearity [128]. Equations (1) and (2) are continuous linear state-space equations for the system state and output, respectively. $\dot{x}(t) = A\,x(t) + B\,u(t)$ (1) $y(t) = C\,x(t) + D\,u(t)$ (2) A—is the system, state, or dynamic matrix of $(n \times n)$ dimension, B—is the input or control matrix of $(n \times m)$ dimension, C—is the output matrix of $(p \times n)$ dimension, and D—is the direct transfer or feedforward matrix of $(p \times m)$ dimension, which is normally the zero or null matrix (Figure 6).
• Nonlinear models	Nonlinear models lack superposition properties but are a more accurate representation of most real-world problems despite their complexity. A general state equation model for a nonlinear time − variant system can be expressed as the dual of state (Equation (3)) and output (Equation (4)) equations where fi and gj are scalar arguments of the state $\left([x_1, x_2, \ldots, x_n]^T\right)$, input $\left([u_1, u_2, \ldots, u_m]^T\right)$, and time (t) vectors (for the time-invariant case, the term t is absent in the model) [129,130] (Figure 7). $\dot{x}(t) = f[x(t), u(t), t)] = \begin{bmatrix} f_1(x(t), u(t), t)) \\ f_2(x(t), u(t), t)) \\ \vdots \\ f_n(x(t), u(t), t)) \end{bmatrix}$ (3) $\dot{y}(t) = g[x(t), u(t), t)] = \begin{bmatrix} g_1(x(t), u(t), t)) \\ g_2(x(t), u(t), t)) \\ \vdots \\ g_p(x(t), u(t), t)) \end{bmatrix}$ (4)
• Time-variant and time-invariant models	If dynamic system parameters remain static and are not changed by the passage of time (only fundamental variables change), the system is called time-invariant; otherwise, the system is referred to as a time-variant system (e.g., adaptive systems) [122,125].
• Continuous and discrete models	For continuous in time (or space) models, the system fundamental variables are defined for all points of the independent variable(s) and described by differential equations, while for discrete in time (or space), the system fundamental variables are only defined at fixed points of the independent variable(s), and the models are described by difference equations. Continuous systems can be readily converted to discrete systems through the use of a proper discretization process, but the reverse is not feasible [122,125].
• Deterministic and probabilistic models	State-space approaches apply both to deterministic and probabilistic (stochastic) dynamical systems where the latter includes element(s) of randomness while the former does not. Whenever possible, deterministic state equations models are preferred over probabilistic ones for the sake of their simplicity, as well being less rigorous [122,125].

Table 4. *Cont.*

Terminology	**Definitions**
Stability	The stability of dynamic systems may fall under the two broad categories of dynamic stability and structural stability.
• Dynamic stability	Dynamic stability of a system is determined by matrix A (including the Jacobian matrix for nonlinear systems) in Equation (1) and is a measure of the tendency of a system's state to return to its equilibrium (original state) or another suitable system state after being perturbed (in the absence of active feedback). Dynamic stability is equivalent to the system return rate (and/or settling time for a time-varying dominant eigenvalue) to the equilibrium which is measured by the dominant eigenvalue horizontal distance (real part) from the imaginary axis in the complex plane. A dominant eigenvalue/pole is related to the slow-moving state of the system and is closest located to the imaginary axis, which corresponds to the slowest and dominant decay/return rate to the equilibrium [131].
• Structural stability	Structural stability is indicative of keeping the system's original form or another suitable system form (e.g., preventing bifurcations) after being perturbed by the changes within the system structure [132,133].
Control action or system feedback	The control action is used for the controllability of the system state vector and is broadly categorized under the open-loop and closed-loop control actions. For linear systems, the control action (Equation (6)) entails both the control law- using matrix H (Equation (5)) and control matrix B (Equation (6)). $u(t) = -\mathrm{H}\,\mathrm{x}(\mathrm{t})$ (5) $\dot{\mathrm{x}}(\mathrm{t}) = \mathrm{A}\,\mathrm{x}(\mathrm{t}) + \mathrm{B}\,(\mathrm{H}\,\mathrm{x}(\mathrm{t})\,) = (\mathrm{A} - \mathrm{BH})\,\mathrm{x}(\mathrm{t})$ (6) For nonlinear systems (Equation (3)), commonly, a local control action is introduced through the system linearization process around an operating state (original state) and, subsequently, a linear control action is used (Equation (6)). For global behavior of the nonlinear systems, control actions such as Control Lyapunov Functions (CLF) (full state-based control) (Figure 7) and Model Predictive Control (MPC) (output-based control) are used [134,135].
• Open-loop control	Also known as feedforward control or passive control, where the control action is independent of the system state/output and is selected upfront [10].
• Closed-loop control	Also known as active feedback and is selected based on the monitoring of the system state/output and its subsequent comparison with a target (reference/equilibrium/steady-state) with the help of a control law or objective function [10] (Figure 8). Closed-loop control falls under three broad categories of optimal, robust, and adaptive controls.
- Optimal control	A control method to ensure state/output/system optimization around a reference point/path [136].
- Robust control	The control law does not change over time for a certain range of the system form's changes (a certain range of parameter uncertainties of the model) and is designed to optimize stability within a particular domain [136,137].
- Adaptive control	The control law does change over time for the system form's changes (parameter uncertainties of the model) and is designed to optimize stability for a certain criterion [138].
Three main engineering problem-solving categories	The majority of real-world engineering problems fall under three fundamental system configurations: analysis, synthesis, and investigation [122].
• Analysis	Finding outputs from input and system model [122].
• Synthesis	Finding inputs from output and system model [122].
• Investigation	Obtaining a system model by using inputs and outputs [122].

5. Resilience-Systems Adaptation

For dynamic systems, modern control systems theory possesses suitable terminology to reconnect resilience with its conceptual basis. It provides the necessary system tools that can help resilience in its analysis, measurement, and design across disciplines.

To explain resilience in terms of systems thinking, a distinction needs to be made as to whether (i) the system itself has changed in response to some event, or whether (ii) it is only the system's state which has changed in response to some event (Figure 4). Both (i) and (ii) can be thought of in the same way. Both lead to interpreting resilience in terms of adaptation, where the system has the ability to change itself or its state according to defined objective functions [139].

Resilience can be thought of in terms of adaptation involving feedback—whereby (i) the system returns to its original form (or another suitable system form), and/or (ii), the system state returns to its original state (or another suitable system state). The return to the original system's form (or state) is achieved by applying controls post the change or the controls are preset prior to the change. What are referred to as management- and system-inherent characteristics in Section 3.3 are both controls—active feedback and passive feedback, respectively.

In (i), the feedback involves the system makeup. The feedback controls are the management actions applied within the system. The system changes and has to be able to return to its original form. In (ii), the feedback does not alter the system (Figure 5).

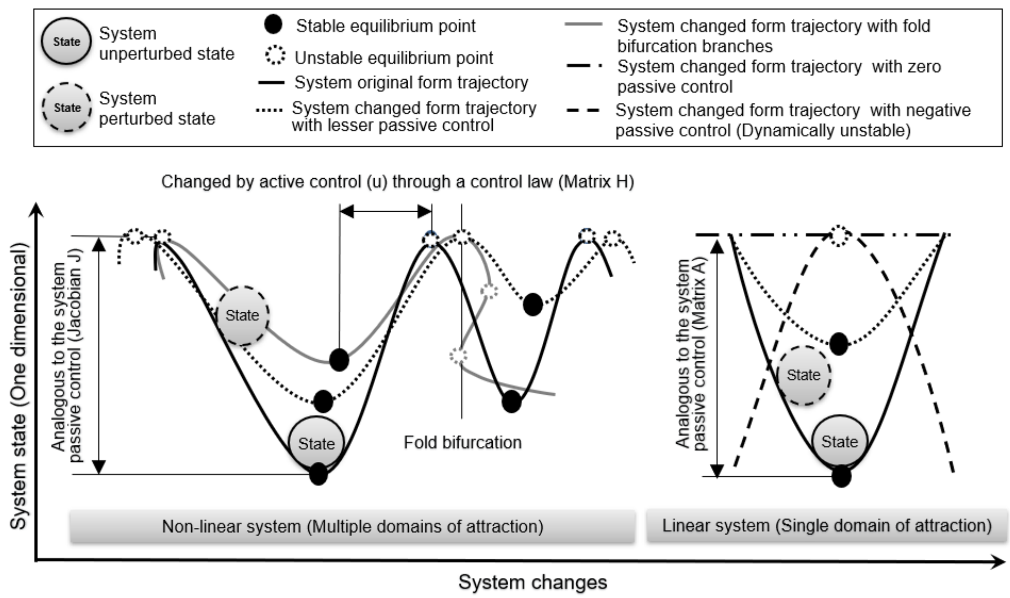

Figure 5. Changes to the system state and form: a graphical illustration of the resilience for a single dimensional system.

For the engineering resilience category, the systems are simple linear systems of a continuous or discrete nature (including locally linearized nonlinear systems) (Figure 6), with a focus on the (ii) system state rate of return to its original state or another suitable state (e.g., maximum constant performance). This in turn is achieved through the passive feedback present within the system and measured by system tools such as dynamic stability, represented by the dynamics (i.e., dominant eigenvalue) of matrix A for linear systems and the Jacobian matrix J for nonlinear systems (Equations (1) and (3)). Changes to the system form —if there are any (i)—lie only within a small and known range (within a single domain of attraction in the vicinity of the original state) and are countered by the system's active feedback after the perturbation event has occurred. The active feedback is achieved in the form of a closed-loop control action where the control law (Matrix H in Equation (5)) does not change, and therefore it may fall below the optimal or robust control categories (Figures 5 and 6).

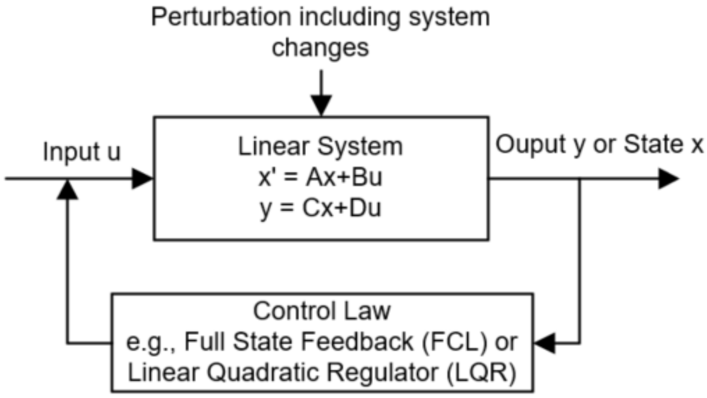

Figure 6. Block diagram illustration of a linear system state equations model with full-state feedback: an illustration for engineering resilience.

For the socio-ecological resilience category, the systems are nonlinear and of a continuous, discrete, deterministic, or probabilistic nature with potential time evolution/variance (Figure 7), and therefore the focus shifts from (ii) towards (i). In other words, the system—return to its original form or another suitable form—becomes crucial as the changes in the system structure become large and of unknown nature. These changes are countered by the system's active feedback after the perturbation event has taken place. The active feedback here is achieved in the form of a closed-loop control action where control law (Matrix H in Equation (5)) changes based on certain criteria (i.e., codes and regulations) and therefore tools from adaptive control systems become better suited. Additionally, system tools such as structural stability—which determines maximum changes in the system form such as fold bifurcations from which it is difficult or impossible for the system to return and which lead to system transformation—and controllability are other equivalent system concepts in terms of passive control for socio-ecological resilience (Figures 5 and 7).

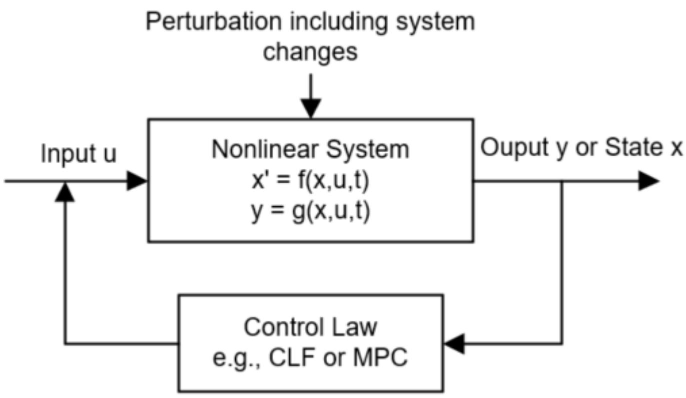

Figure 7. Block diagram illustration of a nonlinear system state equations model with full-state feedback: an illustration for socio-ecological resilience.

Modern control systems possess the tools that can readily accommodate system configurations under which the resilience problems fall. Resilience through passive feedback falls under analysis treatment, while resilience through active feedback treatment falls under synthesis (some aspects of investigation included) treatment. Techniques from dynamic systems optimization such as dynamic programming can solve the resilience problem in terms of adaptation that allow both the system state and form to return to their original or another suitable state and form, respectively.

Additionally, modern control systems possess an established set of terminology to describe both system external perturbations and structural changes. External perturbations for a system can be broadly categorized under the system state variable initial condition (x_0), which is normally a result of a direct management action, while input disturbances (u) generally act as a temporary stimulus, for example, earthquake shocks and flood flows. The system structural changes can be considered as parameters or the model's uncertainty that affect the system form (Figure 8).

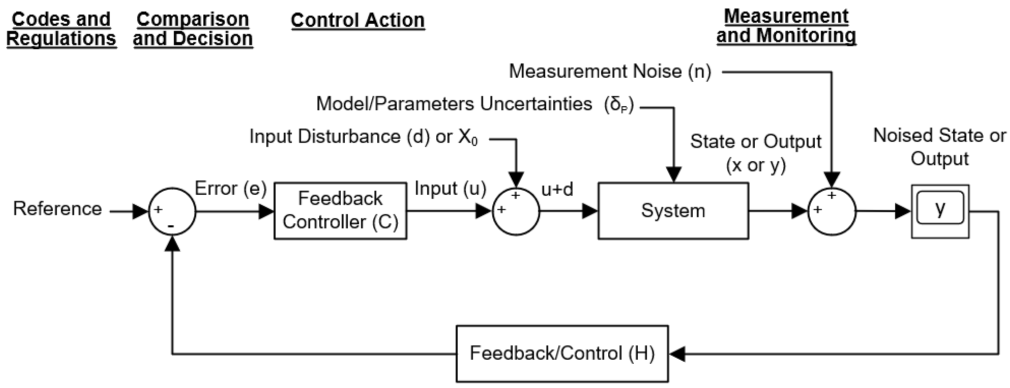

Figure 8. System active feedback along with its constituent elements: an illustration of resilience.

Modern control systems possess the necessary tools to systematically define resilience cost. These include both the loss of service during the system's perturbed state and the cost of restoration efforts. System functioning loss or performance loss found in some of the resilience quantification literature [140] is a vague term that could be equivalent to the system output loss (representing a part—not the entire state of the system). It is an incomplete measure of resilience cost, which often misses the active feedback efforts. A combination of two quantities—given by the system state vector $[x_i(t)]^T$ and control vector $[u_i(t)]^T$ with different weighting factors—in the form of an objective function is a more sensible candidate for resilience cost.

Modern control systems have both the tools and terminology to resolve most of the existing conceptual tension around resilience thinking. Examples of these tensions are desirability of resilience versus non-desirability, perturbation versus changes, a single domain of attraction versus multiple domains of attraction, and whether resilience is inherited or managed.

Most of the present inconsistency in the terminology around the resilience concept in the literature, which is dominated by verbal modeling, can be resolved by system thinking. Table 5 lists equivalent system terms for most of the resilience constituent elements available in the literature and therefore provides resilience with a unified and cross-disciplinary set of terminology. This will alleviate the current conceptual tensions around resilience and pave the way toward resilience operationalization and integration into the relevant standards.

Table 5. System terminology for resilience verbal modeling in the literature.

Resilience Terminology	Equivalent Modern Control Systems (State-Space) Terminology	
• System(s) [1] • System quality [60] • The capacity of a system [141] • The ability of a system [142,143]	System state vector $[x_i(t)]^T$	General system constituent components Terminology
• System performance [140] • System functioning [140]	System output $[y(t)]$	
• Desired services or functionality [144] • Function [93]	System original state $[x_e(t)]$ or another suitable state $[x_s(t)]$	Passive feedback terminology
• System identity or structure [145]	Structural stability	
• System behavior [31]	System state trajectory	
• Resilience cost index [93] • Resilience cost [44]	System state deviation around an objective function (synthesis treatment)	
• Latitude [42] • Diversity [145]	System state vector dimensions/ranges on the phase-space/state-space	
• Rapidity [60] • Resistance [42] • Absorptive capacity [81,82] • Responsiveness [146] • Being modular [83]	Dynamic stability—determined by matrix A (Equation (1)) or Jacobian matrix J, e.g., eigenvalues	
• Cross-scale interactions [1] • Spatial and temporal heterogeneity [1] • Panarchy [42] • Managing connectivity [87] • Openness and modularity [85] • Nestedness [85] • Scale [84]	Subsystem's interaction	
• Robustness [60] • Multiple domains of attraction [1] • Precariousness [42] • Managing slow variables [87] • Critical thresholds [84] • Alternative regimes [84]	Nonlinear state-space models Complexity Bifurcations Stability radius	

Table 5. *Cont.*

Resilience Terminology	Equivalent Modern Control Systems (State-Space) Terminology	
• Functional diversity [1] • Redundancy [60] • Reserves [85,86]	Preset control	
• Rapidity [60] • Restorative capacity [81,82] • Timely recovery [146] • Respond quickly [83]	System state—return to its original or another suitable state	
• Redundant regulations [1] • Response diversity [147] • Resourcefulness [60] • Feedbacks, tightness of feedbacks, polycentric governance [86] • Avoid, withstand [107] • Anticipate, respond [112] • Awareness, preparedness [113]	Robust closed-loop control	
• Adaptive feedbacks [1] • Adapt [107] • Social capital [86] • Adaptability [86] • Learning, experimentation [87] • Learn and monitor [112] • Adaptive capacity [84] • Learning, flexibility, reporting culture [113] • Exposure to disturbances (as a way of experimentation) [83] • Guiding not steering [83]	Adaptive closed-loop control Time-variant state-space models	Active feedback terminology
• Transformation [1] • Irreversible critical thresholds [42,78] • Innovations [86] • Leadership [85] • Inclusive participation [87] • Management commitment [113]	Controllability	

6. Conclusions and Future Research Directions

While the conceptual foundation of resilience does not differ greatly from Holling's seminal proposition, the evolution in terminology across disciplines is predominantly inconsistent and random. This reduces the conceptual integrity and originalism of resilience, creates confusion and unnecessary complexity, and impedes the operationalization of resilience. This is largely due to the fact that the resilience literature has reinvented existing ideas about engineering systems stability—mostly with random verbal modeling that has evolved in isolation—bringing little benefit from the well-established field of modern control systems and relevant system engineering disciplines. There is a diluted use of the term resilience as a synonym to the term robustness (see [148–150]), with the narrow use of the term stability in the resilience context (see [1]) a testament to this confusion.

By reconnecting the resilience literature—which largely remains conceptual—to corresponding ideas in systems will help resilience not only maintain its conceptual integrity but benefit from the rich and well-established tools therein for its design and analysis purposes. Particularly in today's age of big data and automation, the concepts and tools of modern control systems theory will help in the operationalization of resilience thinking in complex socio-technical/ecological systems such as the construction and critical infrastructure sector. This will also pave the way for a more systematic exploration of interrelationships and trade-offs among some of the concepts interpreting resilience as system adaptation. As future research directions, these systematic explorations can include notions of passive feedback, active feedback, system state speed of return to the original state or another suitable state, system structural stability, and other relevant concepts in the context of complex adaptive systems. Application of the proposed resilience systematic framework to the real-world adaptive dynamic systems—from simple second-order mechanical systems to more complex systems such as traffic flow and building infrastructure that are exposed to perturbation and change—are presently being developed by the authors. However, higher dimensionality and global treatment of real-world complex nonlinear systems might hinder the application of the proposed framework, though system tools such as dynamic mode decomposition (DMD) can alleviate the imposed computational rigor.

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