Resilience: A System Interpretation

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Resilience: A System Interpretation

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A thesis in fulfillment of the requirements for the degree of Doctor of Philosophy

School of Civil and Environmental Engineering

Faculty of Engineering

January 2023

To my homeland Afghanistan

for

the unfulfilled dreams and broken commitments

DECLARATIONS

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Publication Details #1

Full Title:	Resilience and Systems—A Review
Authors:	Khalilullah Mayar, David Carmichael, and Xuesong Shen
Journal or Book Name:	MDPI Sustainability
Volume/Page Numbers:	14/8327
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Status:	published
The Candidate's Contribution to the Work:	Khalilullah Mayar performed more than 80% of the work of the publication which includes conceptualization and development of the methodological framework, writing theoretical background, conducting content and results analysis, drafting the initial manuscript, and as the corresponding author addressing all the changes requested by the journal.
Location of the work in the thesis and/or how the work is incorporated in the thesis:	Chapter 2: This chapter constitutes a literature review of the resilience concept as well as introduces the resilience system interpretation framework and relevant system terminology that are utilized in the subsequent chapters case examples.

Publication Details #2

Full Title:	Stability and Resilience—A Systematic Approach
Authors:	Khalilullah Mayar, David Carmichael, and Xuesong Shen
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Location of the work in the thesis and/or how the work is incorporated in the thesis:	Chapter 3: This chapter presents a critical analysis of the stability and resilience concepts and their interrelationships followed by the resilience system interpretation framework application to lumped mass and simple pendulum, two simple linear and nonlinear dynamic systems using the modern control systems theory.

Publication Details #3

Full Title:	Resilience and Systems—A Traffic Flow Case Example
Authors:	Khalilullah Mayar, David Carmichael, and Xuesong Shen
Journal or Book Name:	Civil Engineering and Environmental Systems
Volume/Page Numbers:	NA
Date Accepted/Published:	15 December 2022 (Submission Date)
Status:	submitted
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Location of the work in the thesis and/or how the work is incorporated in the thesis:	Chapter 4: Using simulation scenarios, this chapter applies the resilience system interpretation framework to the modified viscous Burgers' equation and the LWR-Greenshields model equipped with an adaptive Extremum seeking control, and therefore demonstrating the system's state and form return abilities, respectively.

Publication Details #4

Full Title:	Resilience and Systems - A Building Structure Case Example
Authors:	Khalilullah Mayar, David Carmichael, and Xuesong Shen
Journal or Book Name:	MDPI Buildings
Volume/Page Numbers:	13/1520
Date Accepted/Published:	25 December 2022 (Submission Date)
Status:	published
The Candidate's Contribution to the Work:	Khalilullah Mayar performed more than 80% of the work of the publication which includes conceptualization and development of the methodological framework, writing theoretical background, conducting content and results analysis, drafting the initial manuscript including graphical visualizations, and as the corresponding author preparation of the submission package to the journal.
Location of the work in the thesis and/or how the work is incorporated in the thesis:	Chapter 5: This chapter applies the resilience system interpretation framework to sample theoretical and actual building structure dynamic systems. Using the relevant systems' passive and active feedback mechanisms, the systems' states and forms return abilities are demonstrated respectively.

Candidate's Declaration

I confirm that where I have used a publication in lieu of a chapter, the listed publication(s) above meet(s) the requirements to be included in the thesis. I also declare that I have complied with the Thesis Examination Procedure.

PUBLICATIONS

Publications related to this thesis are listed below:

Journal Publications Accepted/Published:

1. Mayar, K., Carmichael, D.G., Shen, X., 2022. Resilience and Systems—A Review. Sustainability 14, 8327. https://doi.org/10.3390/su14148327
2. Mayar, K., Carmichael, D.G., Shen, X., 2022. Stability and Resilience—A Systematic Approach. Buildings 12, 1242. https://doi.org/10.3390/buildings12081242
3. Mayar, K., Carmichael, D.G., Shen, X., 2023. Resilience and Systems—A Building Structure Case Example. Buildings 13, 1520. https://doi.org/10.3390/buildings13061520

Journal Publications Submitted/Under Review:

4. Mayar, K., Carmichael, D.G., Shen, X., 2022. Resilience and Systems —A Traffic Flow Case Example. Civil Engineering and Environmental Systems (Submitted on 15 December 2022)

Khalilullah Mayar
January 2023

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ABSTRACT

Resilience has increasingly become a crucial subject to evaluate the function of various real-world systems from ecology, social sciences, and medicine to engineering, critical infrastructure, and the built environment - as our planet and its constituent systems are undergoing a rising trend of perturbations, uncertainty, and change due to natural, human and technological causes. The absence of resilience measures within systems causes the systems not only to deviate from their intended functions under perturbations but also allows the systems themselves to become inefficient and obsolete in the face of the rapidly changing requirements with considerable social, environmental, and economic consequences.

Despite its ubiquitous use and practical significance, the term resilience is often poorly and inconsistently used in various disciplines, hindering its universal understanding and application. There is a broad acknowledgment in the literature of a lack of consensus on whether resilience is an inherent system characteristic or a management process. Hence, this thesis adopts a holistic approach giving resilience a system interpretation and argues that much of the resilience literature covers the existing ground in that existing engineering systems stability ideas are being reinvented. The approach used here 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 resilience system interpretation framework defines resilience as 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.

Various case examples, from plain lumped mass and simple pendulum dynamic systems to, traffic flow and building structure dynamic systems, are utilized to illustrate the resilience system interpretation framework proposed in the thesis. The thesis provides a conceptual cross-disciplinary system framework that offers the potential for a greater understanding of resilience and the elimination of overlap in the literature, particularly as it relates to terminology. In addition, using state-space approaches it quantitively as

well as qualitatively evaluates the resilience of cross-disciplinary case systems by utilizing the system's inherent characteristics and management processes. The thesis will be of interest to both academics and practitioners involved in resilience analysis, measurement, and design across various engineering disciplines and by extension any other discipline to enable proactive responses to perturbations while actively adapting to change.

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CHAPTER 1. INTRODUCTION

1.1 Motivation

Resilience has increasingly become a prevalent term in the 21st century's scientific and policy discourses as the world undergoes a future where perturbation and change are the new normal, and the concepts of volatility, uncertainty, complexity, and ambiguity (VUCA) are becoming part of our surroundings [1,2]. Resilience addresses this novel and complex understanding of the world by seeking to circumvent traditional equilibria-based approaches and concentrate instead on the adaptation and transformation of existing systems [3]. Considered to be a shift left, resilience takes a proactive approach rather than a reactive response to ensure that systems recover and adapt against both natural and man-made perturbations as well as change. Such perturbations can be triggered and intensified by stress factors and change drivers such as global economic competition, demographic shifts, rapid urbanization, the rise of technology, and the increased level of interconnectedness, climate change, and resource scarcity [4–7]. The increased level of interconnectedness contributes to cascade failures in a perturbed system. Natural or environmental risks have become the most prevalent among the economic, geopolitical, societal, and technological categories [1]; as natural perturbations have increased significantly by 80% since 1950. This increase includes climate change-related events that can severely incapacitate physical infrastructure, endanger both people's safety and environmental conservation, cause economic losses, and therefore impede sustainable development processes [8,9].

Despite its practical significance and its ubiquitous use in the literature, researchers and policymakers have mainly approached the concept of resilience randomly without a systematic and holistic foundation. This has been evident in various policy documents such as the UNISDR Sendai Framework 2015-30 for disaster risk reduction and resilient infrastructure, the new urban agenda 2030 for sustainable and resilient cities, and within the built environment, where resilience regularly serves vague institutional objectives but lacks a systematic and instrumentalized interpretation [10,11]. The randomness of the resilience concept is majorly because of the vast verbal modelling found within the literature to describe resilience and its constituent elements without a systematic foundation [see Table 2.5]. This has led to a poor, even skewed, and conflicting understanding of the term resilience, an insipid implementation in practice, and difficulty with its interpretation and integration into relevant standards and regulations. Cerè et al. (2017) argue that the pale implementation of resilience in the context of the built environment has led to resilience becoming just another buzzword after sustainability.

1.2 Aims and Scope

Given that modern stability has covered similar territory within the context of dynamic systems, this thesis utilizes the control system theory framework, which links stability and its relevant control actions with resilience. The central goal of this study is - using the control system theory to universally apply the proposed resilience system interpretation framework defined as adaptability and adaptive systems to a variety of systems across disciplines. The framework is then divided into two main components of the system state and form return abilities which are enabled by the system passive and active feedback structures respectively. This approach gives resilience a system interpretation that will be applicable across various engineering disciplines and by extension any other discipline.   The thesis makes use of various real-world and theoretical systems models in the form of case examples to support different areas of the study. Models from the selected case examples follow a control systems convention where each system is presented in the form of inputs (controls), states, and outputs (responses) and is shaped by the interaction of inputs and outputs across the system boundary (external environment) through a system state that is not always measurable and observable [13]. The main focus of the study is on the system state vector and its deviation from the equilibrium [initial state] as a result of perturbations, its return to equilibrium, and/or steering [controlling] it into a particular trajectory under change. This thesis aims to give resilience a system and unified interpretation, to understand the interrelationships between its various components and their interaction with the environment. Resilience analysis and design methods can then be more consistent, which will pave the way for resilience implementation in practice as well as its integration in the relevant standards and regulations. Various case examples, from plain lumped mass and simple pendulum dynamic systems to traffic flow and building structure dynamic systems, are utilized to illustrate the resilience system interpretation framework proposed in the thesis.

1.3 Significance

This thesis proposes a resilience system interpretation framework that applies to every system irrespective of its disciplinary association. The concept is supported by case examples from various disciplines, including simple electrical/mechanical systems, traffic flow systems, and building structure systems. The framework also offers the potential for a greater understanding of resilience and the elimination of overlap in the literature, particularly related to terminology. The study utilizes a modern control systems approach with the potential and tools to analyse, measure, and design resilience and its constituent elements across various disciplines. The framework is considered comprehensive and systematic as it encompasses resilience both as an inherent system property and as a management process using passive and active feedback structures respectively. It also has the ability to accommodate non-engineering disciplines in that a resilience problem can be defined in system terms. The thesis will be of benefit to academics, practitioners, and policymakers working across disciplines, particularly construction and the built environment, giving a unified and universal understanding of resilience and thus helping the development of new tools and methods for incorporating resilience into relevant standards.

1.4 Outline and Organization

This thesis is composed of six chapters (Figure 1.1). Following this introductory chapter, Chapter 2 presents a review of state-of-the-art of resilience, structured around the seminal conceptual works on resilience using the modern controls systems theory framework. 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 both passive and active feedback mechanisms. These feedback mechanisms can return the system state or system form to a starting position or transition to another suitable state or form. The review introduces the resilience system interpretation framework, which gives resilience and its elements strict and holistic definitions in terms of passive and active control mechanisms under the modern control systems theory framework. Chapter 2 also introduces general terminology of systems and the control system theory framework such as systems, sub-systems, and sub-system interaction; system state vector, inputs, and outputs; state equations, and their standard forms; continuous and discreet time models; linear and nonlinear models; deterministic and stochastic models; system model constraints, objective function, and three basic types of engineering problem solving configurations.

Chapter 3 is a pivotal part of the thesis, introducing stability concepts such as equilibrium, local and global stabilities, asymptotic and finite stabilities, Lyapunov stability, etc., from the control systems theory framework and then placing stability into two broad categories: dynamic and structural stability. Stability is then linked with resilience thinking, divided under its system state and form return abilities in response to perturbation and change. The return abilities are supported by the illustrations of lumped mass and simple pendulum systems - two simple linear and nonlinear dynamic systems.

In Chapter 4, the resilience system interpretation framework is applied to sample traffic flow systems exposed to perturbation and change. Both components of the system framework are demonstrated through theoretical simulation scenarios on the modified viscous Burgers' equation and the LWR-Greenshields model equipped with an adaptive Extremum seeking control, respectively.

The resilience system interpretation framework to sample building structure systems exposed to perturbation and change is explored in Chapter 5. A sample simulation scenario is conducted for a sample 3-story Steel Moment Resisting Frame (SMRF) office building, along with change integration concepts in a closed-loop control setting of synthesis treatment.

The summary, conclusions, limitations, and future work are presented in Chapter 6.

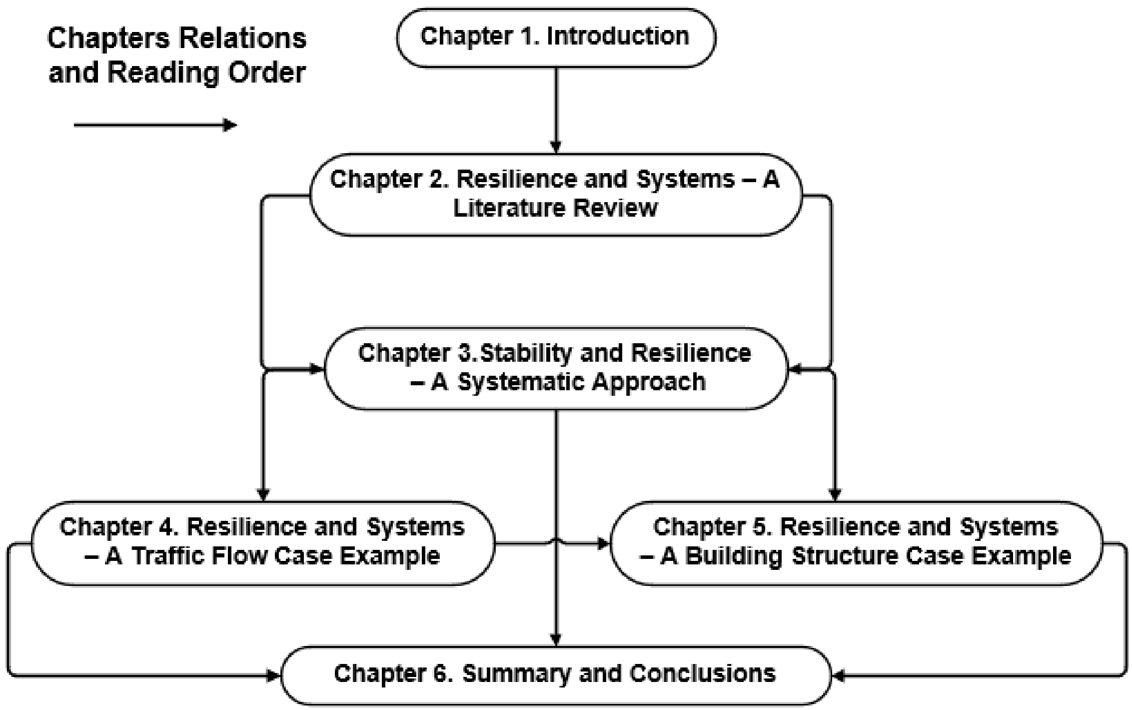

Figure 1.1. Thesis map indicating interrelationships between chapters and suggested reading order

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CHAPTER 2. RESILIENCE AND SYSTEMS – A REVIEW

2.1 Link to Thesis

In Chapter 2, I presented a critical review of the resilience literature across various disciplines since its re -emergence as an ecological concept in 1973. The review confirmed that most of the resilience literature across disciplines is inconsistent, majorly based on verbal modelling and lacks a systematic foundation. The chapter introduced the resilience system interpretation framework which utilizes controls systems theory as a comparison framework and define resilience as adaptation and adaptive systems where the system exposed to perturbations and change has the ability to return to its initial or other suitable state or form respectively. The framework is subsequently applied to four different case examples studied in Chapters 3-5.

I have published this work:

1. Mayar, K., Carmichael, D.G., Shen, X., 2022. Resilience and Systems—A Review. Sustainability 14, 8327. https://doi.org/10.3390/su14148327

2.2 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

2.3 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 2.5.2 and 2.5.4).

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 directly toward that gap by unifying various conceptual understandings of the term resilience across disciplines by utilizing the control systems terminology as well as bringing resilience under a single umbrella that accommodates both resilience as a an inherent system property and as management process.

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. However, a varied disciplinary treatment of the resilience might be helpful for boosting inter-disciplinary discussions, it hurdles the resilience universal interpretation that is consistent with its conceptual integrity and is required for its analysis, design, measurement, and integration into the relevant standards. 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 2.5 looks at a range of variants and extensions of resilience across disciplines, including terminology and resilience conceptual analysis. Section 2.6 defines general terminology on control system theory and system state-space representation. Subsequently, Section 2.7 presents resilience as an alternative to adaptation in system terms. The conclusions and future research directions follow.

2.4 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’ [1](p.17)[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 2.1 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 2.2). 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 2.1), with some authors quite prolific (Table 2.2). Some publications attract citations more than others (Table 2.3), 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.

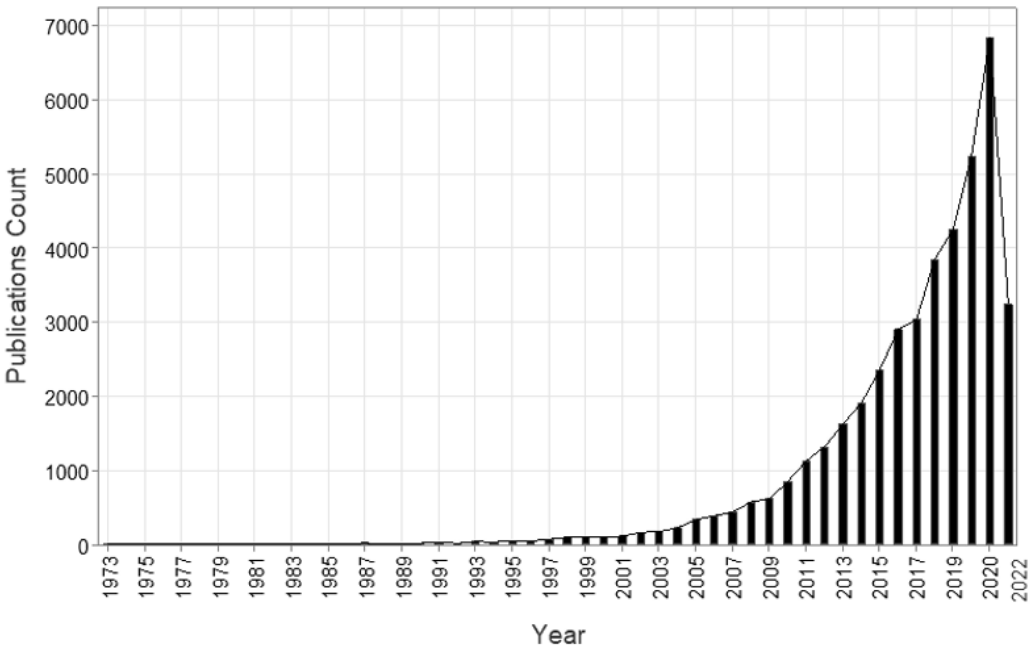

Figure 2.1. Number of publications with resilience in their titles—November 1973 to June 2022. Data source: Scopus [50].

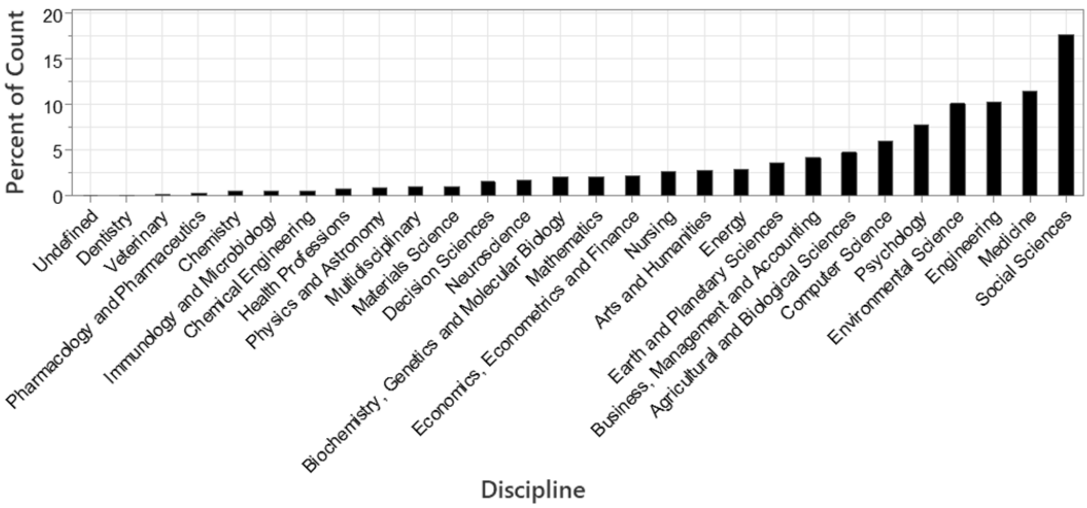

Figure 2.2. Number of publications with resilience in their titles—November 1973 to June 2022. Data source: Scopus [50].

Table 2.1. 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 2.2. 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
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 2.3. 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

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 2.3 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.

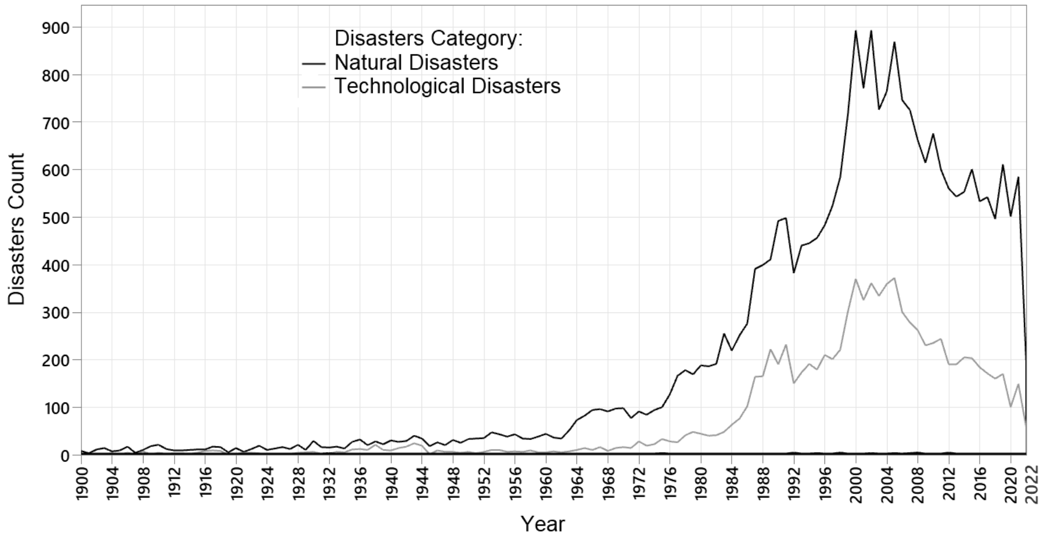

Figure 2.3. World disasters count for natural and technological categories from 1900. Data source: EM-DAT [62]The complex disasters category would not be visible on the scale of Figure 2.3 because the numbers are very small.

2.5 Resilience Variants and Extensions

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

2.5.1 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 majorly verbal modelling and 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.

2.5.2 Introduced Terminology

Resilience is a fruitful source of new terminology, introduced as part of verbal modelling 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].

2.5.3 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 2.4). 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].

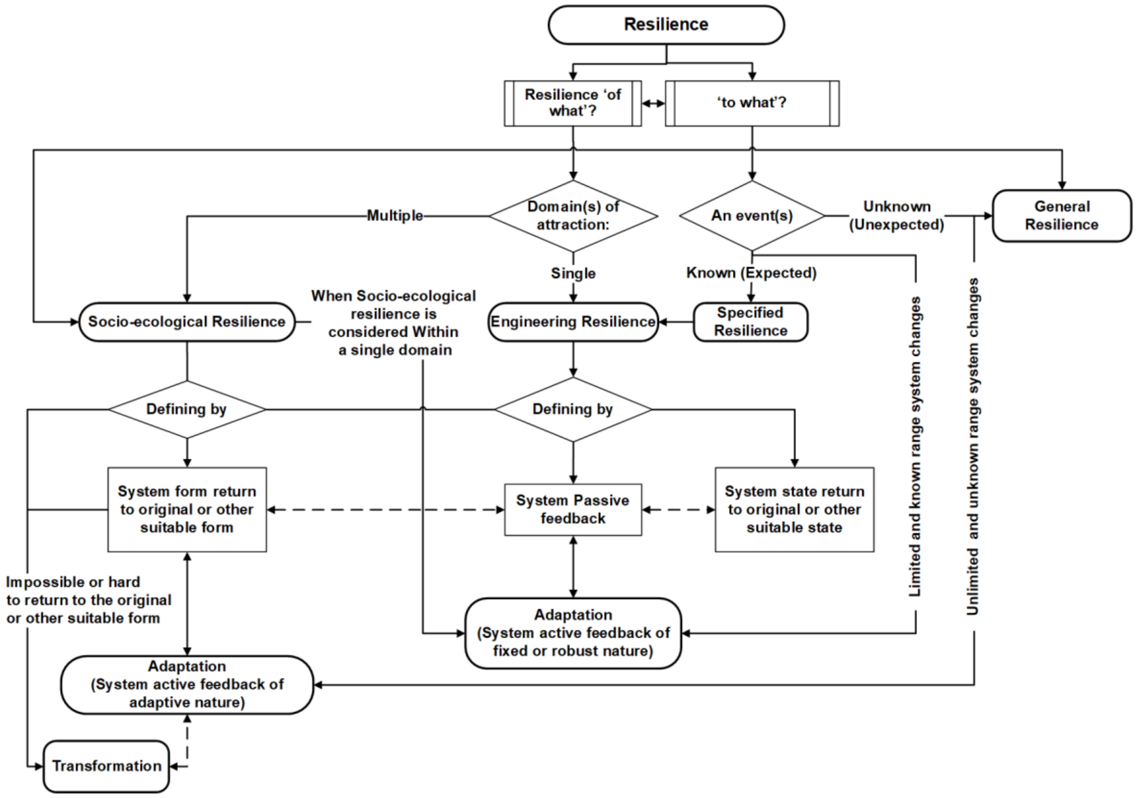

Figure 2.4. Resilience interpretation in terms of adaptation: a big picture.

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 2.4).

2.5.4 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 modelling 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 centred on certain objective functions such as system-required functionality and behaviour.

2.5.5 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].

2.6 Systems Terminology

This section introduces much of the necessary terminology of dynamic systems, with a particular emphasis on modern control systems (Table 2.4), which is subsequently utilized in Section 2.7 to describe resilience in terms of adaptive systems and adaptation. The terminology is also used to regroup most of the inconsistent verbal modelling in the resilience literature around the system terms.

Table 2.4. 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 behaviour [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 behaviour 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 behaviour 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 2.5), where its evolution/trace over time is called the state trajectory and its graphical representation is labelled as the phase portrait [125,126].
• 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 behaviour, 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 (2.1) and (2.2) are continuous linear state-space equations for the system state and output, respectively. $\dot{x}(t) = A\,x(t) + B\,u(t)$ (2.1) $y(t) = C\,x(t) + D\,u(t)$ (2.2) A—is the system, state, or dynamic matrix of (n × n) dimension, B—is the input or control matrix of (n × m) dimension, C—is the output matrix of (p × n) dimension, and D—is the direct transfer or feedforward matrix of (p × m) dimension, which is normally the zero or null matrix (Figure 2.6).
• 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 (2.3)) and output (Equation (2.4)) equations where fi and gj are scalar arguments of the state ($[x_1, x_2, \dots, x_n]^T$), input ($[u_1, u_2, \dots, u_m]^T$), and time (t) vectors (for the time-invariant case, the term t is absent in the model) [129,130] (Figure 2.7). $\dot{x}(t) = f[x(t), u(t), t] = \begin{bmatrix} f_1(x(t), u(t), t)) \\ f_2(x(t), u(t), t)) \\ \vdots \\ f_n(x(t), u(t), t)) \end{bmatrix}$ (2.3) $\dot{y}(t) = g[x(t), u(t), t] = \begin{bmatrix} g_1(x(t), u(t), t)) \\ g_2(x(t), u(t), t)) \\ \vdots \\ g_p(x(t), u(t), t)) \end{bmatrix}$ (2.4)
• 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].
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 (2.1) 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 (2.6)) entails both the control law- using matrix H (Equation (2.5)) and control matrix B (Equation (2.6)). $u(t) = -\mathrm{H}\,\mathrm{x(t)}$ (2.5) $\dot{\mathrm{x}}(\mathrm{t}) = \mathrm{A}\,\mathrm{x(t)} + \mathrm{B}\,(\mathrm{H}\,\mathrm{x(t)}\,) = (\mathrm{A} - \mathrm{BH})\,\mathrm{x(t)}$ (2.6) For nonlinear systems (Equation (2.3)), 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 (2.6)). For global behaviour of the nonlinear systems, control actions such as Control Lyapunov Functions (CLF) (full state-based control) (Figure 2.7) 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 2.8). 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].

2.7 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 2.4). 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 2.5.3 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 2.5).

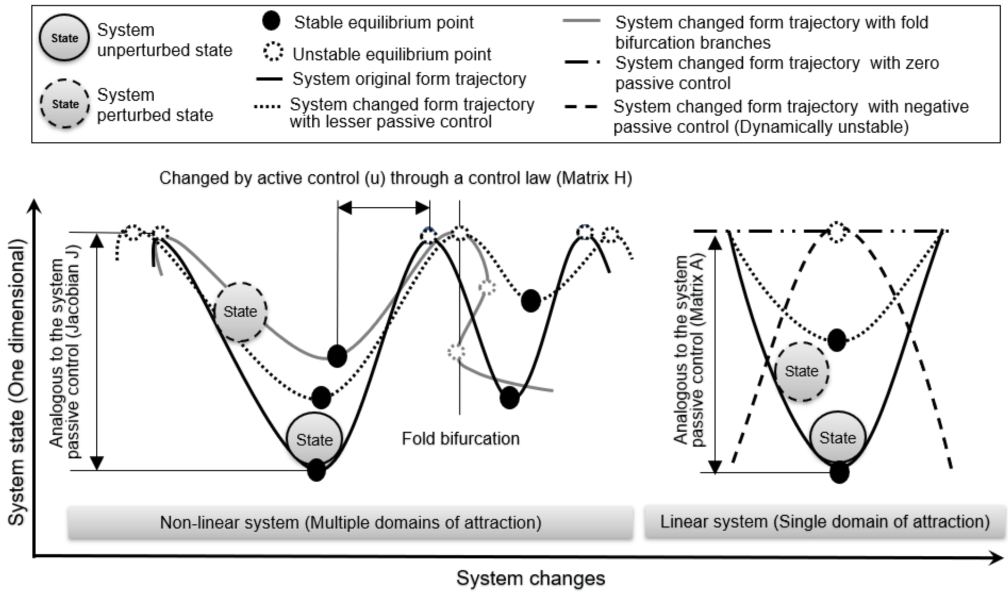

Figure 2.5. Changes to the system state and form: a graphical illustration of the resilience for a single dimensional system.

For the engineering resilience category, the systems are simple linear systems of a continuous or discrete nature (including locally linearized nonlinear systems)(Figure 2.6), 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 (2.1) and (2.3)). 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 2.5) does not change, and therefore it may fall below the optimal or robust control categories (Figures 2.5 and 2.6).

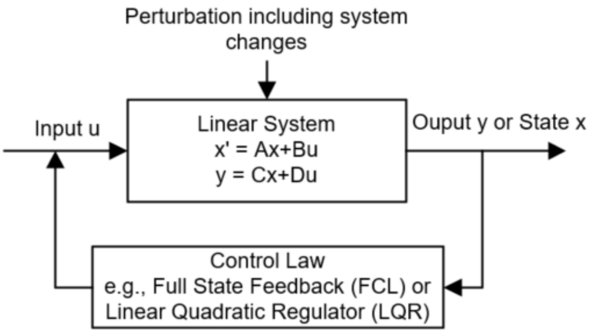

Figure 2.6. Block diagram illustration of a linear system state equations model with full-state feedback: an illustration for engineering resilience.

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 2.7), 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 2.5) 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 2.5 and 2.7).

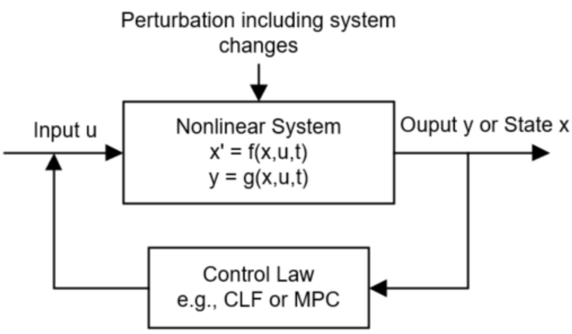

Figure 2.7. Block diagram illustration of a nonlinear system state equations model with full-state feedback: an illustration for socio-ecological resilience.

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 2.8).

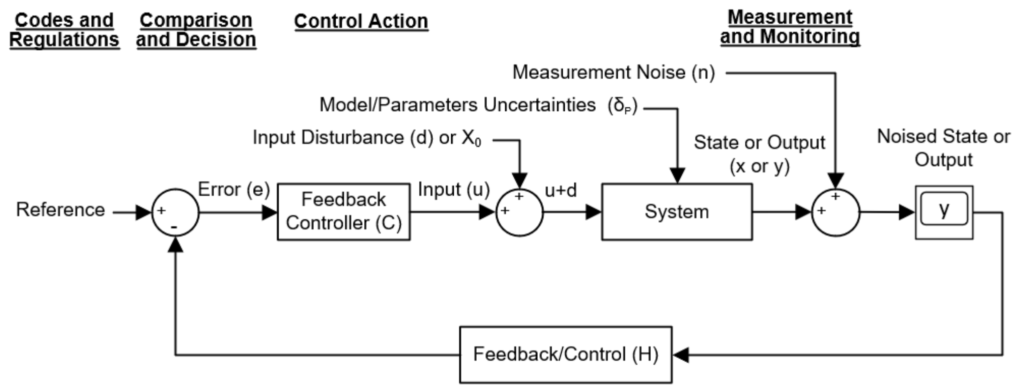

Figure 2.8. System active feedback along with its constituent elements: an illustration of resilience.

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 modelling, can be resolved by system thinking. Table 2.5 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 2.5. System terminology for resilience verbal modelling 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 $[x_s(t)]$	
• 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	Passive feedback terminology
• Rapidity [60] • Resistance [42] • Absorptive capacity [81,82] • Responsiveness [146] • Being modular [83]	Dynamic stability—determined by matrix A (Equation (2.1)) or Jacobian matrix J, e.g., eigenvalues	
• Cross-scale interactions [1] • Spatial and temporal heterogeneity [1] • Panarchy [42]	Subsystem’s interaction	

• Managing connectivity [87] • Openness and modularity [85] • Nestedness [85] • Scale [84]		
• 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	
• 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	

2.8 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 modelling 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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CHAPTER 3. STABILITY AND RESILIENCE—A SYSTEMATIC APPROACH

3.1 Link to Thesis

In Chapter 3, I presented a critical review of the modern stability concepts and their classification into two major categories of dynamic and structural stability. Stability is then linked with resilience thinking using the resilience system interpretation framework which was introduced in Chapter 2. The framework is subsequently applied to lumped mass and simple pendulum systems - two simple linear and nonlinear dynamic systems to illustrate the system state and form return abilities in response to perturbations and change.

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3.2 Abstract

Stability and resilience are two crucial concepts to the proper functioning and understanding of the behaviour of both natural and man-made systems exposed to perturbations and change. However, although the two have covered a similar territory within dynamic systems, the terminology and applications differ significantly. This paper presents a critical analysis of the two concepts by first collating the wealth of modern stability concept literature within dynamics systems and then linking it to resilience thinking, defined as adaptation where the system has the ability to respond perturbations and change through passive and active feedback structures. A lumped mass and simple pendulum, two simple linear and nonlinear dynamic systems following a state-space approach from modern control systems theory, are used to support the analysis and application. The research findings reveal that the two overarching categories of engineering resilience and socio-ecological resilience (extended ecological resilience) are in fact a reinvention of a closed-loop system dynamic stability with different types of active feedback mechanisms. Additionally, structural stability describes some vital aspects of social–ecological resilience such as critical thresholds

where, under change, a system loses the ability to return to the starting form or move to another suitable form through active feedback mechanisms or direct management actions.

Keywords: modern stability concept; dynamic stability; structural stability; passive control; active control; engineering resilience; socio-ecological resilience; state-space approach; modern control systems theory

3.3 Introduction

Stability and resilience are two crucial concepts to the proper functioning and understanding of the behavior of both natural and man-made systems exposed to perturbations and change. However, although they cover a similar territory within dynamic systems, the terminology and applications differ significantly. The concept of stability, initially referred to as classical stability and significantly influenced by celestial mechanics, was first employed in 1749 by the Swiss mathematician Leonhard Euler in the context engineering mechanics–statics to describe the equilibrium of columns as rigid bodies under critical buckling load [1–3]. In 1892, the Russian mathematician Aleksandr Mikhailovich Lyapunov produced the seminal PhD thesis: A general task about the stability of motion introducing the classical stability strand through a precise mathematical formulation. This is considered to be the beginning of the modern stability concept, which has profoundly contributed to the development of modern control systems theory. Since then, the stability concept has evolved greatly, with applications to many other disciplines including economics, numerical analysis, quantum mechanics, nuclear physics, and control systems theory through a unified, consistent, and systematic approach and terminology [1]. A general definition for modern stability might either fall under a system's resistance to change (structural stability) or a system's state tendency to return to its initial state in response to a perturbation (dynamic stability) [4].

In addition, there is another strand of the stability concept, first introduced by Odum [5] as an ecological stability concept in the context of ecology and relevant sciences, which has benefited less from systematic and empirical work and its conceptual integrity remains fragmented with no consensus on its definition [6]. Grimm and Wissel [7] give an exhaustive review of the ecological stability terminology and conclude that ecological stability within a certain ecological context can be fully or partially described by six properties of constancy, resilience (in a narrow sense of returning to the equilibrium after a temporary disturbance), persistence, resistance, elasticity and the domain of attraction. These, on their own, are vague and conflicting notions.

On the other hand, the word resilience originates from the Latin word ‘resiliere’, which translates as ‘bounce back’. This term was first used in 1807 by the English physicist Thomas Young to explain elastic deformation within the context of material sciences [8,9]. As an ecological concept resilience first appeared in academic parlance with Holling and was subsequently divided into two categories: ecological resilience and engineering resilience [10,11]. The former, which is wider in scope, is defined by the dynamics far from any equilibrium steady-state and is measured by the magnitude of perturbation (change) bearable by a system before it flips to another stability domain (flipping to an irreversible or hard to reverse stability domain). The new system structure is achieved through changes in the variables and processes that govern the system. The latter, engineering resilience, is more limited in scope and is defined by the dynamics close to an equilibrium steady-state. Engineering resilience is measured by the resistance to perturbation, and the speed of return to an equilibrium steady-state after a disruption event takes place [11]. Although there has been substantial evolution to the concept of resilience over the past five decades and its extension to applications beyond ecological systems, it is still mostly approached randomly and has benefited less from systematic research [12].

In contrast to the historical precedence and academic prevalence of the term stability (the classical stability strand, currently branded as the modern stability concept) it covers a similar sphere to the term resilience. Although there is a well-established and systematic body of knowledge regarding stability, this has not been applied to resilience thinking, which largely remains scattered and is less ubiquitous compared to stability. Figure 3.1 shows the publications concerned with stability, with engineering and related sciences on the top of the list. The journals with the most publications are the *Proceedings of The IEEE Conference on Decision and Control* and *IEEE Transactions on Automatic Control,* while ecological-related disciplines remain at a considerably lower level. On the contrary, publications related to resilience (Figure 3.2) are dominant in the social sciences journals, with the greatest number of articles appearing in *Sustainability Switzerland* and *Ecology and Society* [13].

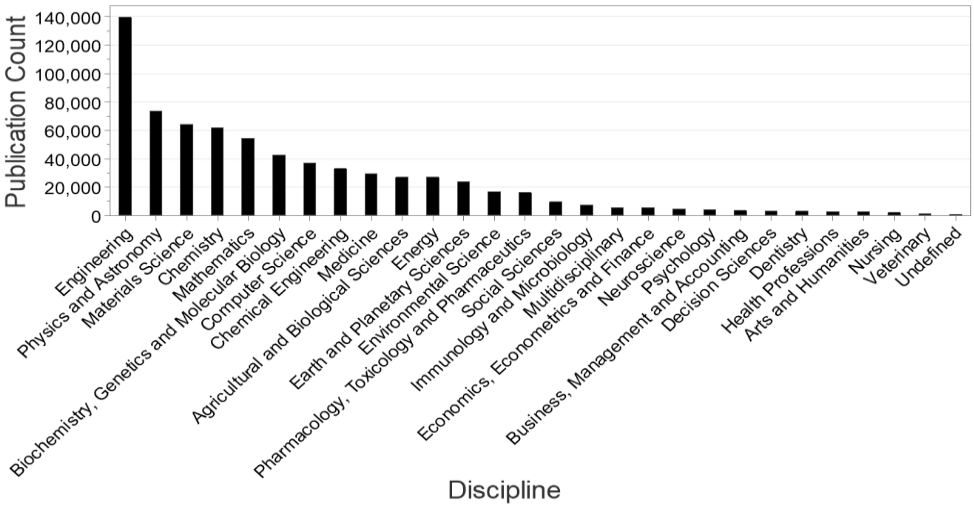

Figure 3.1. Publication counts listing stability in their titles. Data source: [13].

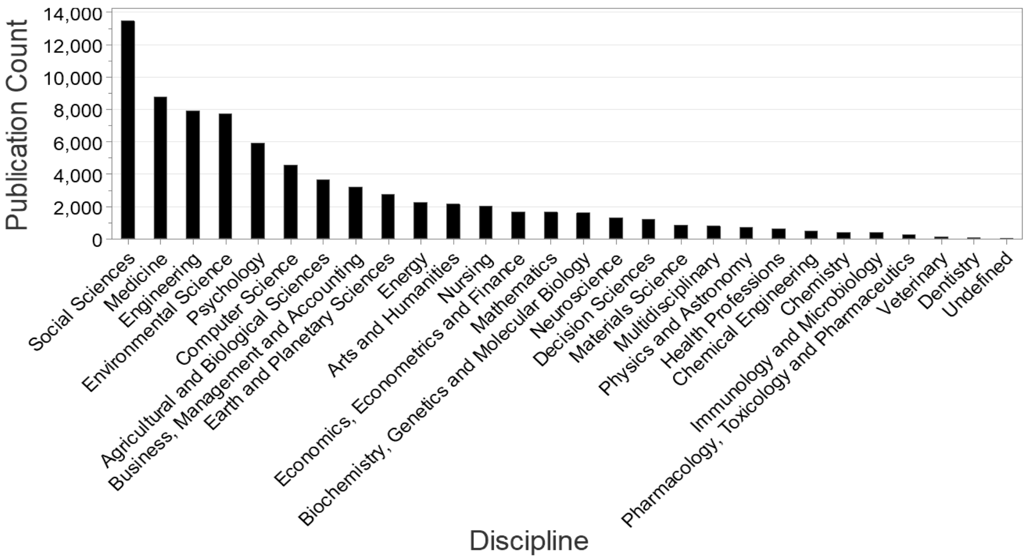

Figure 3.2. Publication counts listing resilience in their titles. Data source: [13].

Some researchers have tried to apply the concept of ecological stability to resilience thinking, where both concepts often lack a unified and systematic conceptual foundation. Figure 3.3 lists the publication counts of articles that mention both the word “stability” and “resilience” in their titles; here, the environmental and social science domains are the dominant disciplines and Ecological Indicators is the top journal [13]. Van Meerbeek et al. [14] conducted a systematic review of stability versus resilience in the ecological context and argue that ecological stability is the overarching concept while resilience along with recovery, tolerance, and latitude are the constituent concepts. This view is also shared in other similar theoretical studies, either in full

[15,16] or in part [17]. However, the main issue in these studies is the narrow and diluted treatment of resilience, equating it only with a system's fixed rate of return to equilibrium without considering the fact that resilience can be achieved through both the inherent system characteristics and management that can be thought of as adaptation. Additionally, the treatment of stability in these studies mostly omits the modern strand of stability and tend to concentrate on the ecological strand of stability, where there is no consensus on its definition. On the other hand, some researchers who have tried to apply the modern strand of stability to the resilience thinking have either covered a sub-class of stability [10,18] or have considered resilience in a diluted and incomplete fashion [18].

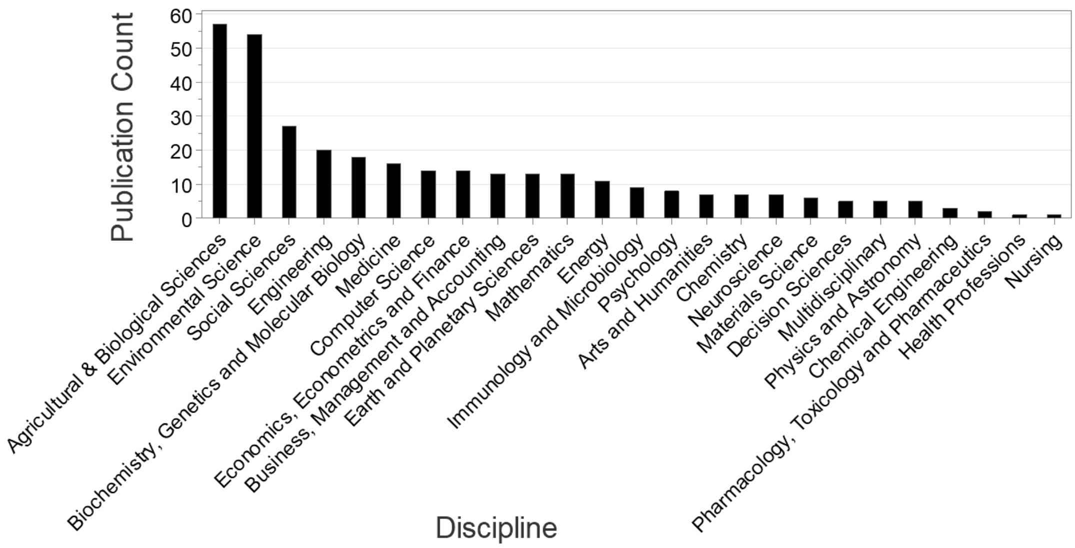

Figure 3.3. Publication counts listing both stability and resilience in their titles. Data source: [13].

This paper attempts to apply the modern strand of the stability concept, with its established and systematic terminology from modern control systems theory to resilience thinking in the form of adaptation [19]. Such a methodology will provide a much needed and original contribution to the body of the knowledge. The study is structured as follows. Section 3.4 introduces the methodological framework and case examples for supporting the arguments put forward in the subsequent sections. Section 3.5 provides a state-of-the-art review of concepts of stability in dynamic systems from a control systems theory perspective. In Section 3.6 stability is categorized into two broad divisions of dynamic and structural stabilities. A comprehensive conceptual framework is introduced in Section 3.7 that connects the concepts of modern stability and their application to resilience thinking, supported by illustrations of two simple linear or nonlinear dynamic systems. Lastly, Section 3.8 presents a summary and discussion.

3.4 Methodology and Analysis Tools

This paper utilizes a state-space approach from the modern control systems theory where every system has inputs (controls), states, and outputs (responses). Such an approach is shaped by the interaction of inputs and outputs across the system boundary (external environment) through a system state that is not directly measurable and observable. The inputs are those that could potentially be influenced by the system operators (excluding disturbance) while the outputs and states represent the system performance [20]. To support and consolidate stability classification and its application to resilience thinking throughout the paper, two simple linear and nonlinear dynamic systems, a lumped mass (a single degree of freedom structure subjected to a lateral loading) and simple pendulum, are utilized (Table 3.1; Figure 3.4).

Table 3.1. Dynamic system case examples for stability and resilience thinking.

System	System Model	System States, Input, and Output	System Parameters and Equilibrium States	Source
Case example 1: Lumped mass dynamic system (a single degree of freedom structure subjected to a lateral loading such as an earthquake)—a linear time-invariant second-order dynamic system.	Model initial form: $m\ddot{y} + c\dot{y} + ky = -m\,\ddot{y}_0$ (3.1) State-space form: $\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\frac{k}{m} & -\frac{c}{m} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ -1 \end{bmatrix} [u]$ (3.2) $[y] = [1 \quad 0] \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + [0]\,[u]$ (3.3) Alternative frequency form: $\frac{d^2y}{dt^2} + 2\zeta\,\omega_n \frac{dy}{dt} + \omega_n^2\, y(t) = u$ (3.4)	$x_1 = y$ (displacement) $x_2 = \dot{y}$ (rate of displacement) $u = \ddot{y}_0$ (seismic acceleration as the input variable) $y = x_1$ (displacement as the system output)	m = 1, mass of the structure; C = damping coefficient; K=4, elastic stiffness of the structural materials; y_0 = ground displacement due to earthquake; y = displacement of the mass relative to the ground due to earthquake. System natural frequency: $\omega_n = \sqrt{\frac{k}{m}}$ (3.5) System damping ratio expressed as a ratio of the damping coefficient: $\zeta = \frac{c}{2\,m\,\omega_n} = \frac{c}{c_{cr}}$ (3.6) $\zeta = 0$ (not damped); $\zeta < 1$ (under damped); $\zeta = 1$ (critically damped); $\zeta > 1$ (over damped); Equilibrium: $(x_{1e}, x_{2e}) = (-\frac{u}{\omega_n^2}, 0)$ (3.7) Eigenvalues/poles: $\lambda_{1,2} = -\zeta\,\omega_n \pm \omega_n\sqrt{\zeta^2 - 1}$ (3.8)	[21]

Case example 2: Simple pendulum system—a nonlinear time-invariant second-order dynamic system.

Model initial form:

$$\ddot{\theta} + \frac{c}{m}\dot{\theta} + \frac{g}{l}\sin\theta = u \qquad (3.9)$$

State-space form:

$$x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} \dot{\theta} \\ \theta \end{bmatrix}$$

$$\dot{x}(t) = f(x, u) = \begin{bmatrix} u - \frac{g}{l}\sin x_2 - \frac{c}{m}x_1 \\ x_1 \end{bmatrix} \qquad (3.10)$$

$x_1 = \dot{\theta}$ (rate of angular displacement)

$x_2 = \theta$ (angular displacement)

u (acceleration triggered by the relevant torque as the input variable)

$y = x_2$ (angular displacement as the system output)

θ = displacement angle of the pendulum with the vertical direction;

l = 1000, length of the rod;

m =100, mass of the attached weight (w);

C = damping coefficient;

g = 9810, gravitational acceleration;

u = acceleration triggered by the relevant torque;

Jacobian matrix:

$$\left(\frac{df}{dx}\right) = \begin{bmatrix} -\frac{c}{m} & -\frac{g}{l}\cos x_2 \\ 1 & 0 \end{bmatrix} \qquad (3.11)$$

Equilibrium1 $(x_{1e}, x_{2e}) = (0, 0)$: stable

Equilibrium2 $(x_{1e}, x_{2e}) = (0, \pi)$: unstable ;

The two equilibria in a combined form:

Equilibrium $(x_{1e}, x_{2e}) = (0, k\pi)$

Eigenvalues/poles:

$$\lambda_{1,2} = -\frac{c \pm \sqrt{\frac{lc^2 - 4gm^2}{l}}}{2m} \qquad (3.12)$$

[22,23]

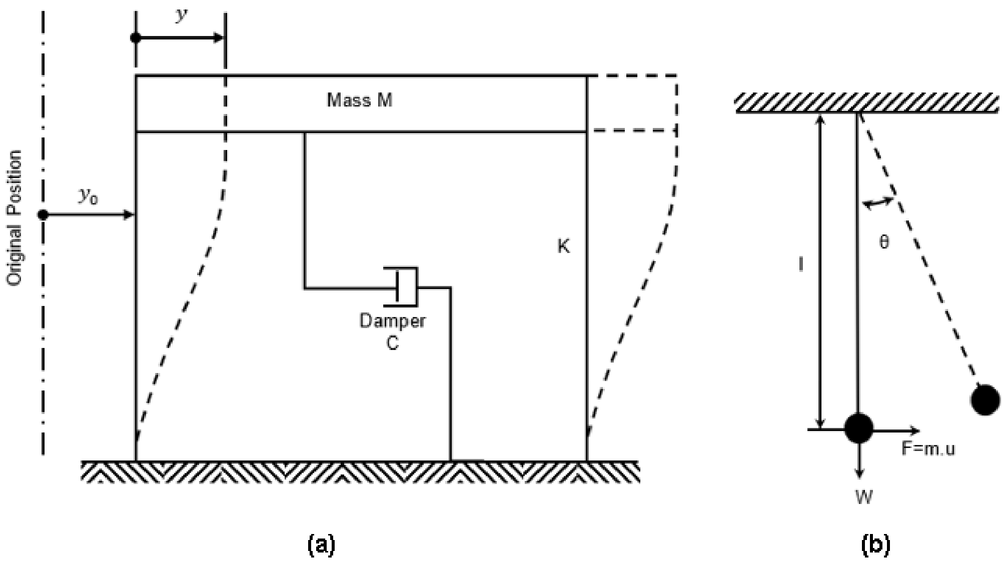

Figure 3.4. Two linear and nonlinear dynamic systems utilized in the study: (a) single degree of freedom structure subjected to a later loading. Source: adapted from Carmichael [21]. (b) A schematic diagram of a simple pendulum.

3.5 A Review of Stability Concept Terminology

This section introduces the main concepts and tools available under the realm of the modern stability concepts within the context of control systems theory. Table 3.2 introduces each of these well-established major concepts in system terms.

Table 3.2. Modern stability concepts terminology.

Stability Concept	Definition
System	A system is an assemblage of functionally related components forming a unity whole to achieve a certain purpose [20,24–26]. A system is described by the overarching fundamental variables of state (x), input (u), and output (y). Equations (3.13–3.16) describe the linear time invariant and nonlinear time variant continuous systems, where A is the system state or dynamic matrix, B is the input or control matrix, C is the output matrix, and D is the direct transfer or feedforward matrix. fi and gj are scalar arguments of the state, input, and time (t) vectors [27,28]. $\dot{x}(t) = A\,x(t) + B\,u(t) \quad (3.13)$ $y(t) = C\,x(t) + D\,u(t) \quad (3.14)$ $\dot{x}(t) = f[x(t), u(t), t] = \begin{bmatrix} f_1(x(t), u(t), t)) \\ f_2(x(t), u(t), t)) \\ \vdots \\ f_n(x(t), u(t), t)) \end{bmatrix} \quad (3.15)$

	$$\dot{y}(t) = g[x(t), u(t), t] = \begin{bmatrix} g_1(x(t), u(t), t)) \\ g_2(x(t), u(t), t)) \\ \vdots \\ g_p(x(t), u(t), t)) \end{bmatrix} \quad (3.16)$$
Perturbations and change	Perturbations and changes cause a system state or a system form to deviate from its initial state or initial form [29,30].
Equilibrium	Equilibrium is a system state value at the system state space where the system lies at rest (with zero rate of change). It has either a stable or unstable region around it [31].
• Stable equilibrium	Equilibrium is said to be dynamically stable (attractor) when a system state perturbed by a bounded external perturbation from its equilibrium state remains bounded, including a return to the equilibrium [32]. It can also be dynamically stable when the system state matrix/Jacobian eigenvalues/poles lie within the left half-plane (LHP) [33].
• Unstable equilibrium	Equilibrium is said to be dynamically unstable (repellor) when a system state perturbed by a bounded external perturbation from its equilibrium state remains unbounded [32], or when the system state matrix/Jacobian eigenvalues/poles lie within the right half-plane (RHP) [33].
Local stability	Common in nonlinear systems where the system domain of attraction covers only a certain area in the phase space. If the system state is perturbed within the boundary of this domain of attraction, it will asymptotically return to the equilibrium state [34].
Global stability	Common in linear systems. Here, the system domain of attraction covers its entire phase space. If the system state is perturbed, it will converge asymptotically to the equilibrium state [34].
Lyapunov stability	Also known as internal stability, it is applied to autonomous systems. A system is stable about an equilibrium state in the sense of Lyapunov, if all initial values of states starting near the equilibrium state, stay near the equilibrium state [27,35]. Lyapunov analysis includes the approaches.
• Lyapunov first (indirect) method	Better suited for smaller perturbations, it is based on the linearization of a nonlinear system around an equilibrium state and subsequently finding its eigenvalues, which need to be equal to or more than zero for the system to be stable [27,35].
• Lyapunov second (direct) method	Provides invaluable insights into the qualitative behaviour of nonlinear systems, including their domains of attraction, thresholds, and global stability. The method is directly applied to nonlinear systems without going through any linearization process. In this approach, using a Lyapunov function, if the total energy of a system is continuously dissipating/decreasing along its state trajectory, it will eventually reach a stable equilibrium state where it will remain at rest. However, both stable in the sense of Lyapunov, and asymptotically stable are mathematically stable systems; from an engineering perspective, they are not desirable as the time taken for the system state to return to the equilibrium state is infinite [27,32].
Asymptotic stability	If a system is perturbed from its equilibrium state and it ultimately returns to the equilibrium state, is called asymptotically stable. More precisely, a system is asymptotically stable if it is stable in the sense of Lyapunov and there exists a positive constant for which the system state deviations converge to zero as time goes to infinity [32].

Exponential stability	If a Lyapunov stable system returns to the equilibrium state with an exponential rate of decay, it is termed exponentially stable. From exponential stability, the time required for the perturbed system to return to the equilibrium state can be readily calculated and therefore this is the most desirable property in engineering systems [32,36].
Monotonic stability	As a special case of asymptotic stability, a monotonically stable system is one in which the perturbed state returns to the stable equilibrium state monotonically (through a monotonic decay of perturbations) [37]. Monotonic here translates into a constant decreasing trend of perturbations over the entire domain of application. The energy function for a more visual representation of this trend would be a uniform decrease in perturbations without any oscillations (no imaginary part of the system state/Jacobian matrix eigenvalues). It is the absence of oscillations that renders monotonic stability a distinctive case of asymptotic stability.
Finite-time stability (FTS)	A dynamical system state is finite-time stable if its trajectory starts from an initial value within a prescribed bound of the equilibrium state and returns to zero in a finite time frame. Various methods are used for calculating finite time stability measures (such as the settling time function), including Lyapunov theory [38–40]. A further practical application of FTS is in the analysis and control of input–output dynamical systems [41]. It should be mentioned that finite-time stability and exponential stability are similar, closely related concepts.
Bounded-input bounded-output (BIBO) stability	Also referred to as external stability or forced response mode stability. In BIBO stability a system is a casual operator mapping bounded inputs into bounded outputs, which means that a stable system should render a bounded/limited/finite output for all time when a bounded/limited/finite input is exerted. This type of stability is well-suited for application in the context of linear systems [42,43].
Input-state stability (ISS). i.e., bounded-input bounded state (BIBS)	A unified approach of internal and external stabilities that is well-suited for application in the nonlinear systems context. Here, for any bounded input there should be a bounded state [27]. In a special case, if the output is equal to the system state, then the system is also BIBO stable (externally stable).
Structural stability	Structural stability is indicative of the robustness of the qualitative behaviour of system equilibrium trajectories that are not affected by small internal perturbations (model/parameter uncertainties) or not changed radically (such as the emergence of a new domain of attraction, bifurcating branches, etc.) as a result of the small parameter changes [17,36]. Depending on the system focus and context, parameter uncertainty can be studied either in the form of assemblage or certain/individual parameters of interest.

3.6 Stability Concepts Classification

It should first be mentioned that any system referred to in this paper is an open-loop system without zero control action (unless stated otherwise) where the flow of information is one way, contrary to the closed-loop control where the flow of information is circular (Figure 3.5). Given the perturbation event type, modern stability concepts can be divided into two broad categories: dynamic stability, related to perturbations in the form of either (i) system state initial values other than equilibrium or (ii) temporary input disturbance after it is discontinued, and structural stability, which is related to changes in the system in the form of (i) parameter uncertainty that affects system matrix A (Jacobian J) or (ii) parameter uncertainty that moves the equilibrium state including control action. Perturbation type (i) are usually the result of a direct management action, while perturbation type (ii) vary based on the system type and act through the system input port (e.g., the seismic ground acceleration in case example (1) or acceleration in case example (2)). Examples of the changes in the system form (type i) are usually the degradation/obsolescence in the system structure, which are generally countered by active control action (change type ii; case examples 1 and 2).

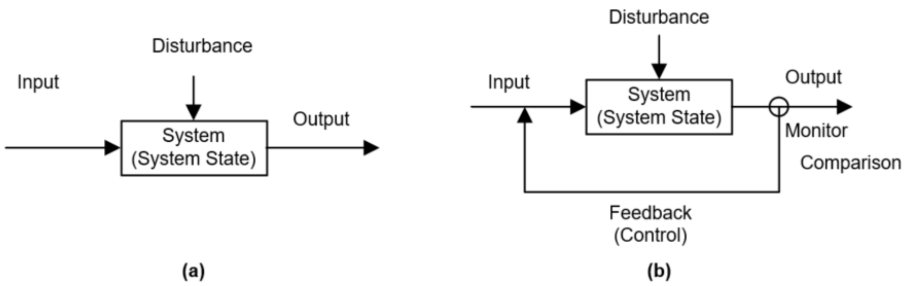

Figure 3.5. Flow of information for: (a) open-loop and (b) closed-loop representation of a dynamic system. Source: adapted from Carmichael [44].

3.6.1 Dynamic Stability

Dynamic or dynamical stability entails all those conditions where the time component cannot be ignored and some sort of dynamic process is involved in the system, either through the input (i.e., temporary input disturbance right after it is discontinued), or the system state including the output value (i.e., state initial value other than equilibrium) [45,46]. Therefore, dynamic stability is essentially the internal stability of the system and is a measure of the tendency for the system to return (smooth and monotonic or oscillatory) to its equilibrium (initial/original state) value overt time (finite, infinite, or never) after being perturbed (in the absence of any control action) [46]. The tendency to return to equilibrium is an identical concept to the system passive control/dissipation/damping, which is further explored in Section 3.7. In control systems terms (generally for linear and linearized systems), dynamic stability is equivalent to the rate of return of the system's state (and/or settling time for a time-varying system) to equilibrium, which is measured by the dominant eigenvalue horizontal distance (real part) from the imaginary axis in the complex plane on a root locus diagram. A dominant eigenvalue is related to the slow-moving state of the system and is located closest to the imaginary axis which corresponds to the slowest and dominant decay/return rate to the equilibrium [47]. Depending on the nature of the system's dominant eigenvalue and its linearity, various types of dynamic stability, explained in Section 3.5, exist and are outlined in Table 3.3 and Figure 3.6. Tools such as the root locus diagram for linear systems and Lyapunov functions, are generally used for nonlinear systems, where no finite rate of return time to the equilibrium state can be extracted and are an important means for assessing dynamic stability.

Table 3.3. Classification of dynamic stability concepts with a focus on the system performance.

Dynamic Stability Concept	Dominant Eigenvalue	Settling Time	System State/Output Behaviour/Performance
Linear systems, single equilibrium and global stability Perturbations: state initial value and input temporary disturbance after it is discontinued			
Asymptotic stability (BIBO and BIBS are also guaranteed)	Negative real part with zero or non-zero imaginary parts	Infinite	Oscillatory or monotonic
Exponential—finite-time stability with monotonic behaviour	Negative real part with zero imaginary parts	Finite	Monotonic
Exponential—finite-time stability with oscillatory behaviour	Negative real part with non-zero imaginary parts	Finite	Oscillatory
Marginal stability—stability in the sense of Lyapunov	Only imaginary parts	Never/not guaranteed	Limit circles/hovering around the equilibrium
Mainly nonlinear systems (particularly time-varying), multiple equilibriums and local stabilities Perturbation: state initial value and input temporary disturbance after it is disconnected			
Lyapunov stability (first method), linearization	Negative real part with zero or non-zero imaginary parts	Infinite	Oscillatory or monotonic (local)
Lyapunov stability (second method)	There has to be a Lyapunov function that is positive definite (global asymptotic stability) or positive semi-definite (local asymptotic stability)	Infinite	Monotonic (global) or oscillatory (local)
Remark: BIBO and BIBS can be considered a part of the dynamic stability for the period immediately after the temporary input disturbance is discontinued. If a permanent input in the sense of an active control is considered, then it becomes a closed-loop dynamic stability (Figure 3.5)			

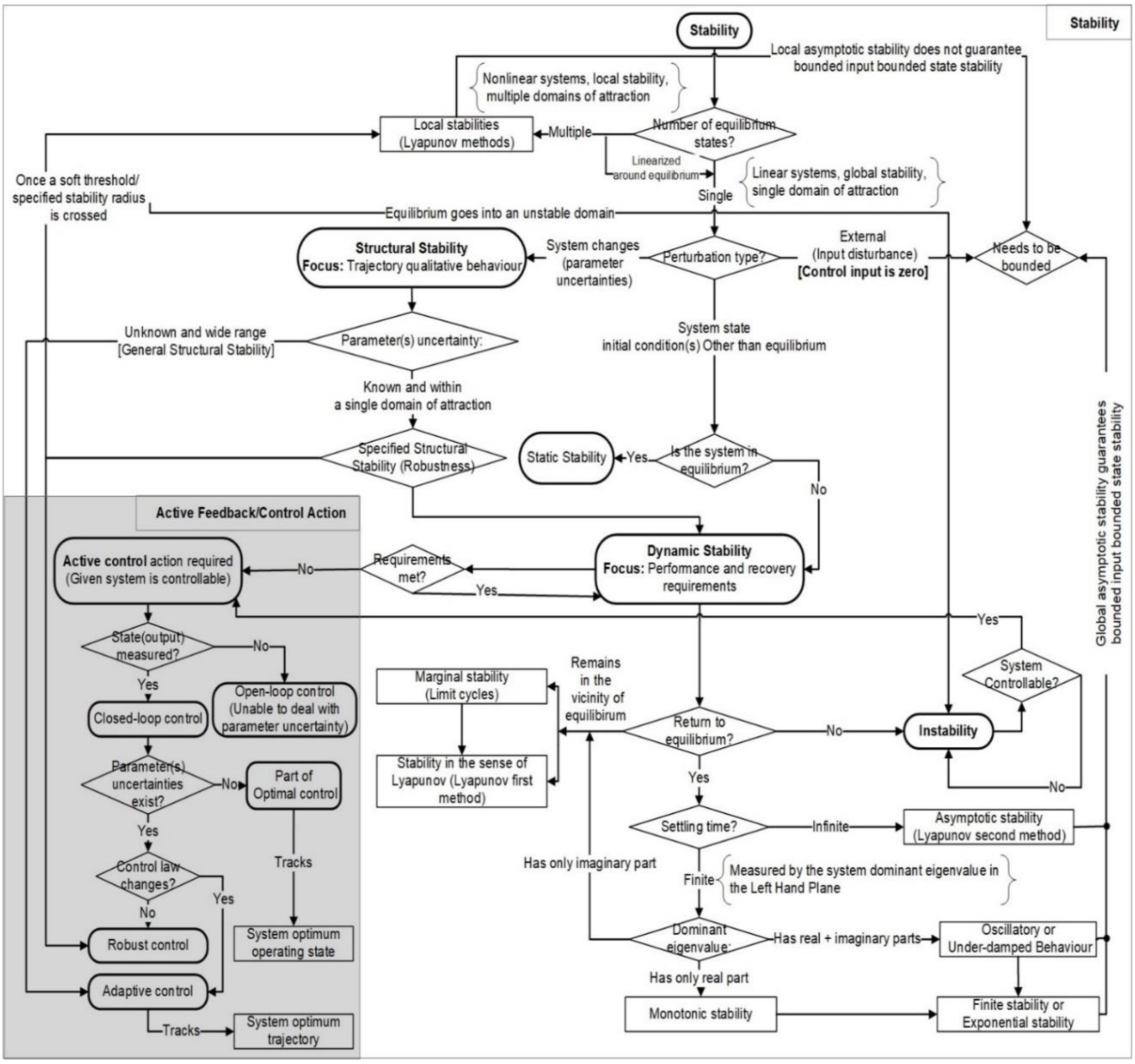

Figure 3.6. Linkages between dynamic stability, structural stability, and active control action—a unified and big picture.

3.6.2 Structural Stability

Structural stability indicates that a system model is stable for all model uncertainties until reaching a critical threshold (stability radius, defined as the minimum destabilizing effect of combined system changes/model uncertainty), which leads to instability [48]. Loosely speaking, the former definition of structural stability (Section 3.5), where parameter changes can cause emergence or disappearance of new equilibrium domains is well-positioned in the context of complex dynamic systems. The latter definition of structural stability is related to changes in the shape of the domain(s) around the existing equilibrium state(s) or simply changes to the dynamics within a single domain of equilibrium. Borrowing terminology from the resilience scenario, the two subject definitions for structural stability can be labeled under general structural stability and specified structural stability, which subsequently determine hard and soft thresholds (unstable points along the system state trajectory) for a dynamic system (Figure 3.6).

Specified structural stability, also referred to as persistence and endurance [49], inertia [50], constancy [51], robustness and resistance [52], is normally used as a measure of the system's functional persistence under uncertainty parameters (inverse of sensitivity) and is generally related to the dynamics within a domain of equilibrium [53–55].

To avoid confusion and to treat stability systematically and with precision, mentioning a sub-class or adjective prior to the word 'stability', such as dynamic stability and structural stability, or their low tier sub-classes is a critical consideration.

3.7 Application of Stability to Resilience Thinking

Anderies et al. [56] argue that specified resilience (resilience to a known type of perturbation) is equivalent to robustness and the robust control analysis used by Csete and Doyle [57] in the context of biological systems with parameter uncertainties through the application of feedbacks. However, most of the available literature fails to provide a unified, comprehensive, and systematic treatment of the broad stability concepts in terms of perturbation, changes, dynamic and structural stabilities, and relevant control actions versus the two prevailing categories of engineering resilience and socio-ecological resilience, as well as the means to obtain resilience.

Resilience here is defined as adaptation proposed in the authors' earlier work [19] where the system has the ability to respond to perturbations and change through passive and active feedback structures; the system state or system form is returned to a starting position or transitions to another suitable state or form. Simulations from the lumped mass and simple pendulum linear and nonlinear dynamic systems are used to support the modern stability ideas to resilience thinking in the form of adaptation. This is further discussed under two main features of the system state and form return abilities through passive and active feedback mechanisms. The two overarching categories of resilience, engineering resilience, and socio-ecological resilience, are distinguished in the analysis process; the range of perturbations and change in engineering resilience is narrow and predictable (normally within a single domain of attraction), while socio-ecological resilience is broader and unpredictable.

3.7.1 Resilience as the Ability of the System to Return to Initial State

The ability of a dynamic system to respond to perturbations and return the system state to a starting position or another suitable state is a local, or within a domain of attraction, phenomenon that is mostly used in the engineering resilience category. Here, constancy, or a target system performance, usually in the form of a system equilibrium/steady state or output as part of it, is the main objective. Such an objective for engineering resilience is precisely translated in the form of a faster system state return rate as well as larger system resistance to input disturbance, which translates into smaller system state deviations from its equilibrium. Both of these elements can be achieved by various sub-classes of dynamic stability where system has the ability to return to its equilibrium state including the quality and form of the state return trajectory. The dissipative measures built within the system, also referred to as resistance to perturbation and robustness, determine the extent of the deviation from the system equilibrium state under input disturbances. These can be instantaneous, such as impulse/pulse input disturbances (e.g., shocks and impact loading) or permanent, such as step/press input disturbances (e.g., stressors such as climate change), which subsequently change the system form and move its equilibrium state.

The rate of return of the system to equilibrium state or the settling time is determined by the system's dominant eigenvalue or dynamic stability and the system resistance to perturbation is determined by the passive feedback/control that is built into the system. Tools such as the root locus diagram for linear systems (Figure 3.7) and Lyapunov functions, generally used for nonlinear systems where no finite rate of return time to equilibrium state can be extracted (Figures 3.8 and 3.9), are important methods for determining the system state rate of return to equilibrium or, alternatively, the settling time. Based on the nature of the system's dominant eigenvalue and its linearity, various sub-classes of dynamic stability and its applicability level to engineering resilience are summarized in Table 3.4.

Table 3.4. Dynamic stability application to engineering resilience with a focus on the system performance.

Stability	Settling Time	Engineering Resilience Application Ranking
Linear systems, single equilibrium, and global stability Perturbations: state initial value and input temporary disturbance after it is discontinued		
Asymptotic stability (BIBO and BIBS are also guaranteed)	Infinite	Least favourable
Exponential—finite-time stability with monotonic behaviour	Finite	Highly favourable
Exponential—finite-time stability with oscillatory behaviour	Finite	Favourable
Marginal stability—stability in the sense of Lyapunov	Never/not guaranteed	Not favourable
Mainly nonlinear systems (particularly time-varying), multiple equilibriums and local stabilities Perturbation: state initial value and input temporary disturbance after it is disconnected		
Lyapunov stability (first method, linearization)	Infinite	Least favourable
Nonlinear systems (particularly time-varying), multiple equilibriums and local stabilities Perturbation/change: system changes/parameter uncertainty		
Lyapunov stability (second method)	Infinite	Less favourable

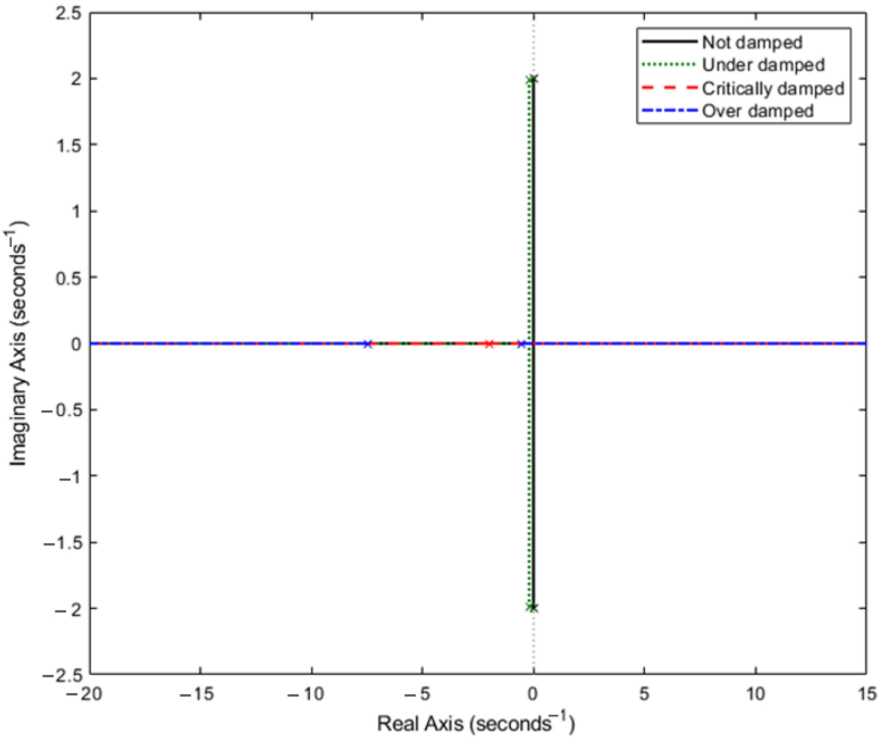

Figure 3.7. Root locus diagram of the lumped mass dynamic system (Case example 1) for four different arrangements of dominant eigenvalue/pole based on the system's internal resistance/damping.

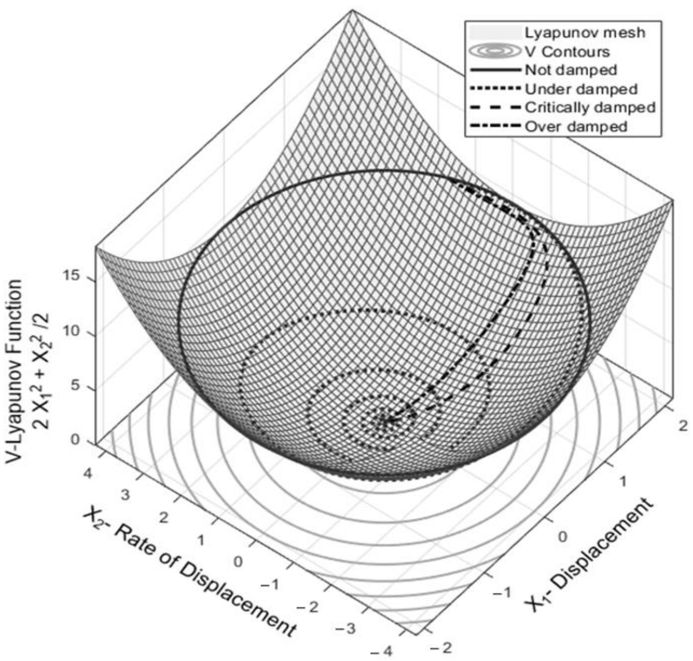

Figure 3.8. Lyapunov function (V), indicative of global asymptotic stability for the lumped mass dynamic system (Case example 1) along with the system phase portraits under [2, 1.5] state initial value.

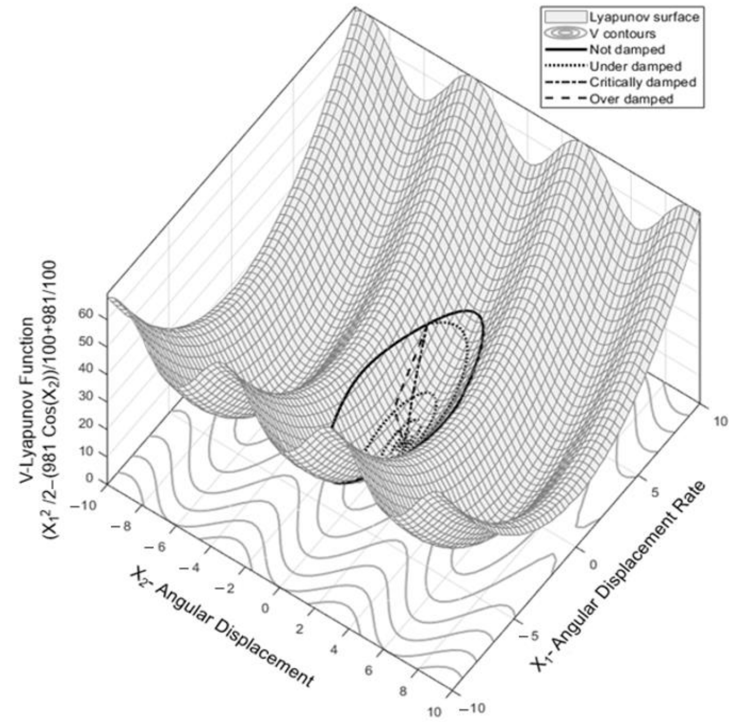

Figure 3.9. Lyapunov function (V) indicative of local asymptotic stability for the simple pendulum system (Case example 2) along with the system phase portraits under [−1.5 rad, 4] state initial values.

As indicated in Table 3.5 and Figure 3.10, two identical systems might have different amounts of passive control (damping) but as long as their dominant eigenvalues' real parts are equal, the resulting settling times will be equal irrespective of their behavior (monotonic or oscillatory).

Table 3.5. System dominant eigenvalue's real part as a direct indication of the system settling time (Case example 1).

Dynamic Stability	**System Matrix** ($\boldsymbol{Matrix\ A}$)	**Eigenvalue-1** ($\boldsymbol{E_1}$)	**Eigenvalue-2** ($\boldsymbol{E_2}$)	**Dominant Eigenvalue Real Part** ($\boldsymbol{E_D}$)	**The Approximate Settling Time within 2% of Steady-State Error** ($\boldsymbol{T_s}$)	**Resistance to Perturbation (Damping)**
System 1: exponential oscillatory stability	$\begin{bmatrix} -0.4 & -4 \\ 1 & 0 \end{bmatrix}$	−0.2000 + 1.9900 i	−0.2000 + 1.9900 i	−0.20	20 s	Underdamped case $\zeta < 1$
System 2: exponential	$\begin{bmatrix} -8.4 & -1.6 \\ 1 & 0 \end{bmatrix}$	−8.0000	−0.2000	−0.20	20 s	Over damped $\zeta > 1$

monotonic stability						
System 3: exponential oscillatory stability	$\begin{bmatrix} -0.1 & -4 \\ 1 & 0 \end{bmatrix}$	−0.0500 + 1.9994 i	−0.0500 + 1.9994 i	−0.05	78 s	Underdamped case $\zeta < 1$
System 5: exponential monotonic stability	$\begin{bmatrix} -8.05 & -0.4 \\ 1 & 0 \end{bmatrix}$	−8.0000	−0.0500	−0.05	78 s	Over damped $\zeta > 1$

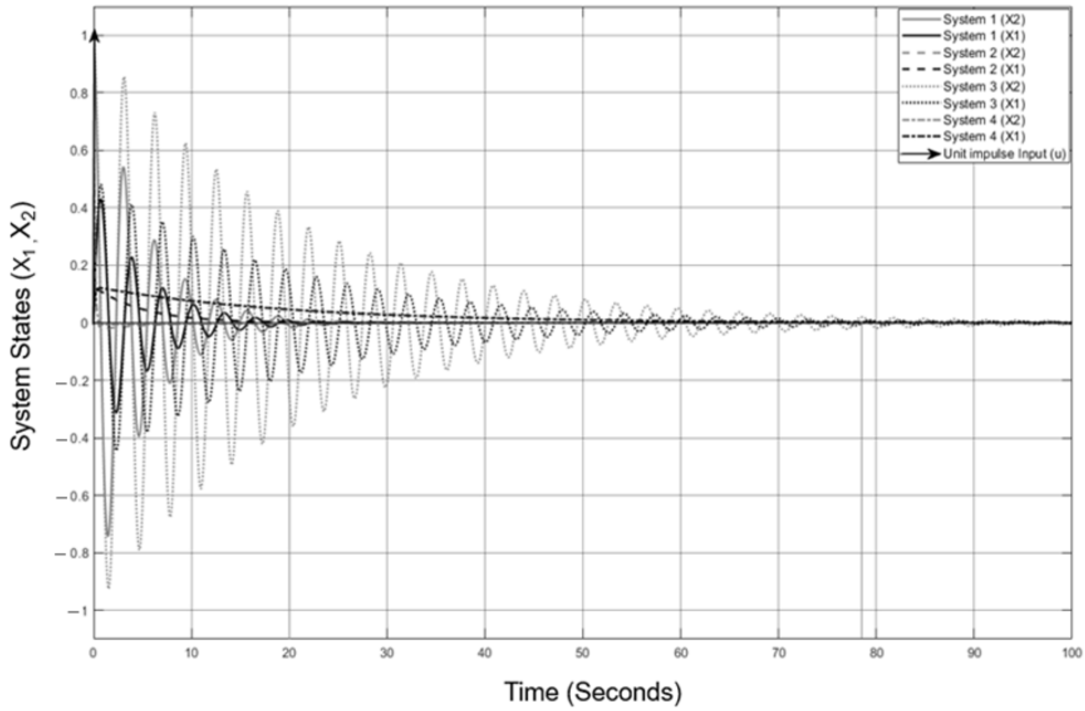

Figure 3.10. System equal dominant eigenvalues rendering equal settling times for a unit impulse in the form of a temporary input disturbance (Case example 1).

In the context of linear systems and a single domain of attraction, within a certain vicinity of the stable equilibrium, both passive control and rate of return to equilibrium increase until an optimum amount of resistance is reached (e.g., critical damping for second-order linear systems). Any further increase in passive control will negatively affect the settling time. Thus, engineering resilience is directly proportional to dynamic stability (within an open-loop setting with zero active control action) for a certain interval of passive control (e.g., critical damping) only. Beyond the interval of passive control, any added amount of passive control might curtail the system's ability for innovation or might lock the system into domains with unproductive conditions such as economic recessions. The relationship between passive feedback and settling time, the two elements of engineering resilience, is demonstrated for two simple linear and nonlinear dynamic systems in Table 3.6 and Figures 3.11 and 3.12.

Table 3.6. Dynamic stability as a measure of engineering resilience for impulse input disturbance (δ(t)) (Case examples 1 and 2).

System	**Case Example 1**		**Case Example 2**	
	Dynamic Stability (Settling Time)	**Resistance to Perturbation as Indicator of Passive Control (c)**	**Dynamic Stability (Settling Time)**	**Resistance to Perturbation as Indicator of Passive Control (c)**
Marginal stable system (not damped $\zeta = 0$)	Never	0	Never	0
Exponential stable system (underdamped $\zeta = 0.1$)	20 s	0.4	17 s	63
Exponential monotonic stable system (critically damped $\zeta = 1$)	3.5 s	1	3 s	626
Exponential monotonic stable system (overdamped $\zeta = 2$)	8 s	2	7 s	1253

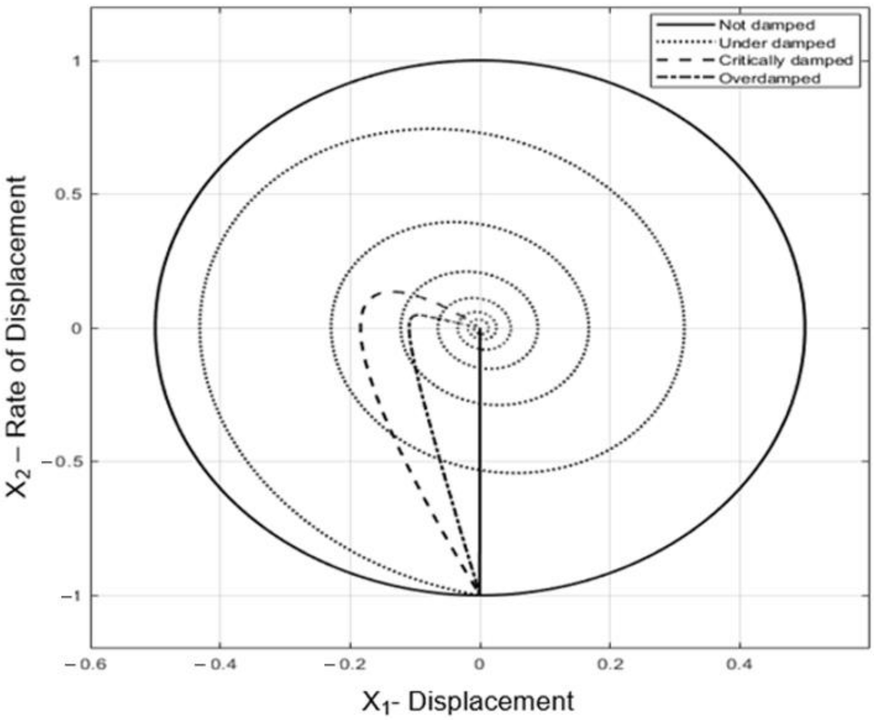

Figure 3.11. System phase portrait under unit impulse input disturbance and [0,0] initial conditions (Case example 1).

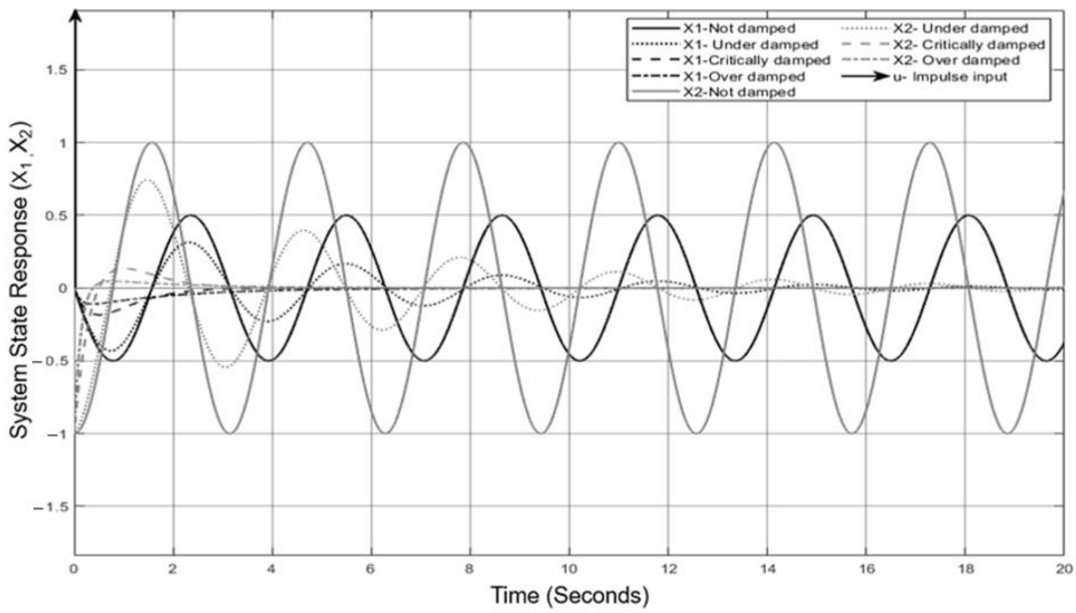

Figure 3.12. System state response under impulse input disturbance and [0, 0] initial conditions (Case example 1).

A good measure for engineering resilience can be considered as the volume of the system's 3-dimenstional state portrait, where the two horizontal axes indicate the system state deviations under input disturbance (passive control indicator) while the vertical axis indicates the system settling time (system state rate of return to equilibrium). This combines both of the engineering resilience elements and the smaller the volume the larger the resilience becomes (Figure 3.13). For an equal value of settling time, monotonic exponential stability renders a slightly higher value of engineering resilience than that of oscillatory exponential stability given the slightly higher area of the system state trajectory around equilibrium of the former compared to the latter (Figure 3.10).

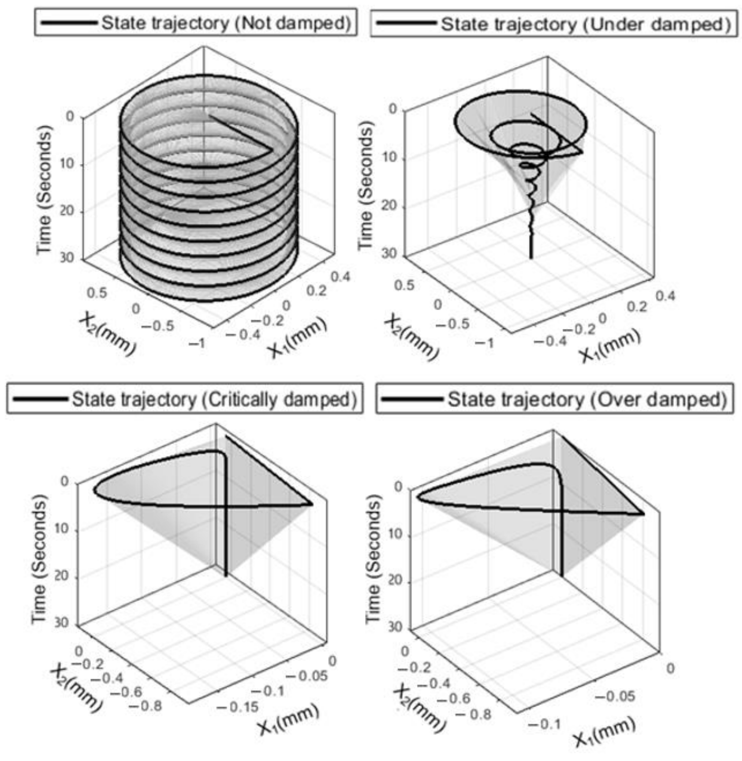

Figure 3.13. System phase portrait (domain of attraction) 3D representation as an indicator of engineering resilience. The vertical axis indicates settling time for a unit impulse input and [0,0] initial conditions (Case example 1).

However, for linear systems the dynamic stability remains constant within the domain of attraction. In the context of nonlinear systems, the dynamic stability critically decreases (lengthy settling times) in the vicinity of unstable equilibrium (instability threshold), which results in smaller values of engineering resilience. Figure 3.14 depicts how the system state response critically slows down near the unstable equilibrium threshold ($x_1 = 6.264\ or\ x_2 = 3.14\ Rad$) as does the resistance to perturbation.

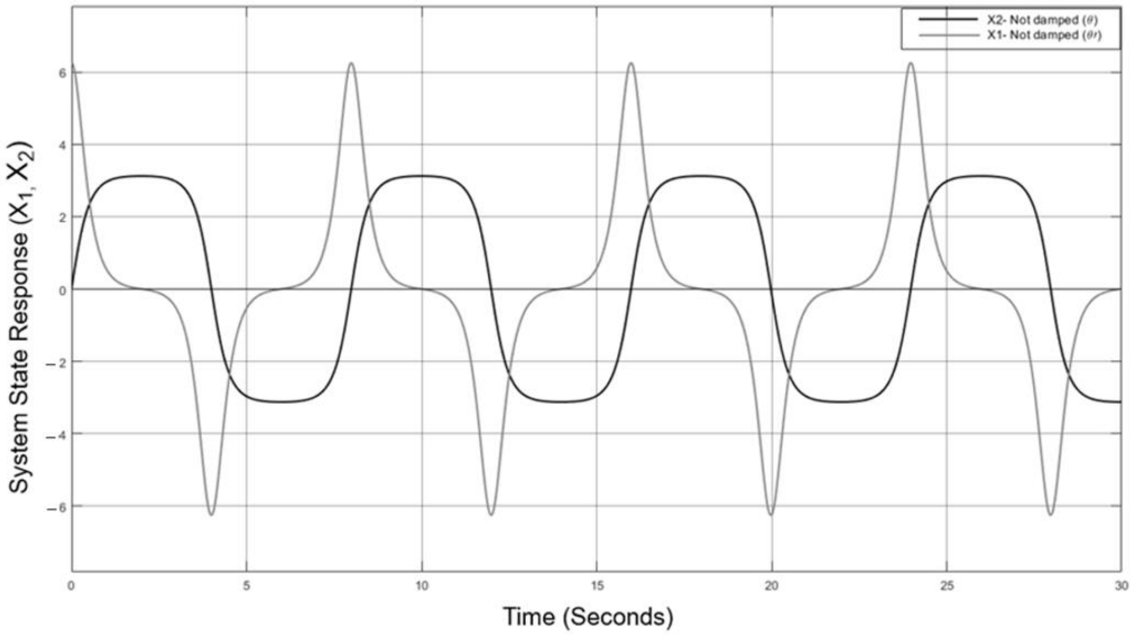

Figure 3.14. System state response indicative of the critical slowing down near an unstable equilibrium threshold (Case example 2 with [0, 6.264] initial conditions).

The ability of the system to return to its equilibrium state ceases once the passive feedback of the system reaches zero (open-loop system with zero active control) or, alternatively, when the system eigenvalues are on the imaginary axis of the complex plane. By crossing the zero limit (c = 0), which can referred to as a soft threshold, the system stable equilibrium state [0, 0] turns into an unstable one (Figure 3.15).

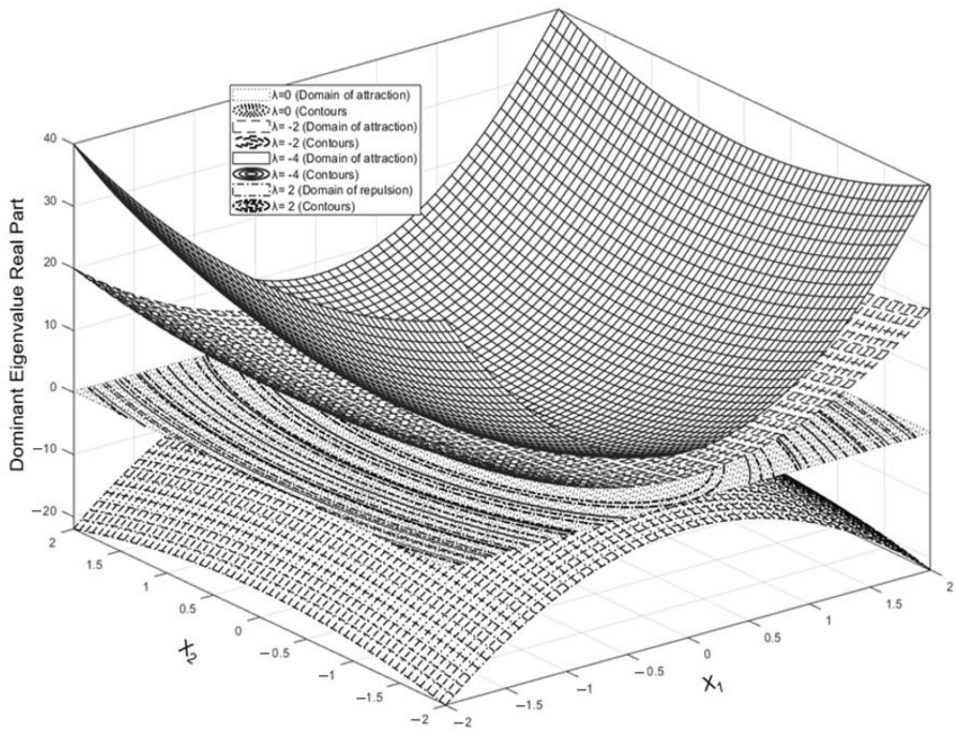

Figure 3.15. An approximate 3D representation of the equilibrium domain changes due to the system passive control levels. Dominant eigenvalue/pole real part indicate the rate of return to the equilibrium (Case example 1).

3.7.2 Resilience as System's Form Return Ability

The ability of a dynamic system to respond to change by returning the system to a starting position or another suitable form can be a local or global phenomenon and is mostly discussed in the socio-ecological resilience category, where maintaining the system identity and/or avoiding critical thresholds are the main objectives. Critical thresholds in the system form can be divided into soft and hard thresholds, where the former is easy, and the latter is hard or impossible to reverse. The reversibility of the system form is a management action under the resilience scenario. It is thoroughly covered by the active feedback/control action under the modern stability concept, which also means that the active feedback action changes the system form and subsequently alters the system's passive control measures that define open-loop dynamic stability (Figure 3.5). Since changes to the system form under the engineering resilience definition are limited and known (generally within a domain of attraction), the control law for the closed-loop system does not change and is labeled as a robust (active) control. For socio-ecological resilience on the other hand, which has a wide and unknown range of system changes, the control law is not constant and therefore is categorized as adaptive (active) control (Figure 3.5). Additionally, there is input disturbance of either an instantaneous (impulse input) or permanent (step input) nature that can flip the system state into another stability domain; this, along with the system's passive control, are the two main elements that are crucial for measuring socio-ecological resilience.

In the context of linear systems and a single domain of attraction and global dynamic stability (Case example 1), there is no limit on the input disturbance that leads to instability. Although the system is theoretically a globally stable system, performance/specification requirements can be imposed to limit the system domain of equilibrium to a certain boundary, e.g., maximum story drift/displacement in Case example 1, which practically renders local stability. Therefore, socio-ecological resilience tilts toward engineering resilience, which is mostly about the passive control built into the system (Table 3.7). In the context of nonlinear systems with multiple domains of attraction, e.g., Case example 2, or more complex nonlinear systems with hard thresholds described by fold bifurcations, a higher value of input disturbance that can flip the system into another stability domain along with a higher amount of passive control measures indicate a high level of socio-ecological resilience (Table 3.7 and Figure 3.16).

Table 3.7. Dynamic stability as a measure of engineering resilience for impulse input disturbance (δ(t)) (Case examples 1 and 2).

System	Engineering Resilience/Socio-Ecological Resilience (Case Example 1)			Socio-Ecological Resilience (Case Example 2)	
	Dynamic Stability (Settling Time)	Resistance (R) to Perturbation—Indicator of Passive Control (c)	Maximum Input Disturbance That Can Flip the System State into Another Stable Domain	Resistance (R) to Perturbation—Indicator of Passive Control (c)	Maximum Input Disturbance That Can Flip the System State into Another Stable Domain
Marginal stable system—not damped $\zeta = 0$	Never	0	Infinite	0	9.81

Exponential stable system-underdamped $\zeta = 0.1$	20 s	0.4	Infinite	63	9.81
Exponential monotonic stable system—critically damped $\zeta = 1$	3.5 s	1	Infinite	626	9.81
Exponential monotonic stable system—overdamped $\zeta = 2$)	8 s	2	Infinite	1253	9.81

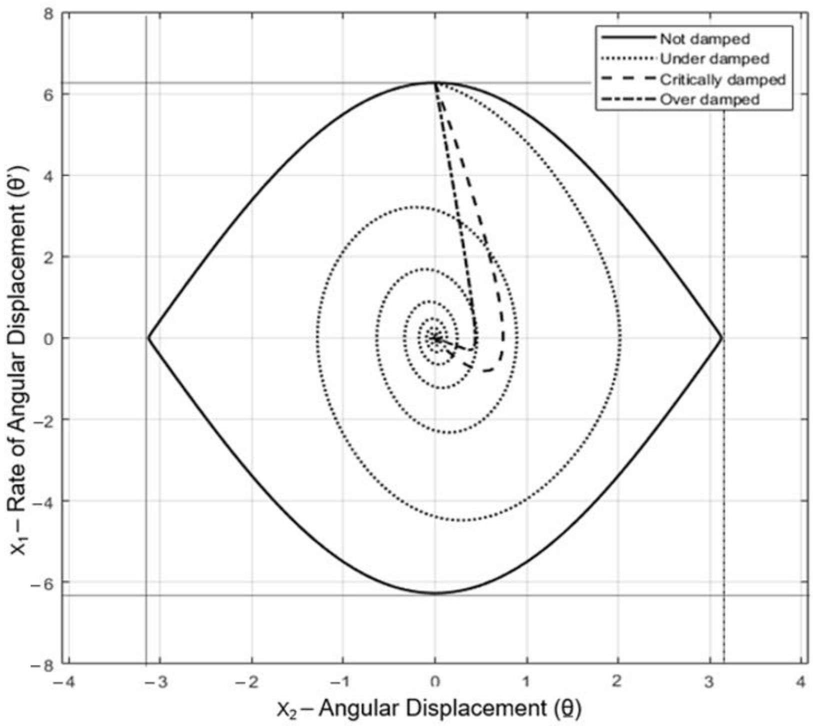

Figure 3.16. Phase portrait indicative of the system's soft thresholds disturbed by initial conditions (Case example 2).

Contrary to the simple nonlinear systems (Case example 2—Figure 3.17), for complex nonlinear dynamic systems the relationship between parameters affecting the system matrix A (or Jacobian) (dynamic stability and passive control) and those moving the equilibrium states (e.g., input or active control action) is an area for further exploration; since the subject parameters are often entangled and/or of a double-edged sword nature, there is increased complexity in the trade-offs between engineering resilience vs. socio-ecological resilience.

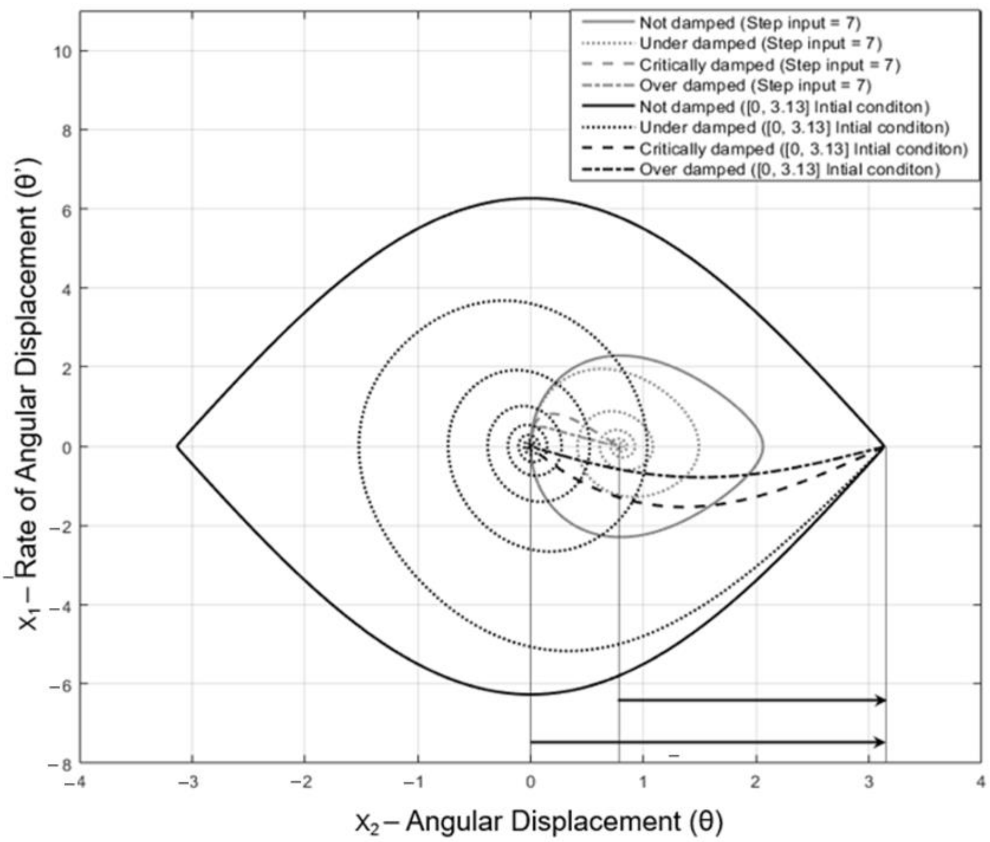

Figure 3.17. Permanent input (step input) acting as a parameter (input perturbation) that moves the system equilibrium state and affects resilience (Case example 2).

Bifurcation diagrams are useful tools from nonlinear dynamics and structural stability that can be utilized for nonlinear dynamic systems with single parameter changes and can help define hard and soft thresholds for socio-ecological resilience. For a single parameter system, changes can assess how far a critical threshold is located from the current equilibrium state, as well as to indicate whether a threshold that has been crossed is reversible (Figure 3.18) or irreversible (Figure 3.19), which corresponds to a soft and hard loss of resilience, respectively [58]. A hard loss of resilience is known as hysteresis (path dependence or path memory) or fold bifurcation in complex nonlinear systems and it shows that the system trajectory not only depends on the parameter value but also depends on which side the parameter value is approached (e.g., parameter R in the spruce budworm model—Figure 3.19). This occurs where there are the multiple domains of attraction [27].

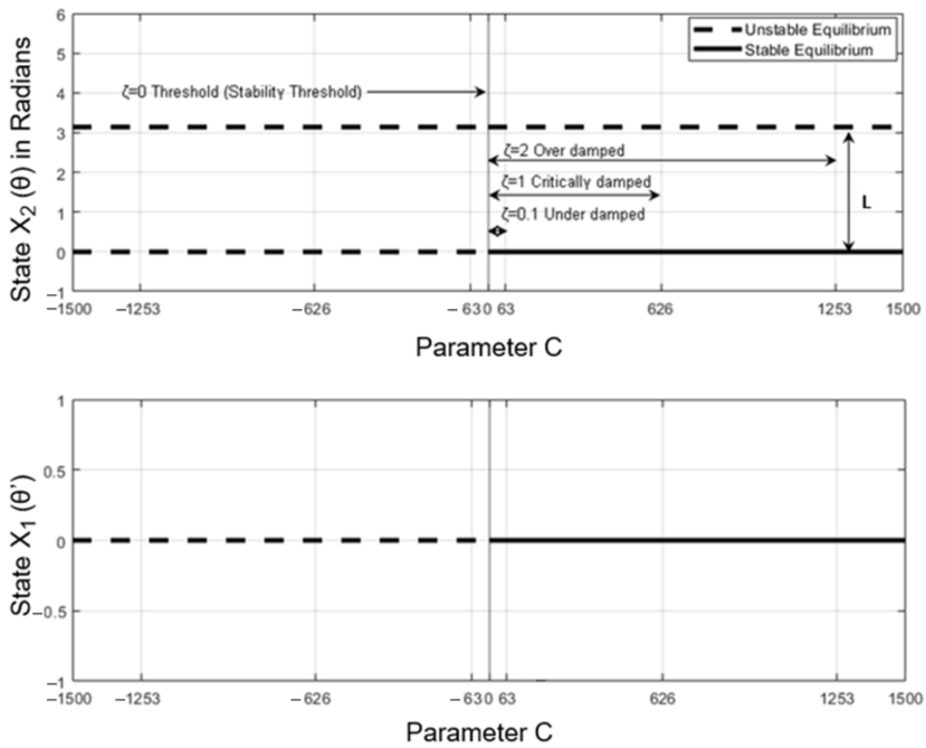

Figure 3.18. A modified bifurcation diagram (Case example 2).

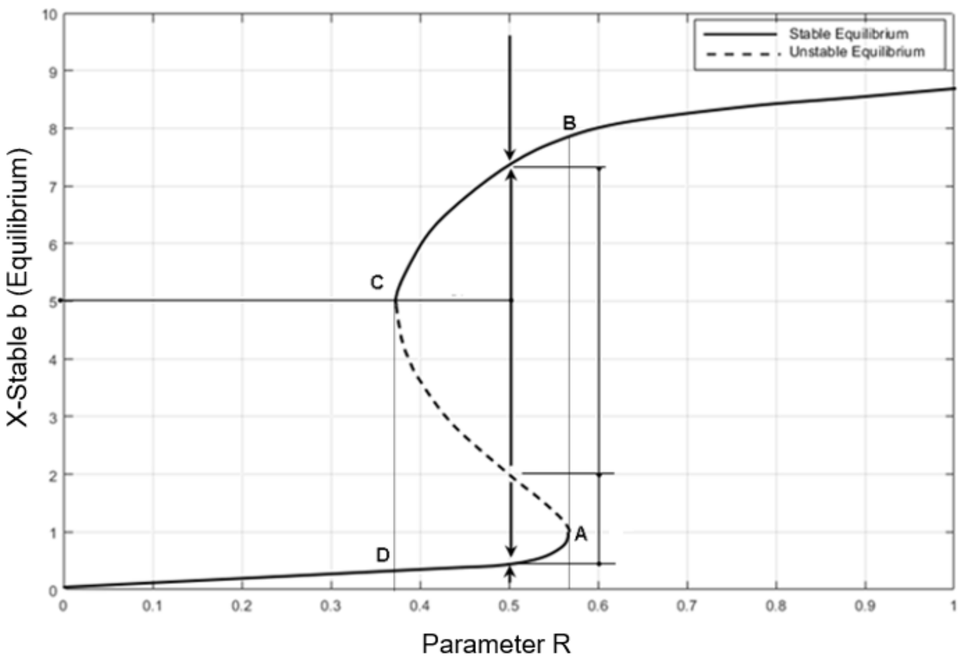

Figure 3.19. Spruce Budworm model S-shaped bifurcation for parameter (R) indicating a hard loss of resilience.

When system resilience under passive control is not satisfactory, active control action (given that the system is controllable) is required to alter the system form by shifting the system eigenvalues to a desired location and adjusting the system behavior accordingly (Figure 3.20). For instance, the subject linear system given in Case example 1 is fully controllable, but its current behavior is oscillatory and not satisfactory. A full state active feedback tool can be used to bring the underdamped oscillatory state behavior to a critical damped monotonic behavior (or, in alternative scenarios, to speed up the system settling time or stabilize the system in the case of instability). This will mean shifting the system poles from the underdamped case ($\lambda_1 = -0.2000 + 1.9900\,\mathrm{i}, \lambda_2 = -0.2000 - 1.9900\,\mathrm{i}$) to a critically damped one ($\lambda_1 = \lambda_2 = -2.000$). The reference scale (r) is set to zero (zero input/equilibrium state) and instead, the disturbance input is introduced in the form of the initial condition of [20 0] (Figure 3.20). The control action bears a cost, which needs to be assessed versus the performance improvement it brings about.

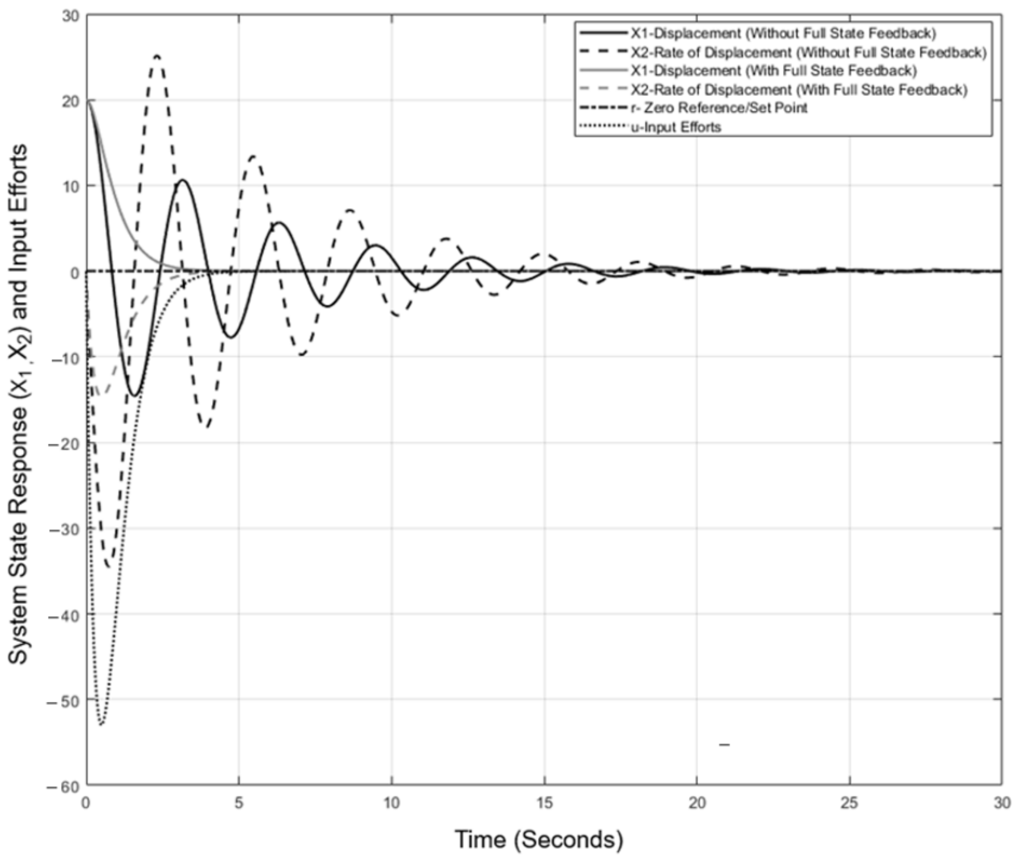

Figure 3.20. System state response with and without full state feedback (closed-loop control) for a zero reference/set point (equilibrium state) and [20 0] initial condition (Case example 1).

3.8 Discussion and Conclusions

Both dynamic and structural stabilities are principally dependent on the system parameters where the former is about the rate of return to equilibrium and the latter is about the current equilibrium distance from a fold bifurcation point, which means staying in the same domain of equilibrium. Engineering resilience, which focuses on maintaining the system performance under limited and known types of perturbations, is therefore partially covered by the open-loop dynamic stability with zero active control. Dynamic stability without active control action can be seen as a static return rate to equilibrium through the utilization of the passive control system after the perturbation stimulus is removed. Moreover, if the system return behavior and return rate are not satisfactory, the control action is the only means of rectifying the unsatisfactory situation. On the other hand, socio-ecological resilience, which focuses on maintaining the system identity and avoiding critical thresholds, is partially covered by structural stability (distance to soft or hard thresholds) by keeping a static distance from equilibrium. Here, control action is needed to adjust that distance as per the perturbation value and type, which are often unknown and with large variability, and requires a closed-loop dynamic stability with adaptive control as an alternative for socio-ecological resilience. Additionally, control systems tools, such as state controllability, are potential directions for developing tools that can systematically describe the reversibility of equilibrium states in complex dynamic systems and the trade-offs between dynamic and structural stabilities. This study reveals that the two major categories of engineering resilience and extended ecological resilience are intrinsically the reinvention of a closed-loop system dynamic stability with different types of active feedback structures. Moreover, structural stability describes key aspects of social-ecological resilience—including critical thresholds where, under change, a system loses the ability to return to the starting form or move to another suitable form through active feedback mechanisms or direct management actions.

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CHAPTER 4. RESILIENCE AND SYSTEMS – A TRAFFIC FLOW CASE EXAMPLE

4.1 Link to Thesis

In Chapter 4, I presented the application of the resilience system interpretation framework - introduced in Chapter 2, to two sample traffic flow dynamic systems. Both components of the framework – the system state and form return abilities in response to perturbations and change were demonstrated through practical simulation scenarios on the modified viscous Burgers' equation and the LWR-Greenshields model equipped with an adaptive Extremum seeking control, respectively.

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4.2 Abstract

Resilience has increasingly become a crucial topic to the function of various real-world systems as our planet undergoes a rising trend of uncertainty and change due to natural, human and technological causes. Despite its ubiquitous use, the term resilience is poorly and often inconsistently used in various disciplines, hindering its universal understanding and application. This study applies the resilience system interpretation framework, which defines resilience irrespective of its disciplinary association, in the form of adaptation and adaptive systems, to two traffic flow systems. The system framework defines resilience as the ability of the system state and form to return to their initial or other suitable state or form through passive and active feedback structures. Both components of the system framework are demonstrated through practical simulation scenarios on the modified viscous Burgers' equation and the LWR-Greenshields model equipped with an adaptive Extremum seeking control, respectively. This novel and systematic understanding of resilience will advance resilience analysis, design, and measurement processes in various real-world systems in a unified fashion and subsequently pave the way for resilience operationalization and its integration into industry standards.

Keywords: traffic flow; extremum seeking control; dynamic stability; passive control; active control; resilience; system thinking; modern control systems theory.

4.3 Introduction and Background

This paper applies the resilience system interpretation framework to a traffic flow system that is subjected to perturbations and change. The system framework employed defines resilience in the form of adaptation and adaptive systems, where the system has the ability to respond to perturbations and change through passive and active feedback structures [1]. The modified viscous Burgers' equation and the Lighthill-Whitham-Richards (LWR) – Greenshields model, coupled with an adaptive Extremum seeking control (ESC), for two macroscopic traffic-flow systems are used in a state-space representation; the system response to perturbation and change is first simulated, and then its resilience characteristics are analyzed.

Over the years, numerous studies have been conducted with a focus on traffic flow systems management and their response to disruptive events and congestions using systems and modern control systems approaches. Some of those system approaches use the transportation system's physical features [2,3] while others use the system's traffic flow characteristics [4–6] in defining their systems' resilience frameworks. Among those, adaptive control mechanisms, such as machine learning in traffic signals control at ramps and intersections [7–11], model reference adaptive control in car following [12] and real-time traffic management [13], model predictive control in urban traffic management [14–18], extremum seeking control in traffic congestion and lane-changing management [19,20], adaptive fuzzy control in traffic flow ramp metering and signal optimization [21–24], as well as other fixed control schemes such as optimal control [20,21] and linear quadratic control [22,23], have been widely applied. However, the majority of the literature fails to establish systematic linkages among the passive and active feedback structures utilized by the system to obtain resilience - described in terms of adaptability with system state and form return abilities. The resilience system interpretation framework introduced by Mayar et al. [1] defines resilience as adaptability and adaptive systems where the system under perturbations and change has the ability to return to a starting or other suitable state or form through the system passive and active feedback mechanisms respectively. The framework was first applied to two simple linear and nonlinear dynamic systems [25] and this study extends the resilience system interpretation framework application to a traffic flow system and therefore making an original contribution to the field.

The study is structured as follows: Section 4.4 provides an introduction to the methodological framework for the two macroscopic traffic flow systems and their constituent elements including perturbations and change. Section 4.5 analyzes the resilience system interpretation under the two broad categories; system state and form and their abilities to return to their initial or other suitable states and forms. Lastly, Section 4.6 presents a summary and discussion.

4.4 Methodology and Analysis Tools

The methodological framework utilized in the study is a state-space approach from modern control systems theory where the system fundamental variables are the system input (control and disturbance), state (system internal behavior), and output (system external performance or response) (Figure 4.1), which accommodates both the system's passive and active feedback features.

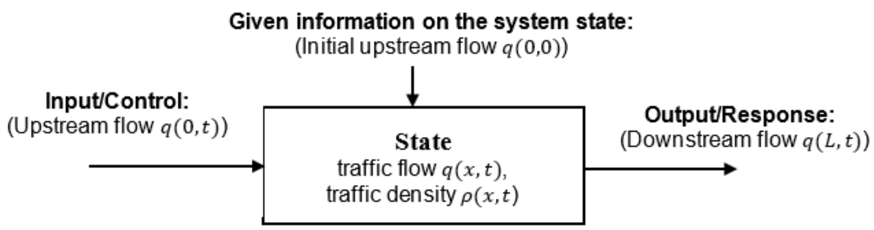

Figure 4.1. Traffic flow system single-level system representation.

The term system here is defined as a set of interacting or interrelated components (or subsystems) isolated from the external environment by its boundary, which is freely chosen by the observer to better serve the purpose of the target study [26]. A transportation system model is generally comprised of three main components: (1) travel demand and user behavior (demand models), (2) transportation services and their functioning (supply or performance models), and (3) interaction of the two (assignment models) [27]. In this study, the selected transportation models are limited to the traffic flow models that fall under the supply or performance component. Several constraints have been imposed for the sake of simplicity such as a single section or link of a road instead of a road network, as well as an initial fixed amount of demand flow and a pre-trip path choice.

In a system methodology, particularly a state-space approach, the first crucial step is to define the system, which entails determining the system boundary, its fundamental variables, and the relevant constituting subsystems. A system can be described both in a single-level (Figure 4.1) or a multi-level (subsystem) of details (Figure 4.2). The subsystems for a traffic flow system can be arranged in the form of four hierarchical interacting layers of structure, member, element, and material, as introduced by Carmichael [28] in the context of structural analysis (system multi-level representation). The behavior of each subsystem is defined in terms of a constituent relationship (similar to a stress-strain equation), while their interaction is defined by equilibrium (similar to a force-stress equation) and compatibility relationships (similar to a strain-displacement equation) [28,29]. The traffic flow system's constituent layers consist of single vehicle movement, microscopic traffic flow, mesoscopic traffic flow, and macroscopic traffic flow layers (Figure 4.2). The fundamental variables of each subsystem are functions of time and space (both independent variables). For the single vehicle movement or material layer, the system model is described by the kinematic equations of the motion, which can be rewritten in the form of ordinary differential equations. The system state is subsequently defined by a dual-tuple of ($\mathrm{v(t)}$ $-$velocity and $\mathrm{a(t)}$ $-$acceleration), output ($\mathrm{v(t)}$) and the control variable as the vehicle jerk (j) and/or the force (F) exerted on the gas pedal. The microscopic traffic flow or element layer describes the interaction of adjacent vehicles in a traffic stream with each other and with the road infrastructure [30,31]. The subsystem models are defined by the ordinary differential equations and the system state is determined by a dual-tuple of ($\Delta\mathrm{x(t)}$, the following vehicle's relative position and $\Delta\mathrm{v(t)}$, the following vehicle's relative velocity with regard to the leading vehicle), output [$\Delta\mathrm{x(t)}$] and the following vehicle's acceleration as the control variable [$\mathrm{a(t)}$]. The mesoscopic traffic flow or member layer, acts as a middle ground and connection between the microscopic and macroscopic models by combining the individual vehicles' velocities through probability distribution functions on a microscopic level with flow and density from a macroscopic level [31–33]. The macroscopic traffic flow or structure level considers traffic as a continuum of fluid flow, assuming the law of conservation of flow, which means that no vehicle can (dis)appear within a certain stretch of road. The analogy between traffic flow and fluid flow is based on the fair resemblance of heavy traffic flow to a fluid stream – considering a macroscopic traffic flow as a one-dimensional compressible fluid [34]. The subsystem models for a macroscopic traffic flow are defined by partial differential equations and the system is determined by a dual-tuple of the ($q(x, t)$ −flow and $\rho\ (x, t)$ - density), output (downstream flow) and the control variable as the upstream flow and/or free flow velocity (v_f) (Figure 4.2). In this study, the traffic flow system behavior is investigated on the aggregate and structure level, and a single-level system representation is adopted accordingly (Figure 4.1).

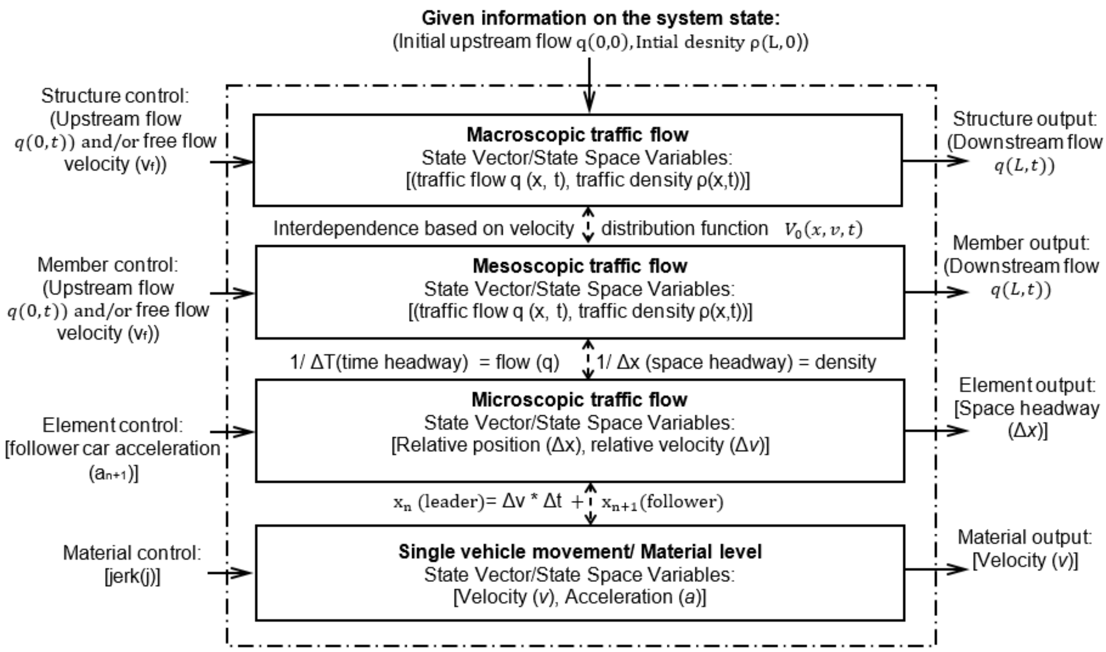

Figure 4.2. Traffic flow system boundary and hierarchical multi-level representation.

The analysis examples selected for this study consist of the modified viscous Burgers' Equation, which is a non-equilibrium macroscopic flow model that has the inherent ability to handle perturbations within the flow, and the Lighthill-Whitham-Richards (LWR)-Greenshields model, an equilibrium model with no inherent ability to handle perturbations and change unless an active feedback structure is incorporated within the system. The perturbation event for the modified viscous Burgers' equation is introduced in the form of a modified unit pulse function that indicates an abrupt temporary drop in the traffic flow or, alternatively, an abrupt temporary increase in the traffic density, which is a common indication of disruptions such as bottlenecks, traffic accidents and stoplights (Figure 4.3). The analysis tools utilized in these studies are theoretical numerical simulations carried out on perturbation events data generated by their respective functions demonstrating real-life traffic scenarios such as bottlenecks and traffic accident sites.

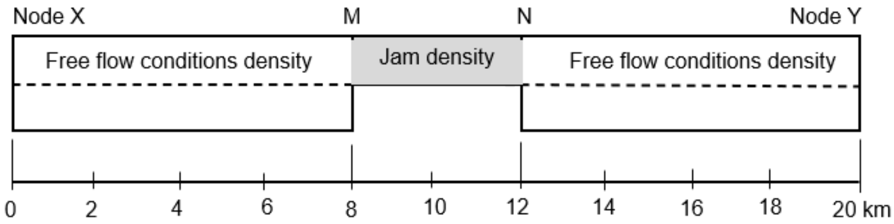

Figure 4.3. Schematic illustration of a two-lane highway link traffic density with a bottleneck in the middle of the link.

4.4.1 Modified Viscous Burgers' Equation

Contrary to the equilibrium models (LWR model in Section 4.4.2), non-equilibrium macroscopic traffic flow models, also known as higher-order relations can better describe real-world traffic scenarios by accommodating perturbed traffic flows. One of the well-known non-equilibrium models is the general viscous Burgers' Equation from fluid mechanics, that is the result of adding a smooth dispersion term ($D\ \partial_x{}^2\rho$) to the conservation equation (LWR model) (Equation 4.1). If the characteristic slope $q'(\rho)$ is replaced with an equivalent density term (ρ) the resulting equation is called the general viscous Burgers' Equation (Equation 4.2).

$$\partial_t\rho + q'(\rho)\ \partial_x\rho = D\ \partial_x{}^2\rho \tag{4.1}$$

$$\partial_t\rho + \rho\ \partial_x\rho = D\ \partial_x{}^2\rho \tag{4.2}$$

In order to make the general viscous Burgers' equation model precisely suited to describe a real-world traffic flow phenomenon, the $q'(\rho)$ term is replaced by the traffic Greenshields constituent equation (Equation 4.3) and, as a result, a modified viscous Burgers' equation emerges (Equation 4.4).

$$\partial_t\rho + \left[v_f\left(1 - \frac{2\rho}{\rho_{jam}}\right)\right]\partial_x\rho = D\ \partial_x{}^2\rho \tag{4.3}$$

$$\partial_t\rho + v_f\,\partial_x\rho - 2\,v_f\,\frac{\rho}{\rho_{jam}}\partial_x\rho = D\ \partial_x{}^2\rho \tag{4.4}$$

In Equations (4.1-4.4); ρ and q are the distributed traffic flow parameters of density and flow, v_f is the free flow velocity, ρ_{jam} is the jam density, $D = \frac{\mu}{\rho}$ is the kinematic viscosity and μ is the viscosity of the fluid.

4.4.2 Lighthill-Whitham-Richards (LWR) Model and Extremum Seeking Control

Equilibrium models, also known as the first-order relations, can only describe unperturbed traffic flow and are based on the law of conversation of flow from fluid dynamics [35]. A famous example of this category is the Lighthill-Whitham-Richards (LWR) model that connects the distributed traffic flow parameters of flow $q(x,t)$, density $\rho(x,t)$ and speed $v(x,t)$ using a Partial Differential Equation (PDE) (Equation 4.5) coupled with a fundamental equation (Equation 4.6). The traffic dynamics are restricted to an equilibrium state curve, also known as a constituent equation (speed-density relation), which has a linear form in the case of the Greenshields model (Equations 4.7) with a parabolic phase space for the two state variables of flow and density (Figure 4.4).

$$\frac{\partial \rho}{\partial t} + \frac{\partial q}{\partial x} = 0 \tag{4.5}$$

$$q = \rho\, v \tag{4.6}$$

$$v = v_f\left(1 - \frac{\rho}{\rho_{jam}}\right) \tag{4.7}$$

In Equations (4.6-4.7), v is the space speed, which indicates the slope of the flow-density curve (Figure 4.4) at each point of the curve ($v=\Delta q/\Delta \rho$). The scalar conservation law (Equation 4.5) in its alternative form (Equation 4.8), after plugging in the constituent equation (4.7), takes on a quasilinear hyperbolic form (Equation 4.9).

$$\rho_t + [q(\rho)]_x = 0 \quad \text{or alternativly} \quad \rho_t + q'(\rho)\rho_x \tag{4.8}$$

$$\rho_t + v_f\left(1 - \frac{2\rho}{\rho_{jam}}\right)\rho_x = 0 \tag{4.9}$$

Provided that the density (ρ) is one of the overall two state variables. The LWR model given by (Equation 4.8) represents a state space equation where $q'(\rho)$ is, in fact, the system state matrix A (Equation 4.10) of the system state-space with only one element and therefore it has one eigenvalue equal to the element itself (Equation 4.11). $q'(\rho)$ is also called the characteristic slope. A characteristic is a straight line intersecting the x-axis at a point equal to the initial value of the density and the density along the characteristic line stays constant and equal to its initial value.

$$A = q'(\rho) = v_f\left(1 - \frac{2\rho}{\rho_{jam}}\right) \tag{4.10}$$

$$\lambda = q'(\rho) = v_f\left(1 - \frac{2\rho}{\rho_{jam}}\right) \tag{4.11}$$

The stability condition for an equilibrium state in the sense of asymptotic stability: the real part of the eigenvalue should be negative or zero [in a general Lyapunov stability sense] is given by equation (4.12). The stability condition in equation (4.12) reveals that for the traffic density to be stable and return to its usual state (state A – located anywhere between D and C in Figure 4.4), it should be bounded to the $(\frac{\rho_{jam}}{2})$ upper limit (Point C). Any values for density (state variable) in the congestion (C-B) region is not recoverable from disruption unless an external intervention (active feedback) is implemented.

$$\lambda = v_f\left(1 - \frac{2\rho}{\rho_{jam}}\right) \leq 0 \qquad \text{or} \qquad \rho \leq \frac{\rho_{jam}}{2} \tag{4.12}$$

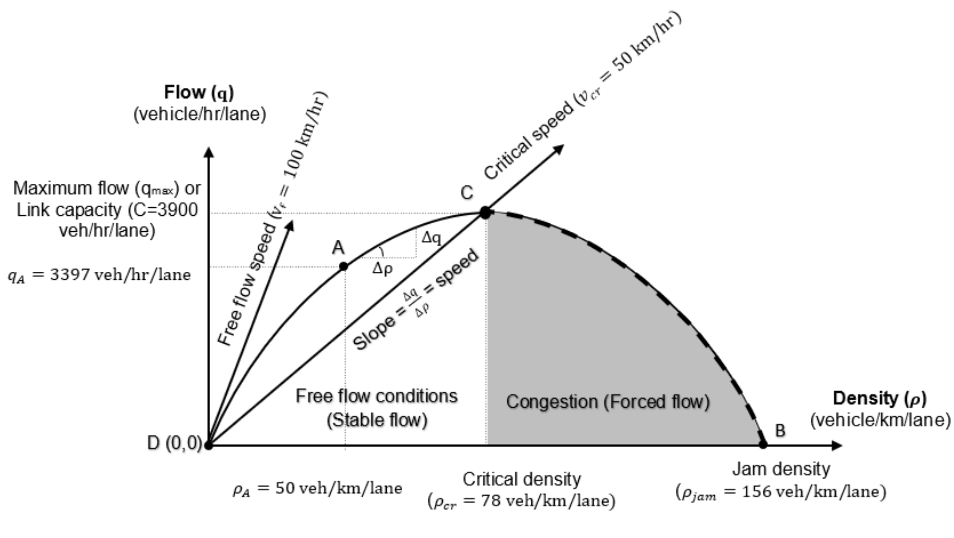

Figure 4.4. Schematic Flow-density curve (phase space) for the Greenshields model: $q = 100\rho - \frac{100}{156}\rho^2$.

Figure 4.4 describes the changes to traffic flow in the LWR and Greenshields equilibrium model; portions of the plot shown with a black solid line indicate free flow/non-congested flow /stable flow conditions ($\lambda \leq 0$) while the portions shown with a black dotted line indicate congested flow/forced flow conditions. The point where free-flow conditions transition to congested flow conditions is the maximum point of the flow-density curve (condition C). At point C, the values of flow, density, and speed variables are critical ($q_{cr}, \rho_{cr}, v_{cr}$) and are considered to be the optimum values for traffic flow, indicating a saturated traffic flow state, after which the system state enters the congested traffic flow zone (curve portion shown with a black dotted line). ρ_{cr} is also called the maximum density under free flow zone (curve portion shown as a solid black line) and is the limit for unforced recovery.

There are three major distinctive conditions/points (A, C and D) on the flow-density curve and its associated density-speed, and speed flow diagrams. Point D is where both the traffic flow and density are very low (close to zero) and therefore vehicles travel at the highest speed limit, referred to as the free flow speed (v_f) without any interaction between two adjacent vehicles. Moving up toward point C the flow and density increase and the speed gradually decreases until point C is reached, which is the transition point between free flow and congested flow conditions. Moving down from point C toward point B results in a gradual decrease in both flow and speed values as the system state enters a congested flow region (adjacent leader and flower vehicles interact with each other). This decrease in flow and speed in turn results in a gradual increase in density until point B is reached, where both the flow and speed values become very low (zero) and result in the maximum density in a congested region (jam density). Any sudden increase in traffic density forces the system into the congested area (Point C to B) and creates shock waves (perturbation) that are mathematically represented by the model characteristic slope (Equation 4.11).

Adaptive extremum seeking control (ESC), also known as an advance form of perturb and observe control, is an adaptive model-free active control structure that responds to changes in the system (underlying unknown dynamics) through input regulations for maximizing an objective function (a suitable form) [36]. ESC with a static objective function based on the Greenshields constituent equation, is applied here to regulate the perturbed traffic flow system by adjusting the system's unknown dynamics (assumed to be following the LWR-Greenshields model) to conform to the perturbed state of the system in the bottleneck (Figure 4.5).

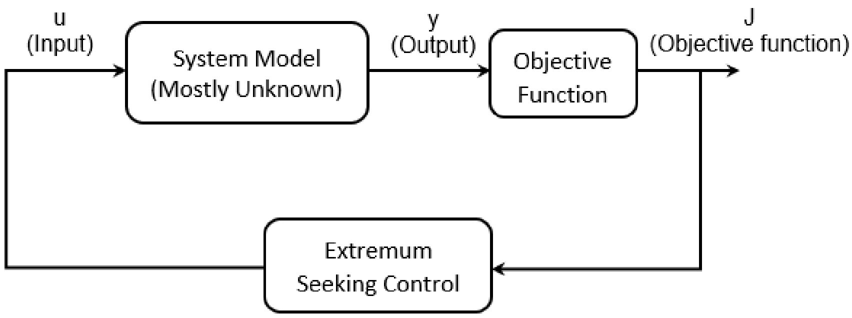

Figure 4.5. A simplified schematic illustration of an adaptive extremum seeking controller.

4.5 Resilience as System Interpretation

This Section numerically demonstrates the application of the resilience system interpretation framework to the two simple traffic flow systems. First under perturbation, the ability of the system state to return to its initial or other suitable state through its passive feedback mechanism is simulated on a modified viscous Burgers' equation, subsequently, under change, the ability of the system form to return to its initial or other suitable form through its active feedback structure is simulated on the assumed LWR-Greenshields-based data coupled with an adaptive extremum seeking control.

4.5.1 Resilience as System State Return Ability

In order to envisage the system state's ability to return to its initial state or other suitable state, a simulation scenario is explored that entails normal vehicular traffic flow moving from node X toward node Y along a two-lane, one-way road section (Link XY of length L=20 km) (Figure 4.3). Link XY has a maximum capacity (critical or optimum flow) of $q_{max} = 3900$ veh/hr/lane, jam density of $\rho_{jam} = 156$ veh/km/lane, critical or optimum density of $\rho_{cr} = 78$ veh/km/lane, a free flow speed of $v_f = 100$ km. The traffic moves in a normal free flow condition at position A located on the left hand side of the Greenshields flow-density curve (Figure 4.4) with a flow value of $q_A = 3397$ veh/hr/lane and a density value of $\rho_A = 50$ veh/km/lane. A perturbation in the form of a bottleneck/stoplight/accident point is introduced by a modified unit pulse function that indicates an abrupt temporary increase in the traffic density between 8-12 km from the normal $\rho_A = 50$ veh/km/lane to the jam density $\rho_A = 156$ veh/km/lane (Figure 4.6). The simulation is run at 1000 discrete points along a 10-hour time scale and subsequently the system state return time to its initial or other suitable state, which is a resilience indicator, is investigated under various values of the kinematic viscosity (D). The values of D which represent the built-in diffusion/dissipation level within the system are selected between 1 and zero that are consistent with the fluid dynamics principles. High positive values of D indicate faster dissipation of perturbation/discontinuity in the flow while a zero value indicates no room for the diffusion of a perturbation event.

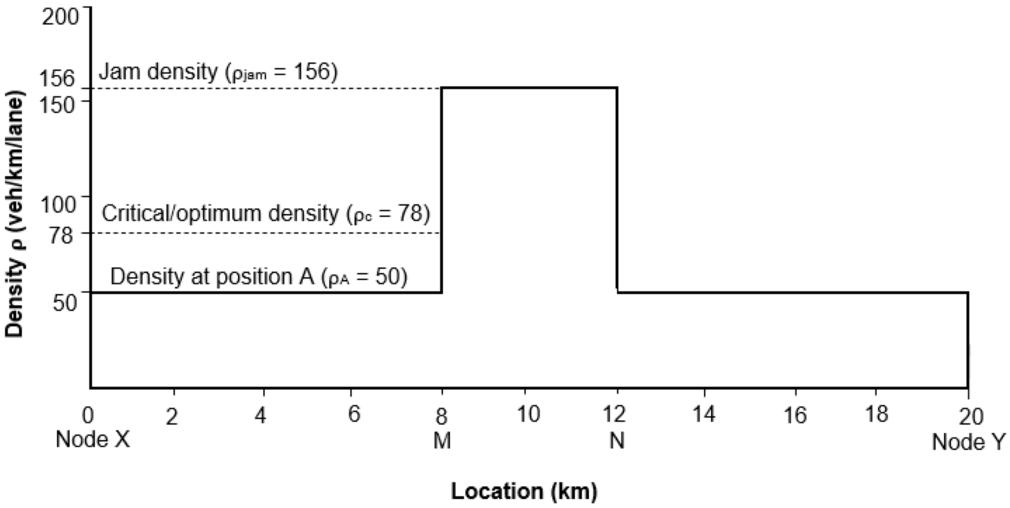

Figure 4.6. Graphical description of the perturbation density described by a modified unit pulse function around the link mid-point.

To simulate the modified viscous Burgers' equation with its distributed system state vector of (flow $q(x, t)$ and density $\rho(x, t)$), a series of Fourier Transform (FT) and Fast Fourier Transform (FFT) operations with some of their inverses are utilized to convert the modified viscous Burgers' equation from its partial differential equation (PDE) form (Equation 4.4) into a nonlinear ordinary differential equation (ODE) form (Equation 4.13), which is then simulated in the MATLAB environment. The detailed mathematical rigor for FT and FFT operations is omitted for the sake of simplicity.

$$\frac{d}{dt}\rho = -v_f\, d\rho + 2\, v_f\, \frac{\rho}{\rho_{jam}} \rho\, d\rho + D\, .\, d\rho^2 \qquad (4.13)$$

Resilience as the ability of the system state to return to its initial or other suitable state [in the sense of elastic or specified resilience] is quantified by the system state rate of return to equilibrium or the settling time, which is in turn determined by the system dominant eigenvalue or dynamic stability. The system state return ability is rooted in its resistance to perturbation, which is defined by the passive feedback features built into the system. For the subject traffic flow system of the modified viscous Burgers' equation, the ability of the system to resist perturbation is equivalent to the kinematic viscosity (D) in the flow which illustrates how compressible the traffic flow is, and a higher kinematic viscosity (D) value translates into a faster state return rate to equilibrium – resulting in higher resilience and vice versa. For the road physical infrastructure, the kinematic viscosity translates into designing a redundancy margin in the road link geometric components, such as an additional number of lanes and increased lane width, that could accommodate the predicted additional amount of traffic density caused by the perturbation (bottleneck) without any external intervention (active feedback).

For a kinematic viscosity rate of (D=1), Figure (4.7) illustrates a perturbed system state (density) spatial and temporal return to a suitable state (optimum density $\rho_{\mathrm{jam}} = 78$) in approximately 3 units of time. The perturbed system's entire state vector trajectory is demonstrated by the system state phase and the system state vector time response (Figure 4.8).

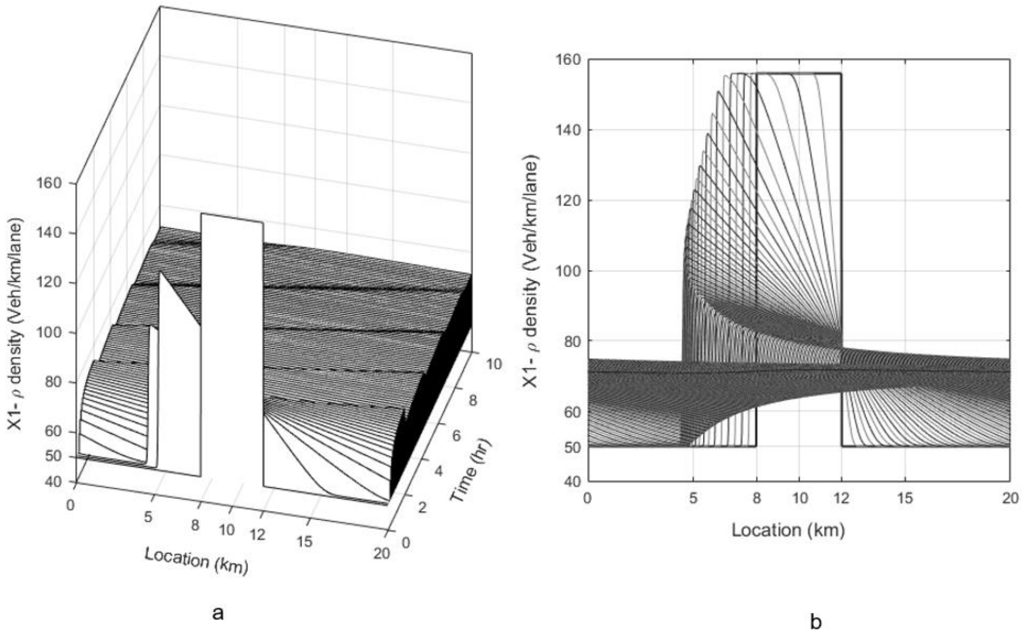

Figure 4.7. Perturbed system state (density) returns to the optimum suitable state of ρ_A=78 with a 3D (a) and its 2D surface projection (b) graphical illustration for D=1.0.

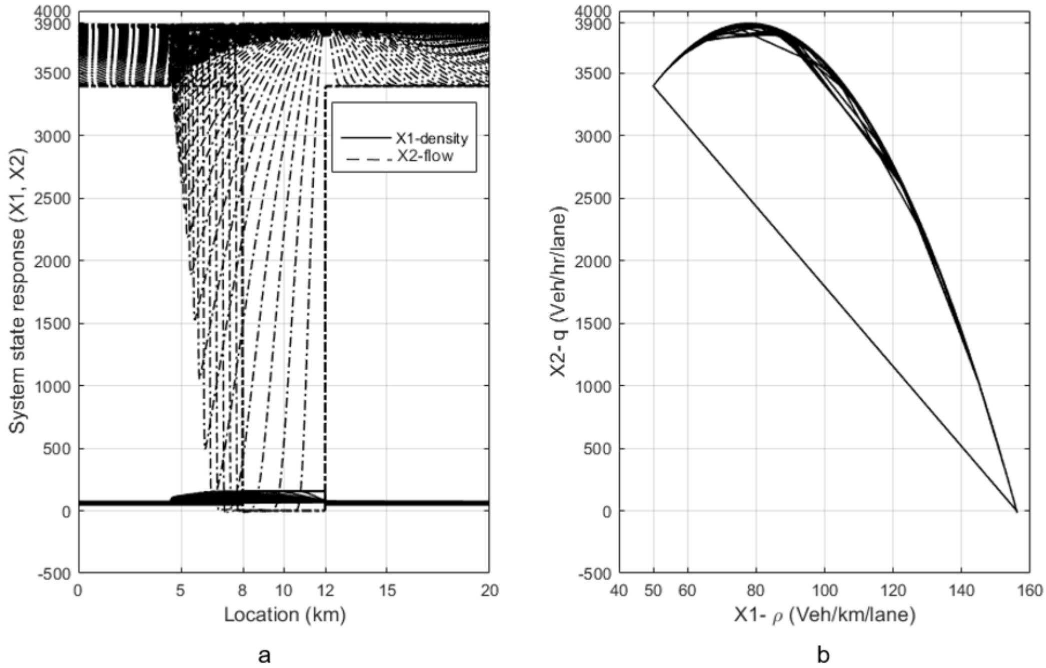

Figure 4.8. Perturbed system state vector time response (a) and the system space phase (b) indicating the system state vector return to the optimum state (ρ_A=78, q_A=3900) for D=1. The density visibility is limited on the scale of Figure 4.8a because of its relatively smaller numbers. For full visibility of the same density distribution see Figure 4.7b.

For a kinematic viscosity rate of (D= 0.51), Figure (4.9) illustrates a perturbed system state's (density) spatial and temporal return to a suitable state (optimum density $\rho_{\text{jam}} = 78$) in approximately 5 units of time. The perturbed system's entire state vector trajectory is demonstrated by the system state phase and the system state vector time response (Figure 4.10). As the values of kinematic viscosity (D) get close to zero, the system starts to lose its ability to handle discontinuity and shockwaves – this abnormality and lack of stability in the flow are visible in the system state variable/output unbounded behavior - going above its theoretical maximum capacity (Figure 4.10).

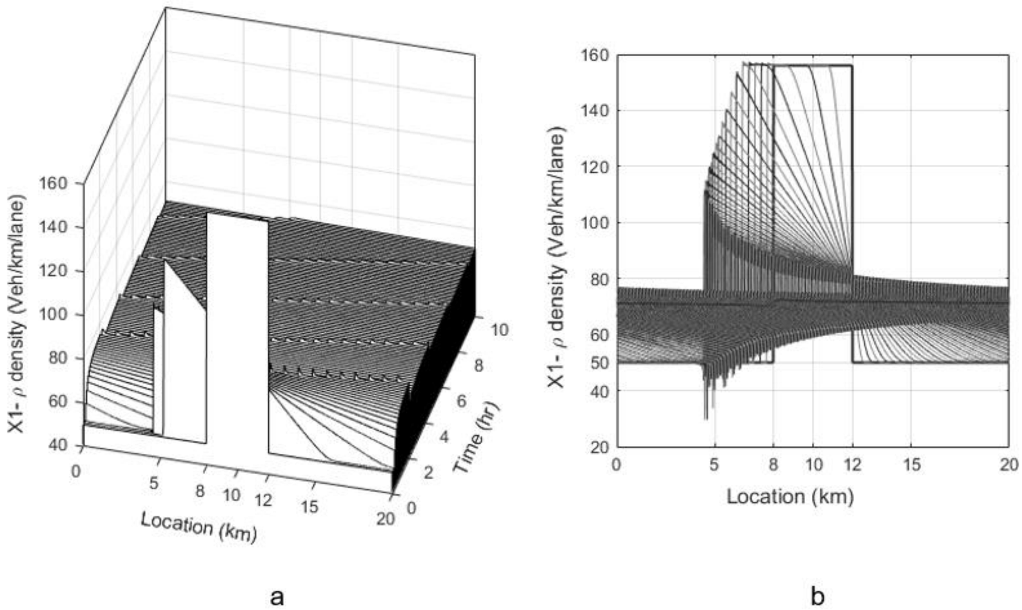

Figure 4.9. Perturbed system state (density) returns to the optimum suitable state of ρ_A=78 with a 3D (a) and its 2D surface projection (b) graphical illustration for D=0.51.

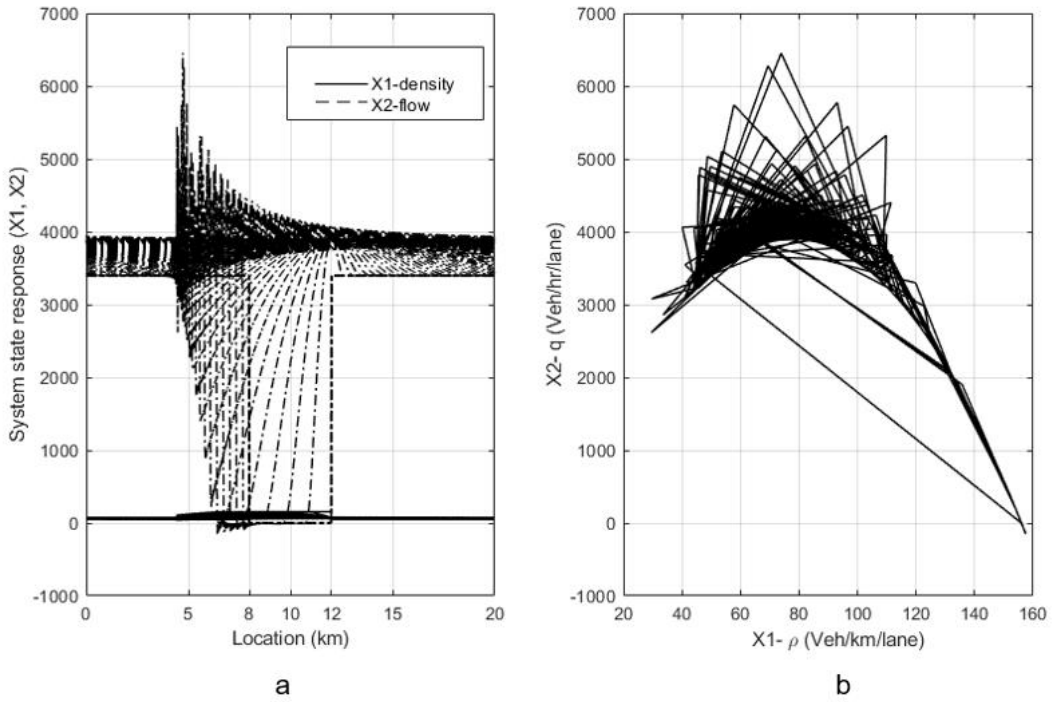

Figure 4.10. Perturbed system state vector time response (a) and the system space phase (b) indicating the system state vector return to the optimum state (ρ_A=78, q_A=3900) for D=0.51. The density visibility is limited on the scale of Figure 4.10a because of its relatively smaller numbers. For full visibility of the same density distribution see Figure 4.9b.

For a kinematic viscosity rate of (D= 0), the modified viscous Burgers' equation turns into a modified non-viscous Burgers' equation or a modified LWR model, which has no passive feedback mechanism for handling perturbation. For positive non-zero kinematic viscosity (D> 0), the reason behind the perturbed system state's return to the optimum state (position C on the Greenshields flow-density curve) instead of the initial state (position A- on the Greenshields flow-density curve) is consistent with the traffic flow shockwaves analysis based on the vehicles distance-time diagrams conducted by May [37] where, as a result of a spotlight along a road stretch, various shockwaves such as frontal stationery, backward forming, backward recovery and forward moving shockwaves are generated. Similar waves are visible in the simulations conducted for drafting the perturbed system state time evolution (Figures 4.7-4.10).

4.5.2 Resilience as System Form Return Ability

To demonstrate the ability of the system form to return to its initial form or other suitable form, a simple simulation scenario is explored which entails normal vehicular traffic flow moving from node X toward node Y along a two-lane, one-way road section (Link XY of length L=12 km) (Figure 4.11). The first Section of the Link XY until the point M (XM) is assumed to be following the LWR- Greenshields constituent equation with a maximum capacity of $q_{max} = 3900\ \mathrm{veh/hr/lane}$, jam density of $\rho_{jam} = 156\ \mathrm{veh/km/lane}$, critical or optimum density of $\rho_{cr} = 78\ \mathrm{veh/km/lane}$, a free flow speed of $v_f = 100$ km and traffic flow in a normal free flow condition (Figure 4.4 – position A; flow of $q_A = 3397\ \mathrm{veh/hr/lane}$ and density of $\rho_A = 50\ \mathrm{veh/km/lane}$). At point M, the start of the second Section of the Link XY (MY), a bottleneck (perturbation) reduces the link width to a single lane with a maximum flow of $q_{max} = 1950\ \mathrm{veh/hr/lane}$, jam density of $\rho_{jam} = 78\ \mathrm{veh/km/lane}$, critical or optimum density of $\rho_{cr} = 39\ \mathrm{veh/km/lane}$, and a free flow speed of $v_f = 100$ km; the traffic is assumed to be still following the Greenshields constituent equation (Figure 4.11).

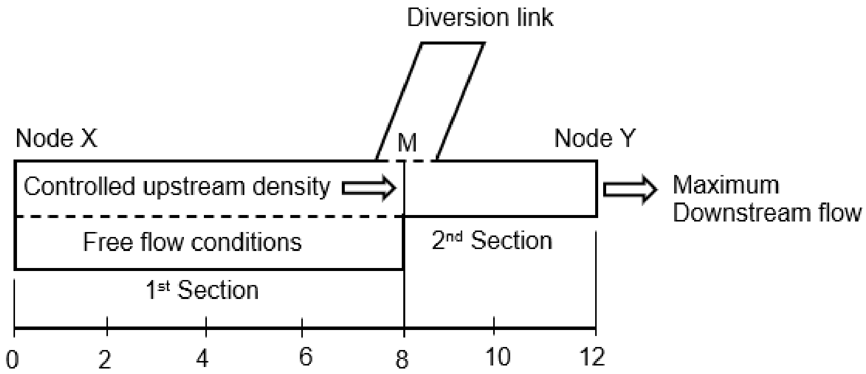

Figure 4.11. Schematic illustration of a two-lane highway link's traffic density with a bottleneck and diversion link.

When the free-flowing traffic in the first section of the Link XY (flow $q_A = 3397\ \mathrm{veh/hr/lane}$ and density $\rho_A = 50\ \mathrm{veh/km/lane}$) is more than the critical flow and density of the second section of the Link XY (flow $q_{cr} = 1950\ \mathrm{veh/hr/lane}$ and density $\rho_{cr} = 39\ \mathrm{veh/km/lane}$) (Figure 4.12), the traffic in the second section of the link will go into a congested state and form and will not return to its initial or other suitable state and form unless an external intervention in the form of an active feedback/control is implemented.

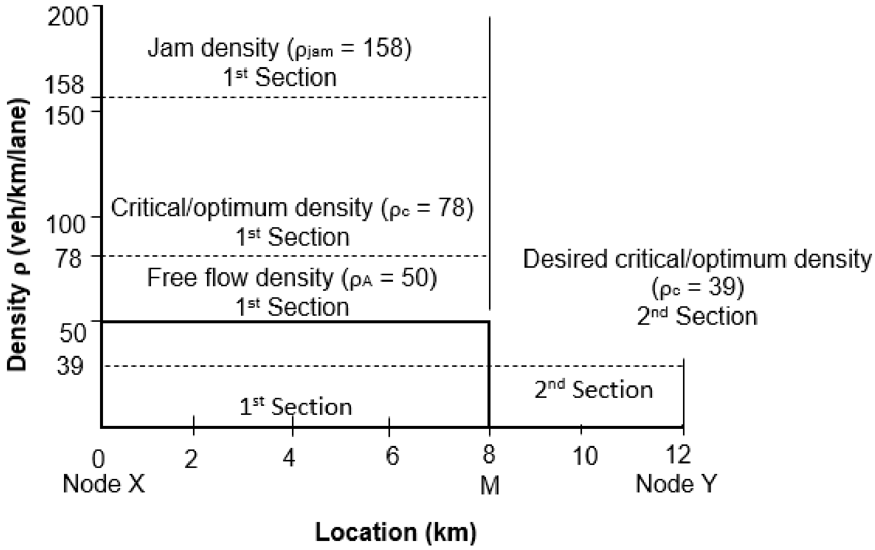

Figure 4.12. Graphical description of the perturbation density for the second section (MY) of the link de-scribed by a normal traffic flow at the 1st section of the link (XM).

In order to keep the traffic flow in the second section of the link XY at its optimum flow conditions ($q_{cr} = 1950 \text{ veh/hr/lane}$ and $\rho_{cr} = 39 \text{ veh/km/lane}$), an active feedback in the form of adaptive extremum seeking control is implemented (Figure 4.13). The controlled upstream traffic density at the left-side of point M (upstream which is calculated as the upstream flow divided by the variable speed limit) is considered as the input and the optimum flow at the downstream or right-side of the point M (downstream) is considered as the output to the objective function. The objective function adopted here is the Greenshields constituent equation (Equation 4.14), which has a different form (jam density is reduced at the downstream) to the constituent equation (Equation 4.15) followed by the traffic on the first section of the link XY.

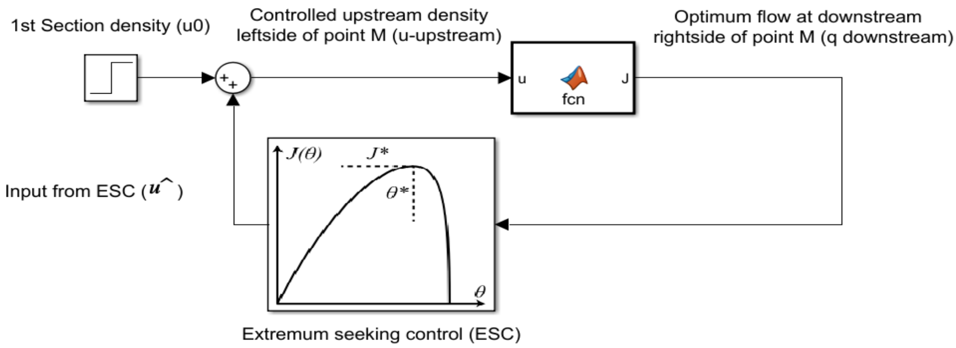

Figure 4.13. Schematic illustration of the extremum seeking control at point M of the link XY.

$$J = q = 100u - \frac{100}{76}u^2 \; ; \; \rho = u \tag{4.14}$$

$$J = q = 100u - \frac{100}{158}u^2 \quad ; \rho = u \tag{4.15}$$

A simulation scenario is run for 20 seconds and subsequently, the upstream density, or control action (input), and the downstream optimum flow, the output (also the system state variable) are plotted against time. The system resilience here is described by the ability of the system to return to its initial or other suitable form where, in the subject case, the system returns to a new suitable form governed by the second section constituent equation (Equation 4.14) and its optimal traffic state ($q_{cr} = 1950$ veh/hr/lane and $\rho_{cr} = 39$ veh/km/lane) in about 10 seconds. The additional traffic density ($\hat{u}$ or $\hat{\rho}$), which is indicated on the negative side of the density axis, is in fact the redirected density to a diversion link located at point M (Figure 4.14). Adjusting the active control (ESC) parameters will subsequently alter its state return abilities in the form of different system settling times. Additionally, the increased robustness and stability of the system feedback/controller mechanism translates into enhanced resilience of the system in the form of resilience. For the physical road infrastructure, this active feedback/control mechanism will translate into road signal regulators such as ramp metering and variable speed limit signs.

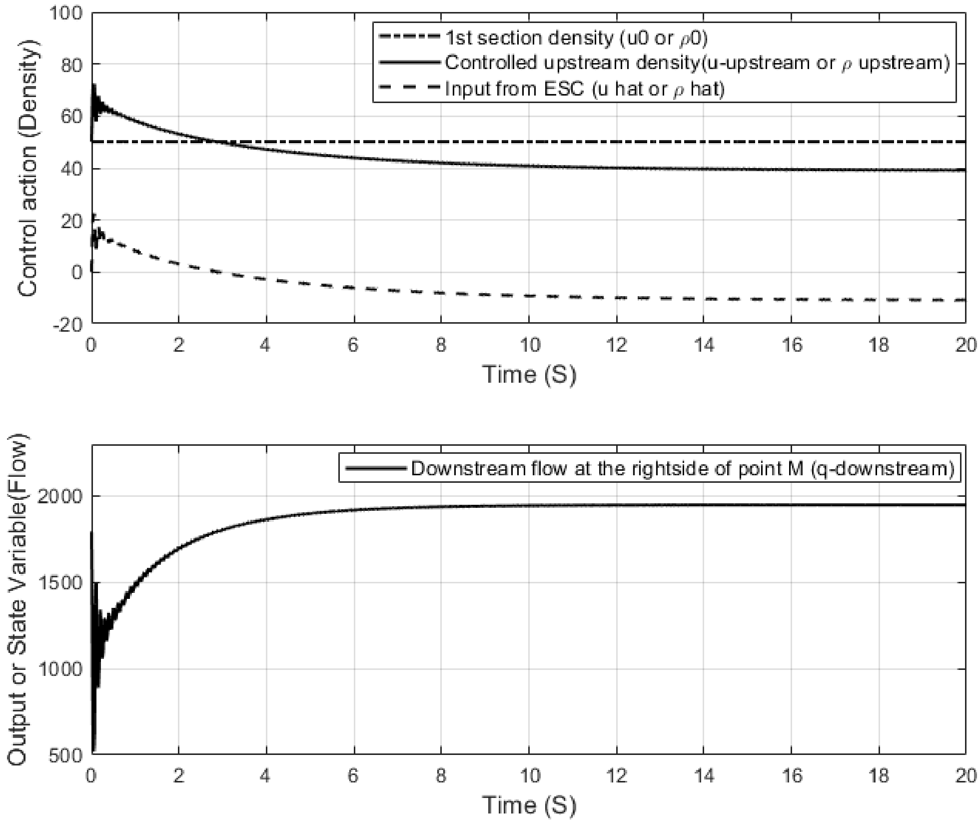

Figure 4.14. Control action (u, the upstream density) and the output (q, the downstream optimum flow) time evolution at point M on the link XY.

4.6 Discussion and Conclusions

This study demonstrates that the resilience system interpretation framework can be applicable to any system, irrespective of its disciplinary association, when defined in terms of control systems rather than by the often abused and conflicting utilization of the term 'system(s)' prevalent in literature. However, this study adopts a single-level system representation for the analysis; the modern control systems approach has the ability to accommodate a more vigorous and detailed multi-level system representation and its subsystem interactions. The two models utilized in this study are simple macroscopic traffic flow systems with homogenous traffic conditions. Whereas for mixed or heterogeneous traffic with variable vehicles, based on the site conditions, a suitable index should be applied to adjust the macroscopic traffic flow system state variables. In absence of the adaptive control measure, traffic in diverging sections- similar to Figure 4.11 might have a resembling or non-resembling behavior to that in Section 4.5.2, given the network layout and the driver's route choice behavior which is beyond the scope of this study.

As the complexity and uncertainty involved in real-the world systems increases, it is not always possible to develop system models based on first principles and the laws of physics. Recent advances in resilience-based designs [38,39], data science and computer-assisted numerical analysis techniques, particularly big data with easier and cheaper access, have made data-based modelling (grey and black box modelling) convenient and relevant. Thus, the adaptive control systems have become increasingly crucial to the resilience design and analysis process compared to the passive control as-built structures. For more complex traffic flow and transportation systems, additional system variables are introduced to the system state vector, which is selected as per the designed objective. By utilizing system tools such as dynamic mode decomposition (DMD), higher dimension systems can be approximated as lower dimension simple systems. The non-uniqueness of the system state vector is a major strength in the space-models and modern control system techniques.

In this study, resilience as the ability of the system form to return to its initial or other suitable form is demonstrated by an adaptive extremum seeking control with a static objective function. It has been demonstrated that more realistic dynamic objective functions along with spatial domain variables (through time lagging) can be handled by incorporating the ESC scheme (see also Yu et al.[19]). Other alternative adaptive control schemes include model predictive control (MPC) and model reference adaptive control (MRAC). MPC has the added value of handling constraints (e.g., critical thresholds for the system resilience) and can accommodate a global treatment of the system compared to the local, single domain of attraction, treatment rendered by the ESC scheme. Model reference adaptive control (MRAC) is a more efficient tool for systems with only a single parameter uncertainty, which is more of a robust control scheme compared to the adaptive control.

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CHAPTER 5. RESILIENCE AND SYSTEMS – A BUILDING STRUCTURE CASE EXAMPLE

5.1 Link to Thesis

In Chapter 5, I presented the application of the resilience system interpretation framework – introduced in Chapter 2, to sample theoretical and practical building structure systems. The system state and form return abilities in response to perturbations and change were demonstrated through practical simulation scenarios on a sample 3-story steel moment resisting frame (SMRF) office building along with the change integration measures in a closed-loop control setting.

I have published this work:

1. Mayar, K., Carmichael, D.G., Shen, X., 2023. Resilience and Systems—A Building Structure Case Example. Buildings 13, 1520. https://doi.org/10.3390/buildings13061520

5.2 Abstract

The resilience of building structures – as plain technical/physical/engineering systems or complex socio-technical systems exposed to perturbations and change, has become increasingly important as natural disasters are on the rise and the world is changing rapidly. Existing resilience frameworks are focused mainly on the building systems' response to perturbation events and their functional recovery, while change appears to be left out. This study applies the resilience system interpretation framework, which defines resilience in a cross-disciplinary environment as adaptation and adaptive systems, to analyse actual and conceptual building structure systems. The system framework, using modern control systems theory, defines resilience as the ability of the system state and form to return to their initial or other suitable state or form through passive and active feedback mechanisms. This novel understanding of resilience accommodates a holistic and systematic integration of both perturbation and change in various building structures' portfolios. The framework will also provide a practical roadmap for resilience design in building structures that effectively responds to perturbation while dynamically adapting to change in order to avoid obsolescence as well as to increase the building's useful life.

Keywords: Resilience, building structures, perturbation, change, modern control systems theory

5.3 Introduction and Background

The resilience of building structures, viewed either as plain technical/physical/engineering systems or complex socio-technical systems [1] exposed to perturbations and change, has become increasingly important as disasters are on the rise and the world undergoes rapid change. Perturbations related to extreme weather and infectious diseases top the global risks for likelihood and impact on The Global Risks Report 2021, respectively [2]. Natural disasters, primarily extreme weather-related perturbations, inflict a huge cost on world economies with an estimated average loss of 38 billion dollars per year for the Australian economy alone [3,4]. The global megatrends of change in natural, social, and technological arenas such as climate change, globalization, urbanization, and digitalization, bring new challenges to the built environment, particularly how building structures are planned, designed, delivered, and operated. To ensure that the built environment and building structures systems remain relevant in an environment that is characterized by uncertainty and change, adaptation in the system performance and useful life becomes critical [5].

The built environment and the construction sector account for one-fifth of the annual global CO2 emissions and half of all materials going into the economy [6]. The buildings portfolio, the largest part of the built environment, is critical to sustaining essential community functions such as housing, education, health, business, government, and other lifeline and critical infrastructure sectors such as water, transportation, energy, manufacturing, food, and agriculture [7]. Considering the increasing trend of uncertainty, the integration of adaptive features into the building structures' systems becomes critical to avoid obsolescence, enhance their ecological footprint, and ultimately contribute to global sustainability [5,8,9].

Despite the exponential growth in resilience literature, particularly disaster resilience over the course of the last two decades [10], the literature on the resilience of building structures remains chiefly constrained to structural recovery under perturbations, ensuring only the minimum life-safety requirements specified by the relevant codes [11]. The perturbation events in these studies include natural hazards such as earthquakes [12,13], floods [14,15], hurricanes [16,17], and fires [18,19], as well as man-made perturbation events such as terrorism [20,21], and military action [22,23]. However, over the course of recent years, several studies have used increasingly realistic and inclusive approaches, such as Performance-Based Seismic Design (PBSD) and relevant tools such as the Federal Emergency Management Agency (FEMA) P-58 [24] and the Resilience-based Earthquake Design Initiative (REDi) [25] methodologies to measure buildings structures' resilience. However, system dynamic functionality/behaviour objectives and change appear to have been left out of the resilience scenarios. This underpins the lack of a unified and systematic treatment that addresses both perturbation and change under one umbrella. This study applies the resilience system interpretation framework [26] to a building structure system. The framework advances a unified and cross-disciplinary resilience system interpretation that defines resilience in terms of adaptation and adaptive systems, where resilience can be obtained through both passive and active feedback structures demonstrated in the system state and form return abilities. The framework was previously applied to simple linear and nonlinear dynamic systems of lumped mass and simple pendulum [27], as well as sample traffic flow system [Chapter 4]. This study is an extension of the resilience system interpretation framework to include a further complex dynamic system of building structures, therefore making an original contribution to the field.

The study is structured as follows: Section 5.4 introduces the control system methodological framework for different system state definitions, including perturbations and change, and is demonstrated by sample building structures categories. Section 5.5 analyses the resilience system interpretation under two broad categories: the system state and form, and their abilities to return to their initial or another suitable state and form, respectively. A simulation scenario is conducted for a sample 3-story Steel Moment Resisting Frame (SMRF) office building along with change integration measures in a closed-loop control setting. Lastly, Section 5.6 presents the discussion and conclusions.

5.4 Methodology and Analysis Tools

The methodology used in this study is a state-space approach from modern control systems theory with the fundamental variables of input (control and disturbance), state (system internal behaviour), and output (system external performance and response). This representation systematically accommodates both the system's passive and active feedback structures and their interaction. The system approach has the conceptual power that can holistically accommodate every system in terms of inputs, state, and outputs in a single or multi-level representation and allows the system designer to draw the system boundaries as per the intent of the study. For a building structure system, this representation allows drawing the system boundary around a single domain of physical/technical/engineering, social, organizational, or economic aspects of a building structure or a combination of two or more of them. It also accommodates the study of building structures on various levels from individual building structures to the neighbourhood and city level under single or multiple events of perturbation, such as earthquakes, floods, hurricanes, and fires, including the change processes.

The conceptual, as well as the practical power of the control systems theory approach, allows the system designer to define the system state as either simply the building structural design features under a single event of perturbation with a perfect system model developed from first principles, or as a rather complex socio-technical system state under both perturbation and change with imperfect or even black box and data-driven models. Figure 5.1 illustrates the elastic design of a building structure under seismic or vertical nodal loading from materials to element, member, and structure level, and their subsystem interactions with the ability to adjust the system controls on various levels to maintain the desired system behaviour under perturbation events. The use of active tuned mass dampers (ATMD) in high-rise buildings exposed to seismic and wind perturbation events [28,29] is an example of the element and structural level active feedback structures that manage the system's response within the required limits.

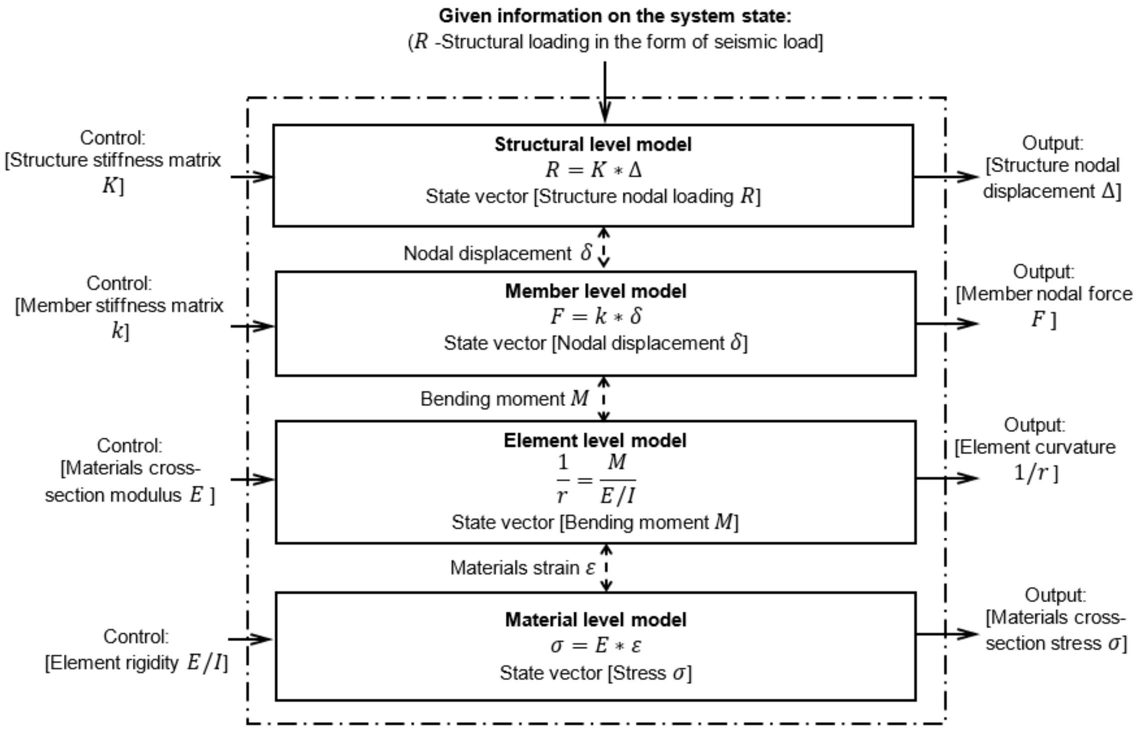

Figure 5.1. Multi-level representation of the structural design of a building subjected to nodal loading (I- the moment of inertia and r – radius of curvature). Source: Adapted from [30].

Figure 5.2 graphically describes a single-level system representation for a sample hospital building exposed to seismic perturbation and technological changes. Table 5.1 lists the potential system inputs, states, and outputs for various building structures portfolios and grouped based on the Australian National Construction Code (NCC) classification [31] under both perturbation and change.

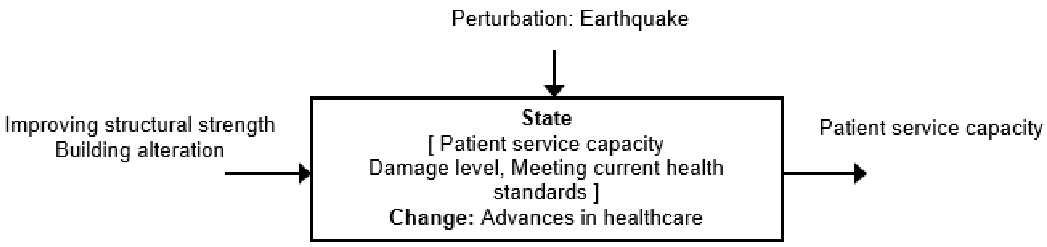

Figure 5.2. Hospital building single-level representation under a perturbation event of an earthquake and technological change.

Table 5.1. System representation of various building structures exposed to perturbation and change

<table>
<tr><th>Building System Use Classification (NCC)</th><th>Input | Perturbation</th><th>State</th><th>Output</th></tr>
<tr><td>Residential buildings (Class 1- 4)</td><td rowspan="6">Possible inputs:
Improving the building's structural strength against the perturbation event as well as changing the building's internal layout, external footprint, and number of stories through movability/convertibility/ upgradability/scalability/ shrink-ability/expand-ability and/or destructibility
Perturbation event:
Earthquake and/or changing socio-technical/economic conditions.</td><td>Occupancy level, Damage level, Meeting current living standards</td><td>Occupancy level</td></tr>
<tr><td>Commercial buildings (Class 5 and 6)</td><td>Customer service capacity, Damage level, Meeting current customer service standards</td><td>Customer service capacity</td></tr>
<tr><td>Educational buildings (Class 9)</td><td>Student service capacity, Damage level, Meeting current educational standards</td><td>Student service capacity</td></tr>
<tr><td>Healthcare buildings (Class 9)</td><td>Patient service capacity, Damage level, Meeting current health standards</td><td>Patient service capacity</td></tr>
<tr><td>Warehouse and car park buildings (Class 7)</td><td>Storage capacity, Damage level, Meeting current storage standards</td><td>Storage capacity</td></tr>
<tr><td>Industrial and non-hospitable buildings (Class 8 and 10)</td><td>Production capacity, Damage level, Meeting current manufacturing standards</td><td>Production capacity</td></tr>
</table>

Both actual and conceptual building systems models are used in this study for simulation and analysis purposes. The building structure used in the study for simulation purposes only is a sample 3-story Steel Moment Resisting Frame (SMRF) office building located in Berkeley California. The building is selected for its simplicity and convenience as most of the building structural dynamics aspects are pre-defined within the Performance Assessment Calculation Tool (PACT) environment. It is adapted from the Federal Emergency Management Agency (FEMA) manual [32] with a typical floor area of 2,112 square meters and a height of 4.5 meters for the first and 3.8 meters for the subsequent stories. The structural analysis tool used in this study is the PACT developed by FEMA. PACT uses building performance models consisting of the building’s geometric and geographical information, earthquake hazard, specification of the building's structural and non-structural elements including their fragility and consequences functions for various Performance Groups (PGs) as well as information on the building occupancy categories. The building performance model outcome in the PACT environment utilized in this study is a probabilistic, intensity-based nonlinear analysis with a total of 8 increasing intensities of the Maximum Considered Earthquake (MCE) in each round of realization [32]. Detailed mathematics and structural dynamics aspects of various performance groups and relevant performance measures such as components and damage states, loss parameters, fragility and consequences functions of various PG's are in accordance with the FIMA requirements and not incorporated in this research [refer to [24,32] for a de-tailed account of such measures for the selected building structure] as this study is majorly concentrated on the system state and form return abilities [demonstrated here by the system functionality].

5.5 Resilience as System Interpretation

This Section numerically, as well as conceptually, demonstrates the application of the resilience system interpretation framework to a building structure system. First, under perturbation, the ability of the system state to return to its initial or other suitable state through its passive feedback mechanism is simulated on the sample 3-story Steel Moment Resisting Frame (SMRF) office building under a certain seismic intensity. The structural strengths are introduced by codes, such as minimum safety requirements or maintaining a certain function under the perturbations of various magnitudes, and the availability of previously envisaged disasters response resources on-site in the form of redundancy. Subsequently, under change, the ability of the system form to return to its initial or other suitable form through its active feedback structure is simulated by adjusting the repair and reconstruction activities sequencing, including pre-repair redundant activities as a tool to achieve the fastest initial or another suitable functional recovery, such as converting a commercial building to a residential building or vice-versa. Additionally in a closed-loop adaptive systems environment, change measures are incorporated in the form of a synthesis configuration, as introduced by Carmichael [33].

5.5.1 Resilience as System State Return Ability

Resilience as the ability of the system state to return to its initial or other suitable state is determined by the system state rate of return to equilibrium [for linear systems] or the settling time [for nonlinear systems], which is determined by the system's dominant eigenvalue or dynamic stability. The system state return ability is embedded in its resistance to perturbation, which is determined by the passive feedback features built into the system. The system state here is defined as a one-dimensional state vector in terms of functionality [occupancy level]; this is related to the building's structural strength [including its non-structural elements] and maintaining the minimum life safety requirements specified by the relevant building codes against a perturbation event. A more comprehensive state can be developed as a multi-dimensional state vector by incorporating the system damage level and meeting the current living standards [a change feature, which is normally static for the passive feedback scenario] in addition to the occupancy level. For a building structure, the ability of the system to resist perturbation is equivalent to over-designing and increasing the safety factor [redundancy margin] against the perturbation event, which can subsequently be translated into an increased level of residual functionality or residual strength immediately after the perturbation event has occurred. An over-design of the building here is not necessarily meant as an increase in the size of the structural elements but rather the selection of innovative and robust structural systems with an integrated system of non-structural elements and other relevant functionality features. It also includes pre-set recovery measures available on site as well as other passive control features that avoid propagation of the functionality drop or failure across various levels of the system through modularity and incorporating cascade failure prevention features. The level of residual functionality, along with pre-set recovery measures on-site [part of larger redundancy category] and their pre-set sequence, determine the settling time [recovery time] for the building structure; this is the main indicator of engineering resilience. Figure 5.3 indicates a functional recovery time of 14 days under a seismic intensity of 2 with a pre-set continuous sequence of repair activities for the sample SMRF office building. Over-designing of the building elements and enhanced integration of the non-structural elements within the building’s structural system increases the building structure's residual functionality, offsetting the building recovery time and, as a result, increasing the engineering resilience.

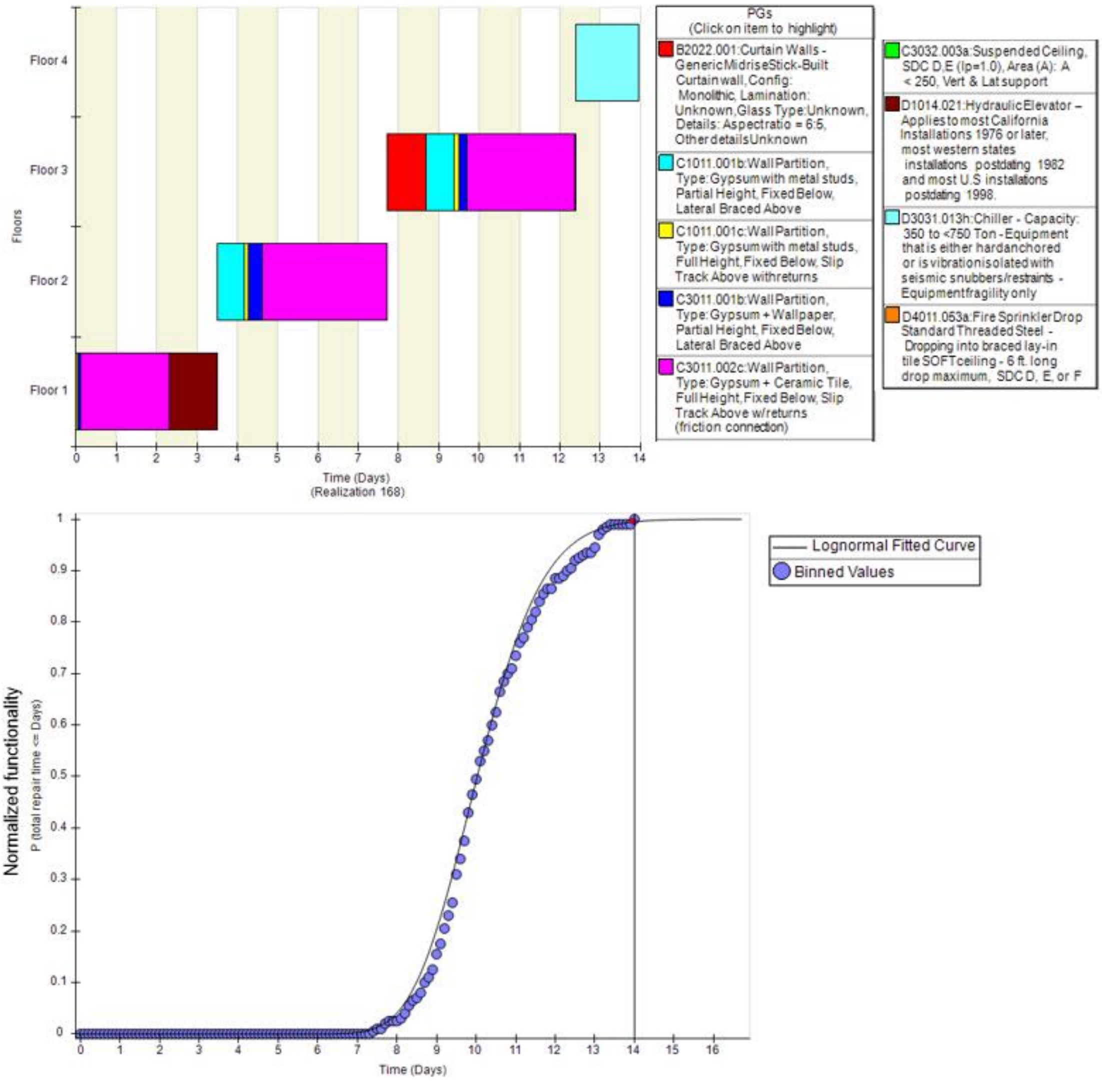

Figure 5.3. Functional recovery time for a 3-story SMRF office building under a seismic intensity of 2 developed in PACT (utilizing fragilities of various Performance Groups (PGs).

Due to the inherent uncertainty in both the building structure system models and the magnitudes and types of perturbation events, it is not desirable to rely on only passive measures that are presetly incorporated in the system architecture, irrespective of future changes, for a static recovery time to a fixed functionality [state]. An active feedback mechanism in the system architecture should be incorporated not only to accommodate for the system functionality's [state] return to the initial functionality [initial state] but also to accommodate the change in the system form when the initial state becomes undesirable in the current domain with a need to cross to an alternative domain of attraction.

5.5.2 Resilience as System Form Return Ability

For building structures, any change in the system form generally means degradation in the system state's ability to return to its initial state [becoming less functional] or the addition or removal of another state variable to the system state vector [transformation]. Changes in the system form and its ability to return to the initial form or another suitable form are accommodated by fixed or adaptive active feedback structures built into the system. Such feedback structures follow fixed or adaptive regulations on various levels to avoid obsolescence of the building structure itself and increase its useful life. Therefore, it’s critical to understand how any such change’s architecture is designed into the system on various levels and outline the stakeholders that can influence that architecture. The design of building structures as part of larger infrastructure system groups falls under the synthesis treatment, which is a closed-loop control with the three main elements of the system model, objective function, and constraints [33]. The synthesis configuration is powerful in that it can accommodate working with imperfect models, including black box models with the ability to choose a static or dynamic objective function as per the system designer's choice as well as catering to the limitations in the system controls, state, and outputs architecture. The non-uniqueness of the system state and, subsequently, the system control values is an added value in the modern control system theory approach. It allows the system designer to choose the system state in a synthesis configuration. This can be as simple as a single-dimensional state of nodal displacements in the structural design system (Figure 5.1) with the objective of minimizing the building story drifts/displacements and/or vibrations during a seismic perturbation event through the application of counteracting forces by the active tuned mass dampers (ATMD); an active feedback structure built into the structural system at the element level [34] (Figure 5.4). For a more comprehensive building structure system, that incorporates the social dimension along its technical/structural component, the system state could be a three-dimensional vector of [occupancy level, damage/displacement level, meeting current living standards]. Here, the objective function might be to match current commercial rental prices [which includes socio-economic factors] through actively adapting the building system to the change.

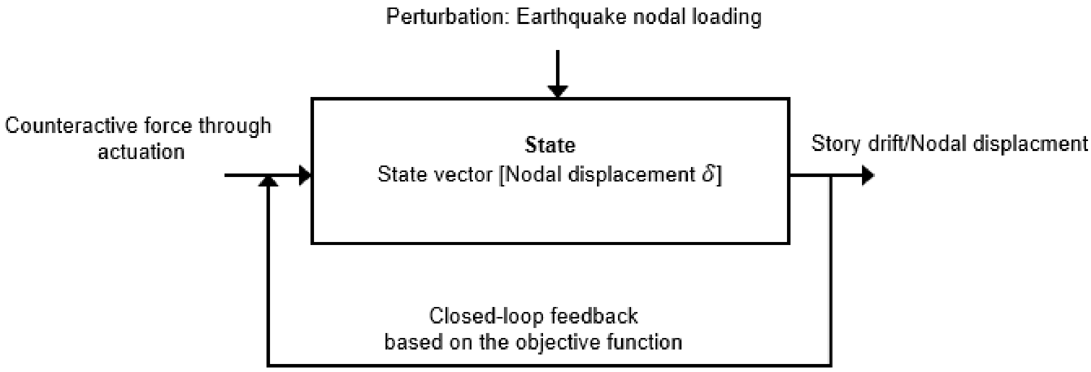

Figure 5.4. Closed-loop control architecture of a simple ATMD to control story drifts at the element level of the building structural system.

In order to systematically accommodate for the change in the system form and subsequently its return abilities, the closed-loop control system's architecture should be incorporated into the system design upfront or even into existing systems, where the feasibility is not necessarily guaranteed. The closed-loop architecture can be thought of as a synthesis configuration, irrespective of the system domain, be it physical or social, organizational, economic, or a combination of these. However, the literature predominantly employs two distinctive terms: engineering adaptability [35,36] and managerial adaptability [37,38]. To handle change in the design and management of building structure systems, the closed-loop architecture caters to both those notions and brings them under the single umbrella of a system closed-loop architecture. Depending on the system domain, engineering adaptability can be also thought of as managerial when the systems are soft, such as in organizational and economic domains, while in simple electrical and mechanical systems, managerial adaptability can be similarly thought of as engineering adaptability. In a closed-loop feedback setting, engineering adaptability is mostly concerned with the feedback architecture [mostly physical] incorporated into the system while managerial adaptability is majorly concerned with the feedback laws. i.e., objective functions in terms of the relevant laws and regulations.

Existing literature fails to provide consensus on a universal and systematic approach to address change within the built environment. Primarily verbal modelling under often conflicting definitions of adaptability and flexibility introduces overlapping concepts such as extendibility and scalability [39], reusability and recyclability [40], convertibility and upgradability[41], and transformability [42,43] to address certain elements of change in the built environment. Some of these concepts, such as open buildings, transformable buildings, modularity, and adaptive zoning/rezoning and regulations with apparent overlaps, are more dominant than others and can be brought under a closed-loop feedback architecture within the synthesis configuration to systematically address change in the building structure systems.

5.5.2.1 Open Buildings

The term Open Building was first coined by Age Van Randen at TU Delft – Netherlands in the mid-1980s. The concept was based on the Dutch architect and professor John Habraken and is a support and infill concept for residential buildings proposed in his seminal 1961 book: Supports: An Alternative to Mass Housing [44,45]. The concept of open buildings, pioneered in the Netherlands and Japan, bypasses the functional rigidity in traditional architectural design of building structure systems and replaces it with a life-cycle design through adaptation in social and technological changes of the building structures. The open building concept offers a novel multi-layer control mechanism by the relevant stakeholders across the building architectural design spectrum, where the two main layers of base building or support and infill or fit-out are controlled by the building owner/investor and the building users respectively. Other studies also include Furnishing, Fixtures, and Equipment (FF&E) in addition to the base building and interior construction in the multi-layer control mechanism structure of open buildings [46]. Base building in a multi-family residential building is the part of the building that directly affects all inhabitants and includes the building structural system and envelope, shared spaces, main ingress and egress, and primary mechanical, electrical and plumbing systems. Infill or fit-out for a residential building indicates that individual building users can control and change the habitable space within the base building without any changes to the base building itself [47].

5.5.2.2 Transformable Buildings

Conventional buildings with a static functional objective have increasingly become vacant, in need of minor or major refurbishments, totally obsolete, and even demolished [48] since they cannot accommodate the rapidly changing and dynamic objectives caused by social and technological changes; they do not have the necessary change architecture within their respective systems. Adopting ideas from open buildings [49], the notion of transformable buildings was introduced as a dynamic design strategy, also known as the Hendrickx–Vanwalleghem strategy [50,51]. The design strategy for transformable buildings indicates the building structure system's capacity to effectively alter itself or its constituent systems to accommodate changing requirements. The capacity to transform is, in turn, accommodated by the "generative form and dimensioning systems" and "disassembly" capacities; these require exchangeable and demountable system components both in the building envelope and the infill. The Hendrickx–Vanwalleghem strategy introduces adaptive capacities into the building design for the materials, elements, construction kits, and system levels [50]. One of the measures that distinguishes transformable buildings from open buildings is the level of adaptation in the building design; transformable buildings can include kinetic envelopes in addition to the building infills [43].

5.5.2.3 Modularity and Standardization

Concepts such as open buildings and transformable buildings can be thought of as the ends of system adaptation to change, while modularity and standardization are among the means that make the system change architecture feasible, irrespective of the system domain, whether physical or non-physical in nature. The first known instance of modular construction is attributed to the English carpenter, John Manning, who made a completely modular and prefabricated house for his son who was relocating to Australia [52]. In modular construction, the building structure is made of standardized parts known as modules. These are normally manufactured in the factory environment and can be independently modified, or replaced with other modules [53]. Modularity and standardization are not limited to the building components, but also encompass the building materials and the entire structure level as well [54]. There is a growing consensus that modularity and standardization improve quality [55], performance [56], and safety [57] as well as reduce the costs [58] and ecological footprint [59]; others list a lack of flexibility as the downside of modularity and standardization [60]. While acknowledging that geometric complexity and the uniqueness of design is an inherent challenge in modular building structure [60], optimizing modularity and standardization on various levels, including materials, elements, members, and structure as well as the interaction of the various subsystems through simple connections, can contribute to the enhanced adaptability of the building structures to change.

5.5.2.4 Adaptive Regulations and Zoning Requirements

There is often a rigidity and lack of sufficient adaptability in building codes and regulations at various levels, as well as a lack of incentives on the part of regulators [61] to systematically accommodate for the change process adapted within the building structures systems by the designers or owners. As with the change-architecture built within the system itself, the building codes and regulations also require a multi-scale and holistic mechanism to adapt to change. This includes regulations at the lower levels, such as allowing modest changes in the building's functional use by the building users. This was piloted by the Japanese construction regulations for skeleton-infill systems [62]; these higher-level regulations include adaptive zoning and rezoning at the neighbourhood and buildings portfolio levels. However, the current building codes establish minimum essential standards for health, safety, amenity, and sustainability [63]; resilience indicators, particularly change [including performance-based building codes] are not sufficiently incorporated. The Regulatory Impact Statements (RISs) used by the regulators in assessing cost-benefit implications for new and changed code requirements [64,65] have to be more holistic and systematic by including all stakeholders in the system design. Additional dimensions of sustainability and resilience indicators to the document for various perturbations and change categories should be included. Furthermore, there is a need for synchronization of such documents by the regulators and those within the industry, such as the Adaptive Reuse Potential (ARP) model [66] for assessing the potential of the existing buildings for an altered functional use.

5.5.2.5 Synthesis Treatment – An Overarching Umbrella to Change Management

A synthesis treatment can systemically bring existing adaptation to change-related concepts under one umbrella, accommodate for the limitations in the adaptation process, and provide an opportunity to reconcile perturbation and change. Open buildings primarily cover the convertibility and reusability of the building structures in terms of smaller functional changes in the same class of buildings. Transformable buildings can be grouped under partially transformable buildings and building transformation categories. The former has the potential for minor adaptations, including ideas of upgradability/scalability/extendibility within the same or a closely related class of buildings, crossing a soft threshold from which reversal is a reasonably feasible option.

The latter accommodates major changes that are not reversible or are hard to reverse, which includes changing the building class to a different [not closely related] building or another infrastructure class, using the system's change-architecture, or through a sustainable demolition process. The transformation of a 5.6 km long obsolete railway into the Queensway Linear Park in Queens, New York, is a good example of built infrastructure transformation [67]. While the system's change architecture discussed here is mostly designed for long-term or permanent use, temporary change potential, particularly within the building's functional use under the minor adaptation class, cannot be ignored. Turning sports halls and community centres into temporary health facilities during the COVID-19 pandemic is a good example of this category.

Modularity and standardization are the tools to achieve the goals of the system adaptation to change as defined in the system's form return abilities. On the other hand, adaptive regulations and adaptive zoning/rezoning requirements are the adaptive feedback laws and constraints that need to conform and be incorporated into the system's change-architecture to make the system treatment of change a holistic process. Using a systems approach, the change-architecture built into the system can be thought of as the same, irrespective of the system domain association. However, for organizational/social or soft systems, the change-architecture might look simpler and more convenient when incorporated into the system upfront, or later in the system life cycle; changing the organizational/social dynamics in some systems is as difficult as in technical/physical systems. Table 5.2 incorporates existing concepts of adaptations to change in building structure, using the synthesis treatment for the residential buildings class.

Table 5.2. Synthesis treatment for handling change in the sample residential building structures systems class.

Change architecture incorporated within the system model	Objective	Constraints
Open Buildings: - Modularity in the infill and partition systems; - Flexibility in infill and partition connections; Example: Improving floor space layout within the same residential	Keeping a certain occupancy level along with meeting current living standards.	Limited change potential- being within a smaller and known radius of the initial/optimum state value: - Only building floor plan layout changes within the same building class.

building class of multi-family building.		- Having adaptable organizational regulations in place that allows building users to make the required changes.
Transformable buildings with keeping the identity or partially transforming buildings: - Modularity in the infill and partition systems; - Flexibility in infill and partition connections; - Larger size/stronger foundations, larger size/stronger perimeter columns; - Innovating structural systems; - Highly displacement tolerant façade systems. Example: Changes to the floor space layout along with potential envelope changes and going from a residential building class to an office building class or vice-versa.	Keeping a certain occupancy level along with the ability to change to another closely related category of building system state standards	Crossing a soft threshold: A major change with a reasonable reversibility option - crossing to another domain of attraction: - Building floor plan layout changes along with the building class change. - Having adaptive zoning/rezoning requirements in place allowing the building owners to make the required changes.
Transformable buildings with loss of identity or building transformation: - Modularity in the infill and partition systems; - Adaptability in infill and partition connections; - Prefabricated slab systems - Modularity and adaptability in building structural systems; - Ease of disassembly and reusability in both building infill and support components. Example: Major envelope and infill changes – such as transitioning from a residential building class to an industrial building class.	Keeping a certain occupancy level along with the ability to change to another completely different category of building system state standards or even to another infrastructure system with or without a sustainable demolition option.	Crossing a hard threshold: A major change with a hard or impossible reversibility option - crossing to another domain of attraction: - Major support and infill changes that are equivalent to the loss of identity with or without sustainable demolition option. Direct management action for change in the site and zoning requirements in compliance with the building owner's requirements.

These concepts fall under the change-architecture and regulations. Open buildings cover the convertibility/reusability and small functional changes in the area normally within the same class of buildings. Transformable buildings often have more space for change through either minor adaptation, including upgradability/scalability/extendibility within the same class of buildings or major adaptations and transformations, even converting to a different building class, which means a different domain of attraction through crossing a soft threshold. However, major changes that are not reversible, such as going from one building class to a different class of building or another built infrastructure through sustainable demolition can be called transformation. Modularity and standardization are the tools that help to achieve the end use of adaptation to change process - defined in the return ability of the system's form. Adaptive zoning is the adaptive feedback laws that are in conformity with the change and make the system handling of change a holistic process.

5.5.2.6 An Example of the Return Ability of the System Form

A synthesis treatment can be used to optimize the building's structure repair activities sequence after a seismic perturbation has taken place to obtain a target level of state [functional] recovery time as an objective function. The length of the repair activities, their sequence and the work method, along with the relevant resources and constraints on site will determine the system state recovery path shape [system form return abilities]; this, in turn, changes the system settling/repair time [state return abilities]. Figure 5.5 illustrates the system state [one dimension state of building function] recovery time of 6.7 days under a seismic intensity of 2 with a parallel sequence of repair activities for the sample SMRF office building. This change in settling time is accommodated by the change in the system form and is almost half of the settling time under a continuous, pre-set sequence of activities shown in Figure 5.3.

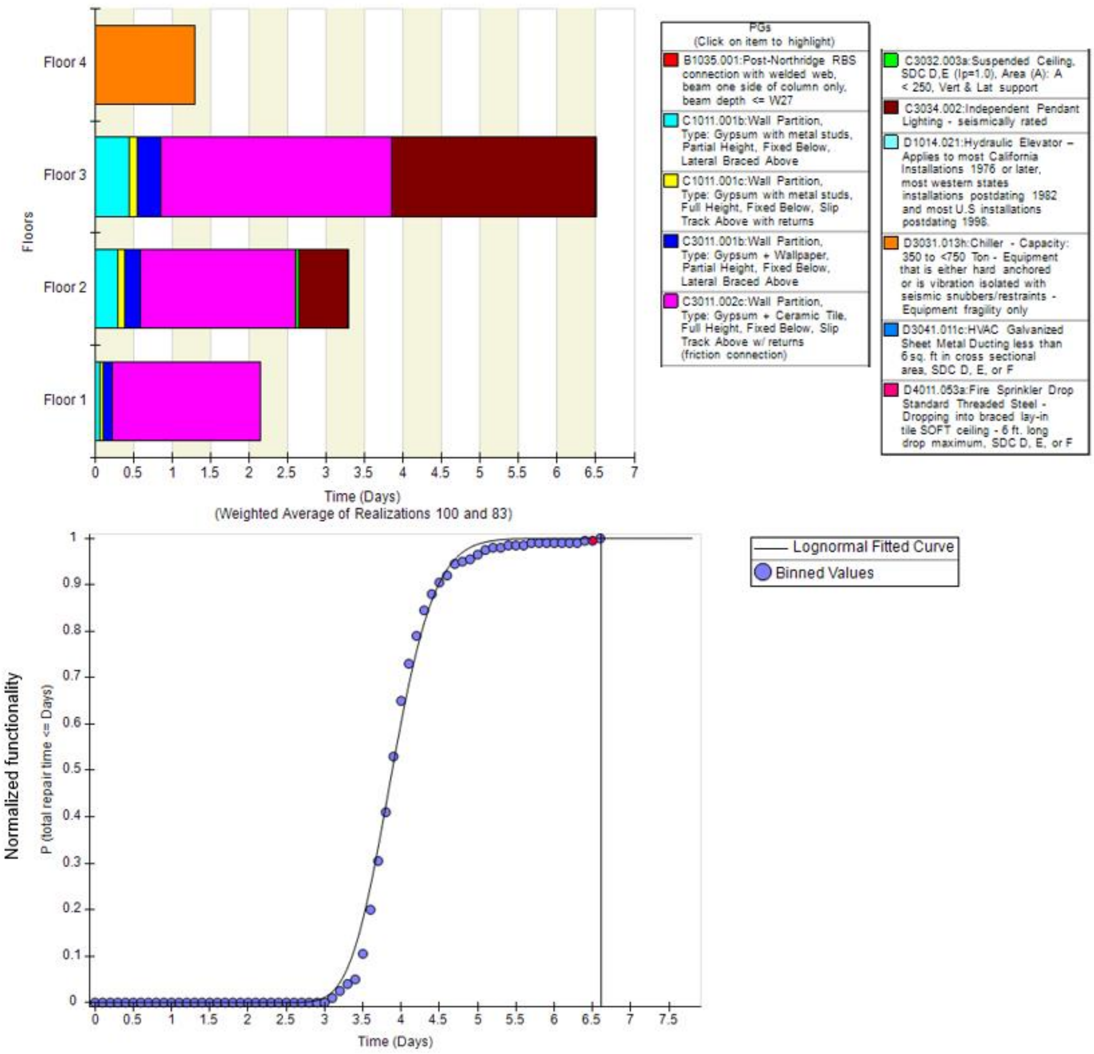

Figure 5.5. Functional recovery time for a 3-story SMRF office building after a seismic intensity of 2 as developed in PACT –with parallel sequencing of the repair activities.

By selecting a further comprehensive system state [such as the ones in Table 5.1], a broader change process can be incorporated into the system change architecture. For instance, for a commercial/office building class, "meeting the current service standards" will be the dynamic component of the system state vector in the objective function. Additionally, system administrators and regulators will need to implement dynamic policies and adaptive regulations that are consistent with the system change-architecture in order to make the system adapt to change both systematically and holistically. The shape of the system recovery paths mainly depends on the repair activities sequence, work method, and the availability of the required resources on site. Three main types of linear, exponential [68], and trigonometric [69] functional recovery path shapes are selected in cases of (i) no resource-specific information being available, (ii) a higher early inflow of resources followed by a slower rate at the end, and (iii) a lack of resources respectively. In addition to the sequence of the building structure's main repair activities, pre-repair or impeding factors, such as inspections, permits, financing, and mobilizations, are critical to the recovery time and recovery path shape [70] (Figure 5.6).

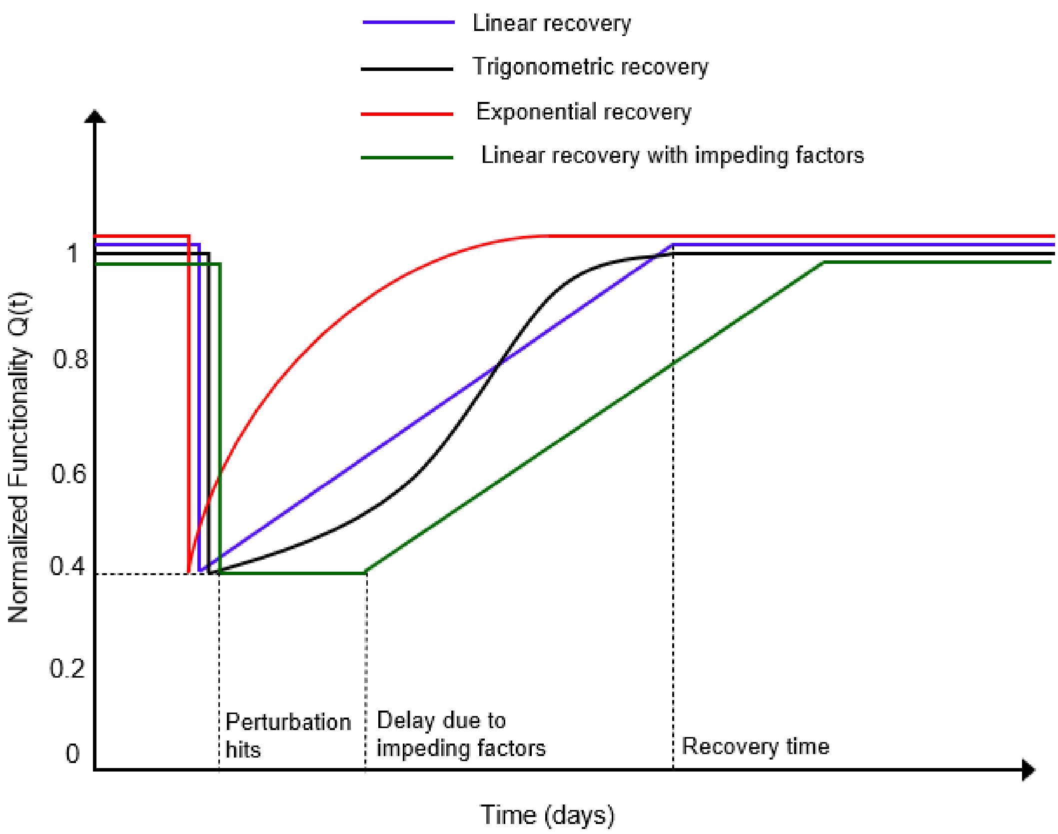

Figure 5.6. Shapes of functional recovery curves. Source: Adapted from [71] with an addition from [72].

5.6 Discussions and Conclusion

This study demonstrates that the resilience system interpretation framework, in terms of adaptation and adaptive systems, can apply to any system including building structure systems regardless of their domain association. Utilizing the conceptual power of modern control systems theory and defining the appropriate system state, output, and controls, as well as the incorporation of clear passive and active feedback mechanisms into the systems will systematically advance the application and measurement of a unified and universal resilience interpretation within the built environment sector. This study used a closed-loop system approach that brings both perturbations and changes under a synthesis configuration such as dynamic programming and optimization that are applicable to both simple one-dimensional or more complex multi-dimensional state-space systems. The state-space approach can accommodate the time-varying nature of both perturbations and change by developing time series and data-driven models in complex building infrastructure projects using project life-cycle approaches. This allows a more holistic evaluation of resilience in building structure projects, contrary to the current, short-sighted single-phased approaches that focus on certain perturbations.

Despite advances in data-driven modelling techniques and the availability of big data, the prevalent discrete nature and time lag of the relevant data and models pose a major challenge in construction projects; these partly depend on the limitation of information flow in real-time and full automation of the construction processes. Additionally, the literature on building structures that are adaptable to change is limited, often fragmented, and isolated from the resilience concept. One of the notable concerns argued within the literature related to the implementation of change management concepts, such as open buildings, transformable buildings, modularity, and adaptive regulations, is their financial feasibility. However, this is not sufficiently backed up due to the limitations in the relevant financial data and the added benefits provided by these concepts in terms of reduced ecological footprint and reduced life cycle costs [49]. Moreover, adaptation to change contributes to a sustainable built environment [73] and circular economy [74]. The main barriers to achieving resilience in the built environment, particularly building structures, through design and the incorporation of foundational active feedback structures within the respective systems for handling change, are convincing the stakeholders of the long-term advantages. There is a lack of leadership, which yet again calls for a holistic and systematic approach to the definition of resilience, design, and valuations in the built environment.

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CHAPTER 6. SUMMARY AND CONCLUSIONS

6.1 Overview

Resilience has increasingly become a crucial topic for the functioning of various real-world systems as our planet undergoes a rising trend of uncertainty and change due to natural, human and technological causes. Despite its ubiquitous use, the term resilience is poorly and often inconsistently used across various disciplines, hindering its universal understanding and application. This thesis presents a resilience system interpretation framework, which defines resilience irrespective of its disciplinary association, in the form of adaptation and adaptive systems and applies it to various dynamic systems.

This thesis achieves the research aim - contributing to the advancement of the literature by giving resilience a system interpretation. This not only maintains the resilience conceptual integrity as initially introduced in the Holling's [1] seminal work "Resilience and Stability of Ecological Systems" but also addresses impeding factors, such as abuse of the terminology and bending the relevant concepts to serve discipline-specific purposes, which has significantly weakened the resilience conceptual foundation over the years. The thesis also addresses the tension among researchers over whether resilience is an inherent system characteristic or a management process. Through the resilience system interpretation framework, resilience can be obtained through both passive and active feedback mechanisms in the form of adaptation and adaptive systems. Chapter 3 presents a critical analysis of the stability concepts by first collating the wealth of modern stability concept literature within dynamics systems and then linking it to resilience thinking, in the form of adaptation. A lumped mass and simple pendulum systems, two simple linear and nonlinear dynamic systems following a state-space approach from modern control systems theory, are used to support the analysis and applications. Chapters 4 and 5 apply the resilience system interpretation framework to traffic flow and building structure systems, respectively. The thesis demonstrates that, by using the conceptual and practical power of the modern control systems theory framework, 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. This allows the system state or system form to return to a starting position or transition to another suitable state or form. Both the engineering and extended-ecological resilience measures are simulated on various simple and complex engineering systems.

6.2 Findings

This thesis proposes a cross-disciplinary resilience system interpretation framework, which is applicable to the real-world systems for resilience analysis, measurement, and design purposes. The thesis first discusses the conceptual evolution of resilience since its emergence as an ecological concept in 1973 across various domains and clarifies the notion of resilience in that: (i) Much of the literature about resilience covers existing ground where the existing engineering systems stability ideas are being reinvented. The two overarching categories of engineering resilience and socio-ecological resilience (extended ecological resilience) are in fact a reinvention of a closed-loop system dynamic stability with different types of active feedback mechanisms. Additionally, structural stability describes some vital aspects of social–ecological resilience such as critical thresholds where, under change, a system loses the ability to return to its starting form or to move to another suitable form through active feedback mechanisms or direct management actions. (ii) Using the control systems theory approach, where each system, irrespective of its disciplinary association, is represented in terms of inputs, state, and outputs, it was shown that resilience can be thought of in terms of adaptive systems and adaptation. (iii) The resilience system interpretation framework 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. (iv) This systematic and cross-disciplinary interpretation of resilience presents the potential for a greater understanding of resilience and eliminates the overlap in the literature, particularly related to terminology.

In addition, using a state-space approach, the resilience system interpretation framework, with its two main components of the system's ability to return to its initial state and form through passive and active feedback mechanisms, was quantitively applied to 4 case examples. The thesis demonstrated that (i) The framework can be equally and universally applied to various engineering disciplines and, by extension, to any other disciplines described in system terms. The framework was applied to two simple mechanical systems, the lumped mass, and simple pendulum which are two-dimensional linear and nonlinear dynamic systems (Chapter 3) as well as to traffic flow (Chapter 4) and building structure (Chapter 5) dynamic systems. (ii) The trade-offs between incorporating passive and active feedback structures into a system require a comprehensive knowledge of the relevant system, the perturbations, and the change process surrounding the system throughout its lifecycle. For instance, for simple engineering systems (Chapter 3) with known perturbations and a limited range of change, the passive and active feedback mechanisms are of a constant and robust nature. For more complex systems (Chapters 4 and 5) with unknown perturbations and a wide range of change, the focus shifts from passive feedback to active feedback with an adaptive nature. (iii) For the case examples considered, it was shown – irrespective of the system disciplinary association, designing the passive and active feedback mechanism upfront or designing the necessary foundation for its future implementation, is critical to system resilience in the face of fast-changing requirements. (iv) As indicated in Chapter 5, contrary to the common attitude that designing passive and active feedback mechanisms within the system are not financially viable, they do in fact reduce the system's ecological footprint and life cycle costs, subsequently enhancing sustainability.

Lastly, the thesis demonstrated that the resilience system interpretation framework has the potential to bring much of the verbal modelling under a unified, holistic, and systematic foundation. Concepts such as resilience, adaptability, and flexibility generally overlap and lack precise conceptual foundations and a quantitative base. The resilience interpretation framework paves the way for resilience operationalization and integration into relevant standards.

6.3 Limitations

This thesis has successfully applied the resilience system interpretation framework to four case examples and has accordingly demonstrated the system state and form return abilities both quantitatively and qualitatively. A number of assumptions were made throughout this thesis and some of the limitations include:

(i) The case examples studied are low-dimensional (two and three state variables) dynamics systems; however, the state-space approach similarly accommodates and treats high-dimensional dynamics systems as well. Some researchers have expressed concerns about the applicability of control systems concepts beyond simple dynamic systems. However, with the recent advances in big data and computational techniques, tools such as dynamic mode decomposition possesses the ability to convert high-dimensional state vectors into compact low-dimensional ones of dominant modes, which can closely imitate the original system behaviour. Additionally, with the increased complexity of real-world systems, it is almost impossible to capture every aspect of the actual system by any relevant model, where missing dynamics within the model can be compensated for by selecting the appropriate active adaptive feedback structure based on extremising a certain objective function.

(ii) Limitations in real-time continuous data collection is another constraint in most real-world complex systems, particularly the built environment and critical infrastructure. However, the system approach introduced in this thesis can also manually handle data collected at discreet time intervals. By using the relevant control systems tools, the time-lag between recording the data and applying the control actions can be compenetrated for.

(iii) A significant challenge in the implementation of the resilience system interpretation framework in real-world complex systems such as built-environment might be to create inclusive collaboration and leadership among stakeholders who acknowledge the inter-disciplinary, multi-disciplinary and cross-disciplinary nature of those systems and act holistically across the levels.

6.4 Future Research Directions

Future research can be conducted to address the research limitations and to extend the resilience system interpretation framework to other real-world complex systems beyond the engineering domain. Some of the potential directions include (i) The resilience system interpretation framework can be applied to systems in other domains such as social science, economics, and organizational theory. The terminology and framework introduced in Chapters 2 and 3 will not change but the system characteristics and the surrounding environment will. (ii) Studies could also be conducted to systemically determine objective functions that not only optimize meeting the system user’s needs but also the expectations of the regulating authorities. (iii) Further complex and multi-dimensional dynamic systems could be investigated through data-driven modelling and trade-offs between passive and active feedback architecture explored, particularly in physical infrastructure systems. (iv) Life-cycle cost analysis of incorporating change-handling architecture within infrastructure systems to provide concrete evidence-based justifications could be addressed to convince stakeholders of the financial viability of these practices. (v) Studies on the effect of multiple perturbations on the systems in the form of a perturbation vector acting through the system input port could also be conducted. Additionally, research on the descriptive and mostly verbal modelling of the resilience features presented in global policy documents such as the Sendai Framework for Disaster Risk Reduction, the Sustainable Development Goals (SDGs), and the UN Climate Change Conference (COP21) could be redefined using the resilience system interpretation framework.

6.5 Reference(s)

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