Resilience of Complex Adaptive Systems: A Pedagogical Framework for Engineering Education and Research

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The discourse on resilience, currently at the forefront of research and implementation in a wide variety of fields, is confusing because of its multi-disciplinary/spatial/temporal nature. Resilience analysis is a discipline that allows the assessment and enhancement of the coping and recovery behaviors of systems when subjected to short-lived high-impact external shocks leading to partial or complete failure. This paper, meant for pedagogical teaching and research formulation, starts by providing an overview of different aspects of resilience in general and then focuses on communities and regions that are complex adaptive systems (CAS) involving multiple engineered infrastructures providing essential services to local inhabitants and adapted to available natural resources and social requirements. Next, for objective analysis and assessment, it is proposed that resilience be characterized by four different quantifiable sub-attributes. This paper then describes the standard techno-centric manner in which different temporal phases during and in the aftermath of disasters are generally visualized and analyzed, and discusses how these relate to reliability and risk analyses. Subsequently, two prevalent types of frameworks are described and representative literature reviewed: (i) those that aim at improving general resilience via soft methods such as subjective means (interviews, narratives) and census data, and (ii) those that are meant to enhance specific resilience under certain threat scenarios using hard/objective methods such as data-driven analysis and performance-predictive modeling methods, akin to resource allocation problems in operations research. Finally, the need for research into an integrated framework is urged; one that could potentially combine the strengths of both approaches. [DOI: 10.1115/1.4046853]

Keywords: resilience, resilience attributes, resilience assessment, pedagogy of technological resilience

1 Introduction

1.1 Sustainability and Its Umbrella Attributes. A previous paper [1] proposed a pedagogical framework for "sustainability and sustainable development (SD)" pertinent to engineering education and research. It suggested categorization of application areas ranging from individual products to wicked infrastructure systems (IS) as the first level of separation and identified those which would qualify as complex adaptive systems (CAS) albeit with varying degrees of complexity. CAS were defined as IS combining natural, social, and engineered systems that provide commodities and services to a large societal base such as communities, cities, and regions. CAS are an integrated class of systems characterized by a high degree of engineered technological complexity, adapted to local ecological conditions, social needs, and governance constraints, thereby translating into hard-to-detect, wicked, and nonlinear adaptive interdependencies [2]. It was also pointed out that sustainability and resilience are multi-dimensional constructs that, for objective analysis, assessment, and capacity enhancement, require delineation of their attributes (similar to the various traits that go to make up an individual's personality): a notion consistent with several publications, for example, review papers by NIST [3] or Johansen et al. [4]. Table 1 assembles the three main umbrella categories proposed to characterize sustainability attributes.

Note that while the first two categories relate to the status of the existing system (or over the short-term time horizon), the longevity capability (which involves a constant assessment over time of both the resilience status of the system and of its adaptation to new or modified environmental threats and societal/political changes) would apply to the medium- and long-term temporal time scales of SD (i.e., years to decades). Based on a literature review relevant to CAS, Reddy and Allenby [1] proposed various sub-attributes for each of these umbrella categories with the intent that one could then quantify them in terms of metrics. An overview of the literature along with illustrative examples was provided followed by a discussion of the difficulties of assigning operational indicators to these sub-attributes, and then of selecting individual weights for them (reflective of the views of different stakeholders) so that an aggregate metric can be deduced. The previous paper was meant to provide the technocentric pedagogical foundational framework for better comprehension of the existing body of work on sustainability and SD to both the student and the future professional. This paper has a similar objective but focuses specifically on issues related to resilience of CAS.

1.2 Objectives. This paper focuses primarily on resilience aspects of engineered IS and CAS. A discussion of different aspects, nuances, and definitions of resilience from different disciplines is first provided followed by a working definition of resilience relevant to CAS. An argument is made that for objective analysis, resilience be characterized, and studied through the behavior of four quantitative sub-attributes related to the robustness, collapse, recovery, and adaptive phases. Next, a classification is

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Table 1 Description of the umbrella categories of sustainability attributes relevant to complex adaptive systems (from Ref. [1])

Categories	Description
Functional	Continuation of operation while meeting accepted standards of resource-use, efficiency, cost, environmental impact, safety, and reliability under *normal* or as-designed operation of the system
Resilience	Coping and recovery traits of a system when subjected to short-lived *extreme* external shocks often leading to partial or complete failure
Longevity	Survivability involving (i) continuous assessment of both functionality state and status of resilience capacity, and (ii) ability of system to adapt to *incipient* natural changes (such as climate change), to gradual shifts in policy and governance due to changes in pressures/attitudes, and to socioeconomic and cultural changes/evolution

suggested of the different types of extreme events affecting CAS, and the standard technocentric view of the different phases and their analysis during extreme events is described. How allied frameworks such as reliability and risk analysis differ/overlap with the resilience analysis is also discussed. A literature review of the two widely adopted analysis frameworks, namely the soft or structural-based (better suited for general resilience assessment) and the hard or performance-based (better suited for specific resilience analysis involving predictive modeling), and the need for research into an integrated framework which combines the strengths of both is articulated. This type of streamlined and structured layout of the broad field of resilience focusing on CAS will be of pedagogic value to engineering students and the professionals new to this field.

2 Resilience: Literature Review, Discussion, and Definition

2.1 Background to Resilience as a Concept. The multi-disciplinary-temporal-spatial nature of resilience along with its different attributes[1] has tended to obfuscate the whole dialogue of resilience. The concept of resilience was first introduced about 200 hundred years back in physics and material science as the ability of an object to resist loads without permanent distortion. Strictly speaking, "resilience" is derived from the Latin word *resilio* meaning to bounce back (analogous to a compressed spring). This implies that the system has already been compromised in terms of meeting its desired functionality; and so, resilience, thus viewed, ought to be limited to post-event recovery issues. However, its scope has been broadened to include the ability to absorb, entirely or partially, the external shock and maintain normal system functionality as much as possible, as well as the ability of the system to recover quickly once the disturbance has passed. Several publications have assembled exhaustive lists of definitions related to resilience (e.g., Refs. [5–8]), but such lists often confuse rather than clarifying.

2.2 Application Areas. There are several broad disciplines to which the concept of resilience has been applied. Table 2 assembles such a list gleaned from various authors (e.g., Refs. [5,6,9–13]) intentionally framed so that the combined list would apply to CAS[2].

2.3 Discussion and Definition. The ecological literature tends to consider resilience in terms of type and magnitude of disturbances which the system can tolerate (i.e., identifying thresholds or tipping points) and, should the system fail, identifying the internal readjustments as the system moves to a different operating regime [14]. Resilience has been framed as an *inherent dynamic emergent system property* or survival characteristic independent of external drivers. This approach has also been modified to apply to biological and certain types of isolated engineered systems such as satellites [15]. Under such instances, one would tend to agree with this view, namely that resilience is a system attribute and should be separate from the magnitude and type of the external event. This is akin to the concept of "time constant" of dynamic linear systems which relates to the recovery period and is independent of the type and magnitude of the disturbance (another analogy is the "strong constitution" of individuals who are less prone to catch a cold or fall sick and who recover quickly should they do so). However, it can be argued that CAS does not fall into this category, and one ought to look at the traditional engineering literature as well.

A definition which is appealing to engineers is: "Resilience is the ability of the system to withstand a major disruption within acceptable degradation parameters and to recover within an acceptable time and composite costs and risks" [16]. In this context, it cannot be a single measure but is a multi-dimensional time-variant vector describing the state of the physical, natural, and social systems defined/measured only in the context of the specific threat and subsequent recovery process (if one can, or decides to, marshal more resources, the recovery time will be shorter).

Table 2 Description of the resilience concept as applicable to different disciplines and systems

Discipline	Description
Ecological	Determined by local biophysical empirical parameters relevant to resilience and inclusive of both pre- and post-disaster periods; examples are location (terrain, nearness to ocean, accessibility, etc.), weather (hot/cold, dry/wet, etc.), surrounding natural resources (rivers, lakes, soil condition, etc.), etc.
Social	Based on empirical data that impact in-place community/regional vulnerability of the population (such as age, health, and psychological state) and the extent to which individuals of the community support each other. This sector is meant to characterize inherent resilience capacity from social inter-connectivity, i.e., the ability of the social entities and organizations within the community to self-organize and alleviate hardship (to some extent) without external assistance, in conjunction with the ability to assist affected local population and federal/state first responders
Economic	Characterized by the local vitality, i.e., parameters such as levels of housing, income, equity, employment. This sector would capture the extent to which the individuals in the community would be willing to spend money to recover from the disaster and also to implement additional capacity such as in-place engineered system functionalities
Engineered	Reflects the status and performance data of in-place engineered infrastructure systems able to meet basic human needs such as food, water, and energy for a few days post-disaster (such as having household water reservoirs, standby refrigerated food storage, local diesel-electric gen-sets, solar photovoltaic systems, and batteries), as well as the robustness or ability of the physical systems (buildings, roads, telecommunication, etc.) to withstand extreme events
Institutional or organizational	Relates to the level of preparedness at the regional or centralized governance level which involve issues such as hierarchy in decision-making, emergency response and recovery plans, resources that can be marshaled quickly, etc.

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[1] It compounded with misuse/laxity of terms and the trend to coin new terminology (prevalent in emerging fields to capture nuances disassociated with words already in use from conventional meaning and/or to draw attention to one for having done so!).

[2] There is of course some degree of overlap between these categories.

Thus, resilience ought to identify/quantify the succession of stages and associated time duration and penalties (dependent on both the recovery speed and the magnitude of loss) during both failure and post-disaster recovery stages. Such problems have been widely studied in operations research engineering under "resource allocation problems" with physical, logistic, and economic constraints; but how to include the additional "soft" (and often subjective) elements related to social, ecological, and political/governance aspects or sectors is ambiguous.

Resilience can also be tackled as a *design* trait or as an *operational* attribute. People often sacrifice resilience for productivity and value (since they are unwilling to spend extra resources for stranded assets that are rarely used, if at all). Resilience-enhancing measures are often (reluctantly) installed, either to meet code and regulations (such as fire sprinklers or emergency standby generators in hospitals), or for insurance needs, or to voluntarily satisfy public or government sentiment/demands. Currently, there has been (and is) a lot of ongoing research in CAS to operationalize these concepts: (i) translate them into pragmatic standards of best practice, codes, or regulations for capacity-building under design phase and (ii) develop optimal decision-making methodologies under actual operation. This research has been distilled to some extent in textbooks (e.g., Refs. [7,17]), but a proper holistic synthesis of all domains is still lacking even though progress is being made in this regard [8].

2.4 Resilience and Its Sub-Attributes. Resilience is best defined as the coping and recovery behaviors under short-lived extreme shocks/disasters (man-made or environmental) on the system, and the ability to learn/adapt from past mistakes. Four sub-attributes are proposed to operationalize the concept of resilience, i.e., one that can lead to actionable and effective remedial measures (see Table 3). The first two traits relate to the resistance and coping behaviors, the next one to the recovery aspect, and the fourth attribute to the learning and adaptability trait. The restorative attribute also includes the agility trait or short response delay of emergency responders to get to the site(s), and the recovery capability involving necessary prior preparation (response plans, spare parts, robust physical IS such as roads and communications) for repair crew to complete the necessary repairs quickly. Further, "adaptivity" also relates to the cognitive trait of individuals or households or communities which leads to *shallow* changes/interventions or remedial actions which can be implemented over shorter time frames (weeks or months). This is in contrast to *broad/deep* modifications or *capacity-building* done over years/decades, which would fall under the "longevity" umbrella category. The above sub-attributes, though different in terminology, align well with those proposed by Woods [13]: rebound (akin to "restorative or recovery"), robustness (similar to "absorptivity"), graceful extensibility (akin to "restructurability"), and sustained adaptability (similar to "adaptivity").

Table 3 Description of the sub-attributes of resilience of CAS

Sub-Attributes	Description
Absorptivity or *robustness* (opposite of vulnerability)	Ability to withstand external shocks and to continue delivering the needed functional services without interruption
Restructurability (accommodating alternative paths)	Ability of a system to be flexible under partial failure such that it can restructure itself in order to meet as much system functionality as possible
Restorative (recovery or rebounding)	Ability to be returned to the original state of function after partial or total failure within acceptable time periods and penalties (monetary, human hardship, etc.) during post-disaster recovery
Adaptivity (remedial or shallow interventions)	Ability to learn from adversity experienced from past undesirable events and to make necessary modifications in order to accommodate or withstand similar future events by implementing remedial system changes and policy measures immediately (weeks or months) after recovery

Different disciplines assess these attributes differently; for example, socio-ecological studies tend to do so subjectively via surveys and interviews and/or objectively via census-based data, while techno-economic studies tend to use objective performance-based mathematical modeling methods (as discussed in Sec. 4).

3 Operationalizing Resilience Analysis

3.1 Different Types of Extreme Events. Extreme events are those external events or forcing functions that lead to system failures, partial or complete. The various types of system failures can be grouped as follows so as to provide the necessary context to distinguish between different analysis methods and their relevance to the sub-attributes of resilience.

(a) *Momentary failure* of the system resulting primarily in loss of functionality with very little (or no) ecological/structural loss or human morbidity. An equipment and/or system failed during normal operation due to *some random cause* such as a mechanical failure of an engineered component. The external and operating conditions were within the normal range of operation for which the system was designed. The penalty for this failure is essentially either an increased cost of operation (since the system is now operated in a non-optimal manner) or the economic penalty of lost functionality. The recovery path is not explicitly analyzed. This case falls largely under traditional *reliability analysis* and should be considered under the *functional* umbrella and not under the *resilience* umbrella.

(b) *Routine emergencies* due to periodic and anticipated shocks resulting in system failure, with relatively limited physical/ecological/monetary damage and human morbidity/mortality. Magnitude of shocks and resulting damage/penalties are within expectations, and the threat of irreversible breakdown is small. The probabilities of the different hazards and their expected damage are ascertained from similar incidents over past years (or from limited technological analysis of the impact and recovery stages), and emergency services have standard technological and management responses in place. The social component is often but cursorily considered. Changes to system and response plans can be modified from events that have occurred; hence, some amount of adaptation is inherent. A well-known example is the seismic approach under minor tremors as applied to IS and engineered systems. This case generally falls under traditional risk analysis.

(c) *Disasters* with severe loss of functionality involving several engineering and social/governance systems along with major physical/ecological/economic damage are accompanied by considerable human hardship and mortality. There may be irreversible loss in system functionality, and this would require major alternative/additional system design alterations and additional operational measures to be put in place to provide the same services. Such situations are clearly wicked ones since inherent non-technological issues/constraints are involved such as social, governance, and financial elements. Further, one can distinguish two sub-cases:

  (1) Known disturbances or shocks whose occurrence was expected but the *warning period* or *magnitude or duration* were unanticipated (examples: hurricanes Katrina in 2005 and Sandy in 2012);

  (2) The magnitude of the disturbance was not the primary cause of complete system failure and disaster but was

mainly due to the inherent vulnerable state of the technological and built IS, as well as the frailty of the social and governance institutions along with poor response during the aftermath (e.g., hurricane Maria in Puerto Rico in 2017). This is where the concept of inherent resilience as a system attribute independent of external forcing events would be useful to assess preexisting vulnerability.

Both the sub-cases apply to CAS, and since the objective function and constraints used to model and optimize the recovery process would include hard-to-quantify techno-social-economic considerations, semi-quantitative analysis is currently the only realistic option available. Here, restrictions on resources available for recovery and inherent time delays in the supply chains are important issues. Such events must be addressed largely on an individual basis, but certain generic and precautionary design and operational practices learnt from past disasters may be adopted. One may not be able to avoid failure (partial or complete) but it would be more realistic to accept failure which is graceful or gradual, and adopt in-place technological precautions, practices, policies, emergency plans, and set aside funds for such emergencies, in order to rebound or recover promptly.

(d) *Black swan events* or catastrophic events that are totally unforeseen or are very low probability events with huge adverse impacts resulting in a paradigm change in thinking. None of the standard analysis tools are satisfactory in such cases. Adopting precautionary measures from Mother Nature is touted as the soundest strategy (see Table 4). However, Mother Nature has the luxury of trial and error over millennia with mass extinctions being tolerated in the process of finding a workable design/solution. Such a strategy is inadmissible for humankind even when faced with rapid socioeconomic-environmental changes and the inability to identify all that one "needs to precaution against." As an example, the Internet is a scale-free network, and so is highly resilient to unanticipated failure of individual components while being highly susceptible to a planned attack. After the 9/11 event, the telephone network went down, but the Internet kept working, because it is a scale-free network. The ongoing COVID-19 pandemic is another example of a black swan event which will result in over hundred thousand fatalities, severe hardship to millions of people, severely strain/break and invariably alter the functioning of our current civil and political institutions, and greatly impact our way of life (financial markets, health-care system, travel and social interactions, government policies, global trade, etc.). In broad terms, some of the generic strategies would have alleviated the impact of the pandemic but which specific measures to implement and how would vary widely by country and region, and be subject to great debate and political controversy.

Table 4 Generic strategies adopted by nature- suitable for Black Swan events [18]

Strategy	Description
Include redundancies	Two types: (i) *Defensive redundancy*—Humans have two eyes which is very different from naïve optimization (which is susceptible to break down under unexpected perturbations or events) (ii) *Functional redundancy*-Similar functions and services can be done/provided by different sub-systems of the CAS
Avoid systems growing too large	Notion of economies of scale becoming more efficient also leads to vulnerabilities to outside contingencies
Avoid too much connectivity or globalization	Excessive connectivity tends to push the systems (biological, cultural, economic, and engineered) to an extreme state while globalization requires balancing economic versus political and national security concerns

3.2 Different Temporal Phases During a Disaster Event.

The traditional technological view of operationalizing resilience is to quantify it as the *penalty cost of failure* due to an extreme event or disaster (as adopted in the *seismic risk literature*). If no health or psychological impacts are involved, the consequences will be primarily due to the financial penalty associated with loss of functionality during the breakdown, and the cost of repairing the physical damage incurred on the system. If health impacts are considered (as one must during disasters), the associated adverse human-related psychological and physical consequences on the affected population must be included as well—which is much harder to do. Whatever is the cause of system failure, the various phases which a system undergoes can be conceptualized as shown in Fig. 1. This figure is widely adopted by numerous engineering researchers, for example, Ouyang et al. [19] and Vugrin et al. [20].

(i) Disruption period: First, there is the basic situation in which the system is robust enough that even when exposed to external shocks and a few component failures, the system is able to meet its full functionality; this reflects its *absorptive/robustness* capacity (shown explicitly in the figure as point A0). Once the disruption exceeds a threshold, the system may lose much, maybe not all, of its functionality thanks to its *restructurable* attribute. The disruption may be abrupt as shown by A0-A1′(hard failure) or gradual as shown by line A0-A1 (graceful failure). Thus, part of the system functionality is still met depending on the restructurability of the system (as shown in Fig. 1). If the system is fully compromised (total failure), the end point would be A1″. Note that a interval shown as A1-B is meant to reflect the time for the hazard to pass (such as when a cyclone is raging during which nothing can be done). The total penalty would involve the economic, health, and social burden/hardship associated with the financial cost of undelivered services.

(ii) Recovery period: This relates to the "restorative" sub-attribute and characterizes the duration and cost due to the system being compromised. The optimal recovery pathway (shown as B-D*) is one where there is no "delay" period; i.e., recovery is initiated immediately with little bottlenecks in supply chains, manpower or needed monetary resource. The system is gradually remedied until

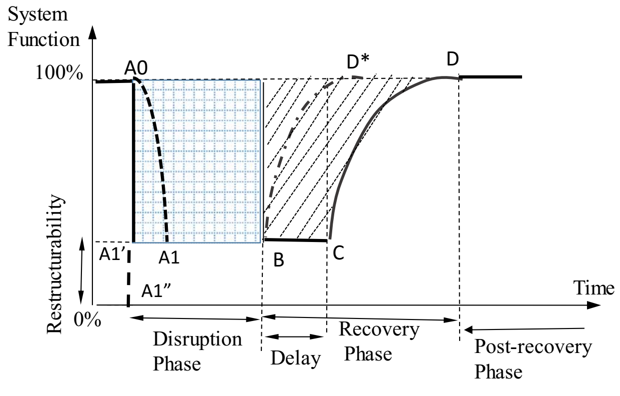

Fig. 1 The technocentric view of various temporal phases during a disaster event affecting the functionality of delivered services of engineered physical IS

it is able to again meet the needed functionality. Note that the recovery may experience a delay period that would be due to the time needed for local emergency services to marshal basic resources or to wait for emergency repair and relief personnel to reach the site. Both loss of productivity and human-related impacts have to be considered. The more *agile* the system, the shorter the delay period (shown as B-C in Fig. 1.)

The shaded area which includes both delay and recovery periods is then indicative of the total penalty cost due to reduced system functionality. Smaller areas would denote higher resilience in terms of this sub-attribute. Restrictions on resources and IS capabilities would result in a recovery pathway shown in a generic manner as paths B-C-D.[3] This pathway could be determined purely by heuristics based on prior knowledge, or from Delphi-like[4] expert opinion/judgment solicitation, or framed as a constrained optimization problem (or more realistically, as a satisficing problem). The issue is that some sort of realistic objective function has to be framed along with well-defined constraints in order to adopt an optimization approach. Under complete failure, one needs to consider not just functionality loss and damage to physical IS, but "social hardship" experienced by the affected population as well. Thus, some indicator(s) of "quality of life" [21] is to be posited and its degradation expressed in a quantitative manner (which remains elusive). The *restorable attribute* is met if the system fully recovers to its original state of functionality within an acceptable time period.

(iii) Post-recovery period: This period is meant to represent the adaptive attribute that applies to the somewhat open-ended period immediately after full system restoration. Here, obvious lessons learned from the disaster are translated into immediate specific actionable measures in terms of both physical systems and social/governance institutions and practices which enhance the other sub-attributes. One may even wish to make changes to what was previously considered as the desirable initial operational state of functioning. This phase would involve weeks/months and should be viewed as distinct from the capacity-building phase which falls under the "longevity" umbrella term.

3.3 Comparison With Allied Analysis Methods. There is some amount of overlap between three related analysis methods: reliability analysis, risk analysis, and resilience analysis. Reliability analysis is a traditional well-developed methodology to determine whether the probability of system or components not meeting functionality due to random perturbations and failures is less than a pre-stipulated value, lacking which necessary changes in system design and in component selection are needed. This analysis (and resulting decision-making process) is done primarily during system design, and periodically whenever major system retrofits are envisioned. Traditionally, reliability does not include the consequences of failure, i.e., inability to meet intended services or the resulting social burden impacts. Hence, reliability analysis cannot be used in the context of public policies, health and socioeconomics [22]. These limitations are overcome by risk analysis that is a more formal and comprehensive treatment. Mitigation of risk involving three rather distinct aspects (see, e.g., Ref. [23]):

(a) Risk assessment involves hazard identification, consideration of probability of occurrence of different hazards, evaluating the consequences (monetary, human life, etc.) of different hazards, and thence determines the aggregate potential loss. This can be done by qualitative or tacit knowledge, or by empirical models using simple risk formulation, or by quantitative methods based on mathematical or statistical methods.

(b) Risk management is the process of controlling risks, weighing alternatives, and selecting the most appropriate action based on engineering, economic, legal, or political issues. It deals with minimizing specific identified risks through remedial planning and implementation (including technological innovations and increased personnel training).

(c) Risk communication can be done on both a long-term or a short-term basis and involves informing the concerned stakeholders as to the results of the two previous aspects.

It is clear that several of the activities falling under the purview of risk analysis also apply to resilience analysis. Risk analysis can be viewed as more comprehensive in its inclusion of all threats and their occurrence probabilities in order to determine an aggregate monetary techno-economic impact.[5] On the other hand, resilience analysis is one which is usually scenario-specific and has to explicitly include, in addition, the recovery phase which considers enviro-social consequences on the affected population immediately post-disaster (i.e., during the "restorative" process). In that sense, risk analysis can be considered to be a technocentric holistic (in that all threats and their probability of occurrence are considered) version of resilience analysis and is more focused on preventing/minimizing undesirable outcomes of large critical engineered systems at a larger spatial level. Many researchers question the practicality of approaching the resilience issue using traditional risk analysis methods, arguing that anticipating outcomes is relatively easy from a theoretical standpoint, but that its practical implementation is more elusive [14]. Further, the issue of recoverability has assumed a critical dimension in view of frequent (and highly publicized) disasters and their monetary, societal, and human consequences. In that sense, the resilience analysis approach can be considered to be better aligned with current societal concerns and wicked complexities inherent to CAS than are traditional risk assessment methods.

4 Resilience Modeling, Metrics, and Assessment Methods

4.1 Broad Lines of Research. Research into resilience has tended to be along two broad lines as shown in Fig. 2. The branch shown as *on-line real-time response* corresponds to the dynamic wherein real-time streaming feedback is provided to emergency responders so that they can forestall potential damage, prioritize, and best channel their relief/recovery/mitigation decisions prior to, during the disaster event, and during its immediate aftermath. This type of feedback requires a number of capabilities to be already in place: (a) numerous types of monitoring stations spread out over the spatial domain, (b) robust and high-speed transmission of data to a central location, (c) high-speed computational models using this streaming data to predict a finite number of hurricane pathways (stochastic), called advisory forecasts, (d) outage models to predict the resulting damage to physical IS (engineered and natural), (e) fast algorithms to suggest different (stochastic) options for pre-positioning of repair crew and for evaluating restoration sequences, and (f) real-time algorithms that allow dynamic sequential updating/modification of prior decisions as the hurricane event unfolds. This application area is the purview of a lot of ongoing research (e.g., Refs. [26,27]), with some researchers viewing "the state of anticipatory preperedness" as an additional basic sub-attribute of resilience. This aspect is outside the scope of this paper, and so this attribute is not included in Table 3.

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[3] Often, the recovery path is shown as a straight line for simplicity. The area under the curve is referred to as the "resilience triangle."

[4] Delphi process involves an anonymous survey using questionnaires with controlled feedback to allow iteration within a panel of experts and reach consensus opinion.

[5] Note that, for the sake of brevity, the discussion omits considerations specific to quantitative risk analysis methodologies meant for human health as in workplace environment and for outdoor exposure to chemicals and pathogens (see, e.g., Refs. [24,25]).

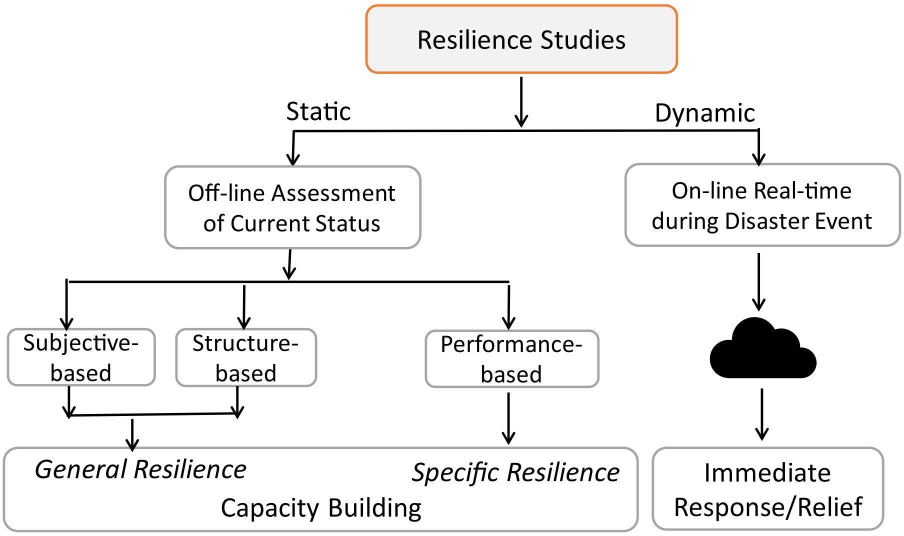

Fig. 2 Diagram showing the purview of the two different types of resilience studies: capacity-building and immediate response/relief

The real-time response path is thus meant to alleviate immediate suffering while the disaster is unfolding and during its immediate aftermath. On the other hand, the *off-line assessment* branch pertains to a more leisurely pursuit of evaluating existing weaknesses and for capacity-building during which the current resilience or disaster-preparedness of the CAS is assessed by:

(i) subjective means involving surveys, interviews, and narratives,
(ii) structural means based on census data of various sectors, or
(iii) performance-based predictive methods.

Tacit knowledge, best captured by surveys, interviews, and narratives, tends to be more holistic, and would consist of a much larger database of knowledge and information than numerical databases that are the basis of performance-based methods. The subjective and structure-based approach under the “off-line assessment” branch (Fig. 2) is meant to describe *general resilience*, i.e., the intrinsic characteristics of the system that contributes to system resilience without a specific threat and magnitude in mind. The activities under the performance-based branch are meant to enhance or build capacity toward specific types of threats, referred to as *specific resilience*.

4.2 Assessment Frameworks. Numerous publications have proposed community resilience assessment frameworks and metrics (for good overview and discussion of challenges, ongoing development, and different case studies, see Refs. [3,4]. One could group them under two broad categories (Fig. 3):

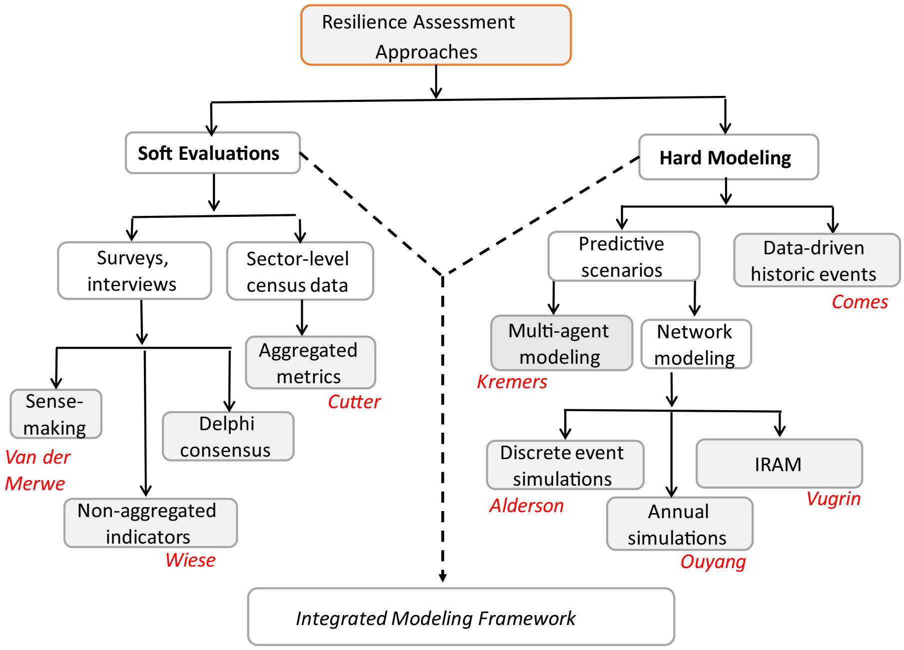

Fig. 3 The two resilience assessment frameworks with sub-classifications along with a representative publication citing primary author. The “Integrated Modeling Framework” box with dotted lines is meant to urge that more research combining the strengths of both frameworks be undertaken.

(a) Soft approaches provide insights into the make-up or structure or features and general characteristics of the system reflective of the general resilience status of the system. They tend to be qualitative/subjective or semi-quantitative; in that, system status is evaluated/scored using results of surveys and interviews or from publicly available census data categorized by pre-identified domains or sectors (such as the five sectors listed in Table 2). One could further distinguish between *non-aggregated* indices/variables and *aggregated* methods which combine various indices/variables from different sectors into a composite score/metric akin to sustainability assessments [1]. Another social approach meant to enhance resilience at the ground-level of the community, called the *sense-making approach* [28], is also included in this category. It does not resort to indices nor to traditional immersive interviews, but is based on interactive and participative sessions meant to explore the complexity of social dynamics (people's attitude, perceptions, and experiences) and to quantify general limitations within the social system. Actual needs of the community are identified by the social approach, but in the sense-making approach, this is done by "transferring the onus of interpretation of narratives from the researcher to the participants." The expert solicitation approach or the Delphi approach is suitable for central planning purposes (unlike the sense-making approach). This well-known Delphi method relies on group judgments of technical experts and administrators to find consensus on which measures are best implemented given technological and financial constraints.

(b) Hard modeling approaches or performance-based assessment methods evaluate system behavior based upon its dynamic functional response and tend to be viewed as objective (this is somewhat contentious since the inputs specified as well as the type and detail of modeling adopted differ among researchers). These approaches have largely been applied to engineered systems that tend to be better defined in terms of component, sub-system linkages, specification, functioning, constraints, and scope, but are narrower in applicability to resilience as a holistic concept. One of the sub-paths shown is the *data-driven* or empirical where historic data from past disasters are collected and analyzed for behavior patterns and weaknesses. The other sub-path is the *predictive* approach involving mathematical modeling and simulation of the system, so that its response can be studied quantitatively under a specific interruption scenario, along with the evaluation of sub-attributes such as robustness along with the assessment of different dynamic recovery pathways. This approach is considered by many to be the more precise and insightful, but it suffers from being narrow in technological complexity (*unable to bridge the gap between the problem modeled and the model of the problem* [29]), and inability to realistically treat the soft/qualitative attributes which defy quantification.

Reddy and Allenby [1] discussed the advantages and limitations of structure-based and performance-based methods in the context of sustainability evaluations; the discussion also applies to resilience assessments. It would be best if the two assessment frameworks could complement each other by providing specific insights into different types of attributes. While the structure-based assessment approach can suggest whether the necessary data needed for general resilience evaluation (features, characteristics, etc.) have been included or not, the performance-based predictive approaches are, in theory, able to determine the quantitative impact on the system performance based on attributes, such as the figure of merit. The pathway in Fig. 3 shown as "Integrated Modeling Framework" represents an approach which combines the strengths of the other two frameworks (Biringer et al. [7] refer to this as the "hybrid approach"). The different branches in the tree shown in Fig. 3 are discussed in Secs. 4.3–4.5. This is not meant to be a detailed literature review but, rather, to be illustrative of the diversity to be found in the literature and how these align/differ between themselves.

4.3 Examples of Soft Resilience Framework. Several studies have proposed and discussed social indicators and metrics for the resilience of communities, and how those metrics can be usefully implemented for enhancing resilience at city and/or community-wide levels [5,30]. The underlying theme of these studies is that because communities are composed of dynamic linkages between engineered, physical, and social networks along with the complexity that this engenders, understanding and maximizing resilience is more difficult than in other systems. Further, a clear methodology is lacking for how to better integrate social, economic, ecological, and technlogical trade-offs that support IS system resilience.

The detailed discussion by Vale and Campanella [31] makes it clear that cities are resilient because humans strive to make them so; good IS design and good planning are necessary, but not sufficient. Significantly, many of the human systems that confer urban resilience are not local to the disaster-struck city. So, where city resilience is important, the authors state that it is vital to see that the system scale is a hybrid; physical IS may be local, planning may be regional, but social and cultural systems scale to the entire society or culture. If the physical IS breaks, given time and resources, it will be rebuilt; but only if there is a societal or cultural mandate. In these cases, it is the rapidity and ease of the recovery process that could be enhanced. Thus, according to the authors, there is a need to emphasize hidden IS that confer urban resilience.

Several studies have defined social metrics for the resilience and sustainability of IS and have discussed how those metrics could be usefully implemented into the planning, design, and operation of IS systems. These indices/metrics and variables/parameters can be tacit/subjective or objective, usually gleaned through questionnaires and surveys or census/public data sources, respectively. Examples of a few studies relevant to community disasters and IS are given below (for more detailed overviews, refer to Ref. [3]).

Two typical examples of studies which fall under *non-aggregated structural-based assessment* category are: (i) Attoh-Okine et al. [32] who formulated a resilience index for urban infrastructure using belief functions accounting for interdependencies among systems, and (ii) Chang et al. [33] who developed a practical approach to evaluate IS resilience at a community scale based on historical experiences and judgments of technical specialists to identify which critical services could be lost, to what extent, and for how long. They have also investigated the ripple effect, i.e., into how disruption in one IS sector can have impacts on downstream sectors.

Linkov et al. [34] identified physical, information, cognitive, and social characteristics for a system's energy resilience which are then presented in a matrix format to help decision-makers focus on ways to increase the resilience. Wiese [35] extended the approach by presenting an inter-disciplinary framework which includes what he calls as "the seven principles of resilience thinking" to assess a particular energy system. These principles or functionalities can be identified from specific survey questions and the results used to develop three tables meant to support planning decisions to assess current energy system's state of resilience, identify pathways to reach the desired resilience level, and manage the development scenarios.

An example of an *aggregated method* relying on census or published data records is that by Cutter et al. [11,30] who introduced a framework called the disaster resilience of place (DROP) model at the community level, which allowed various counties in the United States to be ranked on a relative basis according to a set of 36 baseline characteristics/indicators of five sectors: social, economic, institutional, IS, and community capital. These ordinal/categorical indicators are normalized and simply summed without any weighting to yield a composite/aggregated score.

4.4 Examples of Hard Resilience Framework. Resilience assessment frameworks can be used as decision-making tools either during the design phase or during the retrofitting/development of the system. One can distinguish between different general performance-based predictive analysis/modeling methods (Fig. 3) as follows:

(a) Data-driven (or empirical) methods are based on collecting data from various streams (GIS, ground-based sensors, interval data from discrete manual measurements, and heuristic reports), during and in the immediate aftermath of a disaster, and analyzing the consequences on certain IS in order to glean broad system response behavior and deficiencies. Though this approach does not permit predictive modeling of system failure under future events, it does provide a realistic appraisal, albeit at a simplified aggregate level. An example study is that by Comes and van de Walle [36] who proposed a way to analyze observational data in order to determine the technological resilience of the power and subway systems of New York and New Jersey in the aftermath of hurricane Sandy in 2012. Another example is that by Moslehi and Reddy [37] who evaluated the costs of lost productivity and penalty of non-optimal operation of an integrated energy system (consisting of electric and gas utility supply, combined heat and power system, and large solar photovoltaic penetration levels). The analysis was based on hourly monitored sub-aggregated data for a complete year to which several failure scenarios, without any resulting physical damage, have been assumed along with the time in the year during which these events can occur. This type of analysis overlaps with reliability analysis and did not consider recovery pathways nor social impacts

(b) Network models are "simplified representations that reduce a system to an abstract structure capturing only the basics of connection patterns with vertices or nodes for components and edges capturing some basic relationship of the node and of the system" [38]. The focus is on the topology of the essential structural interconnections among components (and not just on individual components), and the behavior of the system under event-based disruptions of such interconnections. Network analysis has been applied to both social sciences [39,40] and also to engineered systems [40,41]. However, network modeling, though seemingly intuitive and appealing, has not been widely adopted by system engineers who tend (i) to focus on single-functionality well-specified systems, (ii) to develop models which include detailed system dynamics and related control algorithms, and (iii) to avoid long-term speculations of constraints on system functionality requirements and forcing functions. The network can be modeled using matrix algebra which can provide direct solutions in rather simple cases of single or even coupled IS (described by Refs. [40,42]), but generally a numerical system simulation approach is needed for any type of realistic system. It has been pointed out (say, by Ref. [43]) that the representation of an actual engineered system by a simplified surrogate network can be misleading if done simplistically. Hence, some sort of validation of the network topology, modeling equations, and simulation is needed before one can place confidence in the analysis results.

(c) Multi-agent system (MAS) is considered to be a more versatile and sophisticated approach to analyze the behavior of complex adaptive interconnected systems and is arguably more complex to model, simulate, and analyze (e.g., see Ref. [44] for power networks). MAS is based on assuming the system to be composed of several independent or discrete agents (or autonomous computational entities) with varying degrees of intelligence (captured by stipulating certain rules) which sense the environment and take decisions by interacting with each other and the environment. The view is that such systems have the ability to self-organize and create emergent behavior, similar to what happens when engineering and social/human behavior systems interact. Thus, the MAS approach has the potential to model the complex interactions of well-controlled engineered systems with ecological and economic processes and the somewhat irrational social/human/political behavior framed by certain rules. It could provide flexible scenario-based what-if analyses of the effectiveness of different strategies. However, MAS has two major limitations: it is difficult to realistically capture the *rules of engagement*, i.e., identify specific actions/reactions of the various individual agents of the system, and difficulty in calibrating the parameters of the models since the data are very often inadequate [45].

(d) Annual simulations approaches: Most modeling studies related to IS are akin to engineering reliability studies assuming certain threat scenarios but overlooking the social element and associated complexity (or, at best, including them cursorily). Ouyang et al. [19] developed a three-stage framework to assess and analyze IS resilience based on simulation results. Ouyang [46] improved on their earlier work and developed a trilevel decision-making model that supports critical IS resilience optimization in order to find the best defensive strategies by identifying vulnerable system components and protecting them against intentional and spatially localized attacks. They introduced the resilience metric based on the performance of the interdependent IS under natural hazards (such as hurricanes) and random failures relative to the target performance of the system. The analysis also involved modeling the probabilities of occurrence of discrete natural events and thereby estimating annual damage costs (as done during risk analysis). A similar framework was proposed by Prete et al. [47] to assess and quantify the sustainability and reliability of different power production scenarios in a regional electric grid with different levels of microgrid penetration under different policy measures. A diverse set of thermodynamic, economic, and reliability metrics were determined for various scenarios through detailed annual simulations, based on which a composite sustainability index was deduced. A sensitivity analysis was finally done on the indicators to assess whether social considerations could change the outcome of the technical analysis.

(e) Infrastructure resilience assessment methodology: Researchers (e.g., Refs. [20,43,48]) have developed resilience assessment models to quantify operational resilience of an IS under discrete events, and help developers and policy-makers identify critical vulnerabilities in the system and frame contingency plans. A book by Biringer et al. [7] describes this general approach called infrastructure resilience assessment methodology (IRAM). It is said to be an extension of Risk Analysis and Management for Critical Asset Protection (RAMCAP) originally developed for terrorist threats on critical IS systems [49]. IRAM is said to have the following features (which traditional methods usually tend to overlook): (i) provides a precise and actionable definition of resilience, (ii) explicitly considers costs and resource requirements of adaptation and recovery, (iii) proposes definitions and resulting measurement methods which are generally valid to all IS, (iv) proposes a performance-based assessment that is flexible and uses different methods and models to generate performance metrics, (v) minimizes subjective elements, and (vi) meant not only to assess resilience but also to design resilient systems.

(f) Other studies: Cimellaro et al. [50] proposed a framework for quantitatively evaluating resilience of health-care facilities subjected to earthquakes by using an analytical function that fits both technological and organizational issues. They also describe some studies reflective of the semi-performance-based predictive approach. Maliszewski and Perrings

[51] have investigated resilience of the power distribution systems, suggesting that the resilience of such systems depends on power distribution IS and its biophysical environment and also on the priority given to restoration by the power company. Francis and Bekera [6] also proposed a resilience analysis framework and a metric for measuring resilience of engineered and IS systems. They reiterate the unresolved issues pointed out earlier in this paper: (i) the idea of resilience as epistemological (how much is justified belief versus opinion) versus inherent property of system and (ii) design for ecological versus engineered resilience in socio-technological systems. Zobel and Khansa [52] proposed a new resilience measure for multiple related disaster events adopting the concept of disaster resilience triangle that characterizes system resilience based on the functionality loss and duration of the recovery time. The earlier performance-based studies are somewhat conceptual and present limited engineering analysis and results.

The National Infrastructure Advisory Council (NIAC) [53] has prepared a report meant to fortify government policy frameworks, improve government coordination, and clarify roles and responsibilities of various agencies involved in critical IS protection. It also suggests ways to encourage public-private partnerships and market incentives. The report also urges that extensive interviews be conducted, and soft data collection be done, and suggests ways that this information can be used to enhance traditional risk analysis methodologies.

4.5 Integrated Assessment Framework. Despite recent attempts (e.g., Ref. [8]), there is no coherent and well-accepted predictive modeling approach which allows to integrate socio-ecological considerations with technological-economic performance. In terms of the latter, the difficulty lies in framing both the objective function and constraints that properly capture the socio-ecological burdens (which are inherently normative and wicked). A hybrid socio-physical framework to quantitatively assess the disaster resilience of urban systems was proposed by Bozza et al. [21] who introduced the terms *efficiency* and *quality of life* as indicators to be identified before and after an extreme event, and also during the recovery period when limited resources have to be allocated on a priority basis. The study suggested that the network modeling approach be adopted to model engineering network behavior as one network, and the combined ecological, social, and governance behavior as another network, both of which can then be coupled to predict the combined behavior under different scenarios. This study though promising is very conceptual in nature, and no illustrative examples are provided. It is noteworthy that the RAMCAP method developed by ASME-ITI [49] is said to integrate both frameworks (Biringer et al. [7] refer to this as a hybrid method), but it is still primarily a technocentric risk analysis framework which does not extend to the human/social dimension nor to the recovery phase which is a critical component of resilience.

Another line of thought expressed in the literature, for example, Comes and van de Walle [36] and Ouyang [46], is that the social and technological elements are so fundamentally different that they cannot be combined in a single predictive modeling framework and that it is better to analyze the two elements separately. Comes and Walle illustrate a two-step process using hurricane Katrina as a case study, and based on heterogeneous data sources, which resulted in: (i) a quantitative data-driven resilience analysis (robustness, recovery aspects) of the power and subway systems in the states of New York and New Jersey; and (ii) a qualitative narrative description of how four ISs relevant to emergency and health care (note that the scope is broader than that of power and transportation systems) failed over time, along with their interdependencies and their social impacts. No clear connection between both approaches was made.

Figure 3 shows the two frameworks and their sub-branches along with the name of the primary author of a representative publication. Both approaches require location-specific extreme events to be identified, but the soft or structural-based approach requires generic events and their overall magnitude, while the hard or performance-based modeling approach requires more specificity. The additional pathway shown in Fig. 3 is meant to urge that research be undertaken to identify sectorial socio-ecological governance metrics/indicators that can be integrated with the techno-economic performance-based modeling and analysis methodology consistent with the constrained resource allocation problems studied by operations research engineers. As a simple example of a possible integrated modeling approach, consider the absorptive/restructurability disruption phase (see Fig. 1) which is akin to the risk assessment phase of evaluating the consequences of a hazard. One could: (i) assign ordinal fuzzy numbers to describe the social burden (psychological impact, health and hardship consequences on the affected population) and the resulting ecological damage, (ii) estimate the financial loss due to physical damage of IS and due to interrupted utility services, and (iii) adopt a specific multi-criterion weighting scheme which combines the two above terms so as to obtain a penalty function more representative of the total penalty incurred. How best to perform these steps while explicitly including the inherent wicked complexity of the different stakeholders (affected inhabitants, population at large, emergency services, public authorities, etc.) is a research question worth addressing (one possible approach is the Pareto methodology). A similar research gap also exists in modeling the recovery/response pathways that involves socio-ecological-institutional-economic considerations quite different from those during the disruption phase.

5 Summary

This paper started by presenting different aspects, nuances, and definitions of resilience from different disciplines following which a definition of resilience as applied to CAS systems and communities when subjected to disasters was suggested. A clear distinction between general and specific resilience was made, and it was pointed out that soft evaluation methods were better suited for the former, while the latter can be analyzed by hard analysis methods under selected threat scenarios. The standard technocentric view of the different phases experienced by CAS during extreme events was presented, and it was urged that for objective analysis, resilience be characterized and studied through the behavior of four quantitative sub-attributes related to the resistance, collapse, recovery, and adaptive phases. It is suggested that future studies clearly state which of these attributes is being specifically addressed rather than using the broad term of "resilience." The distinction and overlap between the terms reliability, risk analysis, and resilience analysis were also discussed. A literature review of the two widely adopted analysis frameworks, namely the soft or structural-based (better suited for general resilience assessment), and the hard or performance-based (better suited for specific resilience analysis involving predictive modeling), was followed by suggesting the need for research into an integrated framework which would allow combining the strengths of both. For example, tacit knowledge, best captured by surveys, interviews, and narratives, tends to be more holistic and contains a much larger database of knowledge and information than numerical databases that are the basis of performance-based analysis methods. This paper intended to provide a structured technocentric pedagogical framework of resilience-related concepts as relevant to engineered systems and CAS which would be useful for engineering education and future research.

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