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Conceptualizing resilience in engineering systems: An analysis of the literature

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Abstract

It is now widely recognized that many important events in the life cycle of complex engineering systems cannot be foreseen in advance. From its origin in ecological systems, operating without the use of foresight, resilience theory prescribes presuming ignorance about the future, and designing systems to manage unexpected events in whatever form they may take. However, much confusion remains as to what constitutes a resilient system and the implications for engineering systems. Taking steps toward a synthesis across a fragmented body of research, this paper analyses 251 definitions in the resilience literature, aiming to clarify key distinctions in the resilience concept. Asking resilience *of what*, *to what*, and *how*, we first distinguish systems serving higher ends and systems that are ends in themselves, and, within these, performance variables to be minimized, preserved, or maximized. Second, we distinguish systems subject to adverse events, adverse change, turbulence, favorable events, favorable change, and variation. Finally, we distinguish systems capable of recovery, absorption, improvement, graceful degradation, minimal deterioration, and survival. Together, these distinctions outline a morphology of resilient systems and suggest answers to the principal design questions, which must be asked of any resilient engineering system.

KEYWORDS
SEE01 Systems thinking, SEE10 Project Planning/Assessment/Control, SEE13 Risk and Opportunity Management

1 | INTRODUCTION

Across system types, areas of application, and technologies, there are now many indications that complex engineering systems suffer from unresolved challenges. Many, if not most, complex engineering systems experience instances of significant underperformance or failure sometime in their life cycle: During construction, cost and schedule are indicators of this: 77% of complex infrastructure projects experience cost-overruns,[1] while the construction industry reports that only one in four large construction projects finishes on time, while one in three finishes on budget.[2]

During deployment and operation, many engineering systems face a new set of challenges. An increasing number of large engineering systems fall short of social expectations and face increasingly organized public opposition.[3] Large infrastructure systems experience frequent disruptions,[4] and are increasingly vulnerable to attack.[5] Adding to these challenges, many engineering systems face technological obsolescence earlier than expected.[6] Oehmen et al.[7] concluded that infrastructure programmes tend to spend their time firefighting, fixing urgent problems, instead of proactively preventing them.

From an engineering systems perspective, a number of explanations for these challenges have been proposed. Engineering systems are becoming larger and more technically complex in and of themselves (e.g., Oehmen et al.[8]). At the same time, these systems are increasingly dependent on surrounding systems, producing unexpected interactions.[9] Following Oehmen et al.,[7] these systems have long life cycles, evolving requirements, and unrealistic baselines for cost, schedule, and performance. Cantarelli et al.[1] found that deliberate misinformation, often politically motivated, explains many instances of severe underperformance. de Bruijne and van Eeten[4] pointed out that

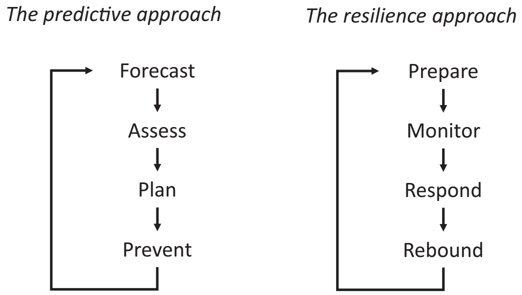

FIGURE 1 Two approaches to uncertainty, adapted from Kutsch et al[69]

large infrastructure systems are increasingly governed by fragmented organizations, not capable of responding effectively to incidents and change.

It is now widely recognized that many important events in the life cycle of a complex systems cannot be foreseen in advance.[10–16] This recognition has called attention to the ability of engineering systems to rebound from unexpected events, as opposed to predicting and preventing them, that is, to become more resilient.[17]

From studies of ecological systems, operating without the use of foresight, Holling[18] outlined a nonpredictive approach to systems design. He derived two core propositions from resilient natural systems to artificial systems: First, resilience rests on the "recognition of our ignorance; not the assumption that future events are expected, but that they will be unexpected." Second, "resilience […] does not require a precise capacity to predict the future, but only a qualitative capacity to devise systems that can absorb and accommodate future events in whatever unexpected form they may take." This shift can be summarized as in Figure 1.

Since the introduction of the concept, resilience thinking has attracted wide interest for its applications to man-made systems. Resilient properties have been studied across multiple disciplines, including supply chains,[19] disaster management,[20] and business models.[21] In engineering, the concept of resilience is relatively new compared to other domains,[22] where it was introduced by the safety engineering community.[23] Gaining wider application, efforts have been made to design resiliency into critical systems, for example, telecom,[24] defense systems,[25] cyber systems,[26] and energy systems.[27] Fricke and Schulz,[28] Jackson and Ferris,[29] Uday and Maralis,[30] and others have proposed generic design principles for designing resilience into engineering systems.

Perhaps because of its generic nature and wide adoption, much debate remains about what constitutes a resilient system, and how resilience is to be achieved.[31] Carpenter and Brock[32] described resilience as a "broad, multifaceted, and loosely organized cluster of concepts, each one related to some aspect of the interplay of transformation and persistence." Several authors have attempted to define and operationalize the resilience concept in various domains.[20,33–36] Woods,[36] for example, distinguished four major schools of the resilience literature "robustness," "rebound," "graceful extensibility," and "sustained adaptability." However, as Martin-Breen and Anderies[37] concluded, "there remains a considerable amount of work before resilience in systems will be a useful *off-the-shelf* concept for practitioners." The same seems true for the development of a precise taxonomy of resilience as a property in general systems theory.[38]

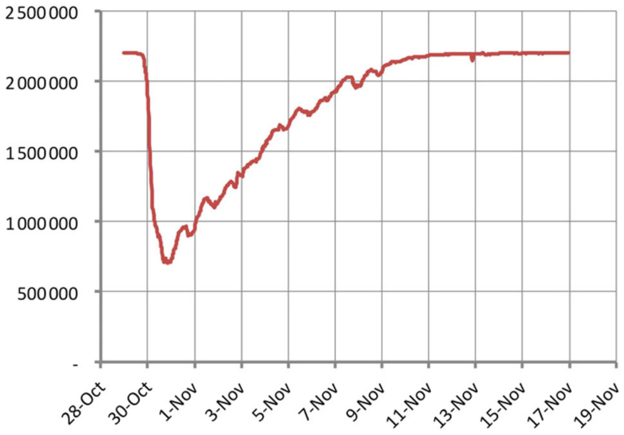

FIGURE 2 Customers with power in Hudson County, New Jersey, before, during, and after Hurricane Sandy[41]

Taking steps toward a synthesis across a fragmented body of research, this paper analyzes the literature, aiming to clarify key distinctions in the resilience concept, and to outline implications for engineering systems. To that end, this paper (a) outlines a framework for analyzing the resilience concept, (b) employs this framework analyze resilience literature across a range of disciplines and system types, and (c) outlines implications for engineering systems. Thus, the next section outlines a conceptual framework for analysis, while the third section details our methodology. The fourth section analyzes the resilience literature and identifies key distinctions of the concept. Finally, the fifth section concludes the paper.

2 | CONCEPTUALIZING RESILIENCE

This section develops a framework for analyzing the resilience concept. As our starting point, we combine Carpenter et al.'s[39] simple question; "resilience of what to what?" and Meerow and Stults's[40] distinction from their review of the literature between bounce-back and bounce-forward. This framework will guide our efforts in subsequent sections.

Operationalizing the resilience concept in the field of ecology, Carpenter et al.[39] parsimoniously distinguished between just two sets of variables when asking: "Resilience of what to what?" Using this distinction, Carpenter et al. (ibid.) investigated the resilience of one set of variables to variation in another, and proposed this as a model for measuring the resilience of ecological systems.

Generalizing from this model, any system performance variable can be assigned to the category "*Of what?*". These are variables indicating some aspect of the "value" of the system, compared to one or more performance thresholds. Drawing on Henry and Ramirez-Marquez,[41] Figure 2 gives an example of a system performance variable: The number of power outages in Hudson County, New Jersey, immediately before, during and after Hurricane Sandy in 2012. Figure 2 likewise implies a performance threshold, that is, the pre-hurricane number of power outages.

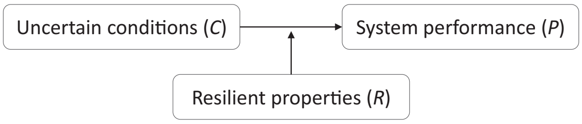

FIGURE 3 A conceptual model for understanding system resilience

To Carpenter et al.'s[39] second category, "*To what*?", any uncertain condition variable can be assigned. These are variables that influence the system's performance, and which may change unexpectedly over the lifetime of the system. In the example shown in Figure 2, uncertain conditions include the number, duration, footprint, and force of hurricanes over a given period of time.

Adding to this model, we propose a third category, "*How?*", referring to the resilient properties of the system. We define this category as the set of variables mediating between uncertain conditions and system performance. In Figure 2, resilient system properties might include the speed and cost of restoring power, or, taking a broader view of the system boundaries, the availability of decentralized backup power generators. Thus, the set of performance and condition variables, and the resilient properties mediating between them, depends on both the scope and life cycle over which system resilience is considered.

Combining the three variable types and the relationships between them, Figure 3 outlines a simple analytical framework for understanding system resilience.

As shown in Figure 3, a system's performance (P) is determined by a set of uncertain conditions (C), and a set of resilient properties (R), mediating between C and P. Taking a step further, the three sets of variables and their relationships can be expressed as a function:

$$P = f\,(C,\ R) \tag{1}$$

In which,

- P is the set of variables defining the performance of the system;
- C is the set of uncertain variables influencing P;
- R is the set of mediating variables, which, together with C, determine P; and finally,
- f is the relationship between P, C, and R.

Taking this view, the resilience of a system is determined by its ability to mediate between performance and uncertain conditions. Further, this distinguishes resilient systems from "brittle" and "robust" systems: The behavior of what Kalra et al.[42] term a "brittle system," that is, a system with no resilient properties can be expressed as $P = f(C)$, where the system's performance P is determined by uncertain conditions C, with no mediating variables. Conversely, a "robust system," as defined by De Weck et al.,[9] can be expressed as $P = f(R)$, where the performance P is insensitive to uncertain conditions.

Drawing on Meerow and Stults,[40] we can further distinguish between two types of resilience, "bounce back" and "bounce forward," as illustrated in Figure 4.

Figure 4 illustrates the two bounce directions of a resilient system: (a) "bounce back" from worse-than-expected conditions and (b) "bounce forward" under better-than-expected conditions. Figure 4A mirrors the example depicted in Figure 2, where system performance bounces back from worse-than expected conditions, plotting a "resilience triangle" of deviation from and return to its equilibrium.[20,43,44] Figure 4B depicts the equivalent "inverse resilience triangle," in which system performance bounces forward under better-than expected conditions.

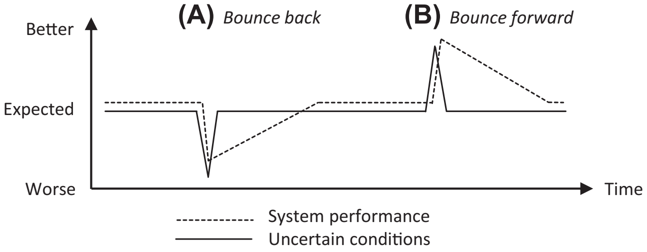

FIGURE 4 The two bounce directions of a resilient system: A, bounce back and B, bounce forward

Further, this distinguishes "fragile" and "antifragile" systems, as defined by Taleb,[45] as two species of bounce-back (Figure 4A). Thus, the performance of a "fragile system" bounces back from worse-than-expected conditions to less than its predisturbance value, while the performance of an "antifragile system" bounces back to a state of greater than its predisturbance value—both as a consequence of the disturbance.

Having thus distinguished three variable types of a resilient system and two bounce directions, the following section outlines our approach to analyzing the literature.

3 | METHODOLOGY

Employing the framework described in the previous section, we base our research design on Francis and Bekera,[46] who used definitions to analyze resilience concepts across disciplines and system types. Focusing on definitions allows for coverage of a large number of studies by systematically identifying a shared and concisely formulated part of the resilience concept: its definition. A definition, for the purpose of this paper, is understood as a statement of the meaning of a term (a word, phrase, or other set of symbols).[47] Coupling this with a systematic review methodology enables transparency and reproducibility in our coverage of the field.[48]

Coverage is a significant challenge for any review of the resilience concept. The search term "resilience" yields 63 238 hits in the Scopus database (as of November 2017). While efficient, this method does not, however, capture the richness and nuance of the resilience concept as it appears in its original context. In addition, any qualifications, elaborations, or limitations accompanying the definition are omitted—that is, coverage comes at the cost of nuance.

Accepting these limitations, an analysis of definitions seems well suited to our purpose of elucidating the key distinctions of the resilience concept across domains and system types. Further focusing efforts, this study is based on existing literature reviews of resilience definitions, covering a broad range of system types and

TABLE 1 Criteria of exclusion and inclusion in the systematic literature review

Steps in the review	Included	Excluded
Scopus search: TITLE-ABS-KEY (resilience)	63 238	–
Scopus search: TITLE-ABS-KEY (resilience AND literature AND review)	1630	61 608
Excluding Scopus subject area “medicine”	–	554[a]
Excluding Scopus subject area “psychology”	–	288[a]
Excluding Scopus subject area “nursing”	–	116[a]
Excluding Scopus source type; “book chapters”	–	76[a]
Papers identified for manual review of abstracts	787	843
Review papers identified for manual study	111	676
Literature reviews identified containing definitions of resilience	18	93
Literature reviews suggested by anonymous reviewers	3	
Total number of definitions identified in the literature reviews	380[b]	–
Definitions excluded for consistency (from the field of psychology)	378	3
Repetitions eliminated from the sample of definitions	251	126
Unique definitions identified and included in the study	251	

[a] Due to overlapping categories, the criteria sum to more than the total of 843 papers excluded.
[b] As defined by Levi[47]

disciplines. Building on definitions already identified and compiled by second-source research enables greater coverage than reviewing the original studies, at the cost of limiting our coverage to those areas of the field already included in existing literature reviews. Doing so, we necessarily accept the omission of literature not (yet) reviewed.

Further narrowing the scope, Scopus subject areas of “nursing,” “psychology,” and “medicine” were excluded from the search, on the basis of direct relevance to the engineering systems field. Finally, further reducing the body of literature, book chapters were excluded as a source type.

Using these criteria, the following search string was formulated for the Scopus database: TITLE-ABS-KEY (resilience AND literature AND review) AND (EXCLUDE (DOCTYPE, “ch”)) AND (EXCLUDE (SUBJAREA, “MEDI”) OR EXCLUDE (SUBJAREA, “PSYC”) OR EXCLUDE (SUBJAREA, “NURS”)). The terms “literature” and “review” were used in the search string in place of Scopus’ own document type “review,” as this excluded known literature reviews from the sample. The operator “AND” was used between “literature” and “review” rather than “OR,” as the latter included five times as many hits, and with low relevance. This search string yielded 787 hits in the Scopus database (as of November 2017). Based on these criteria, this search was chosen as the basis of the study.

The abstracts of the identified documents were reviewed manually. All literature reviews (criterion 1) on the subject of resilience (criterion 2) were selected for further study. Documents excluded at this step contained the word “resilience” and the word “review,” but with no connection between the two. On the basis of the review of abstracts, 111 documents were selected for further study. These documents were screened manually, and all literature reviews compiling formal definitions of resilience were selected. This process identified the literature reviews 1-18, listed below. Reviews 19-21 were included upon suggestion from anonymous reviewers, resulting in the following 21 reviews:

1. Bhamra et al.[49]
2. Hosseini et al.[22]
3. Francis and Bekera[46]
4. Wilt and Long[50]
5. Kamalahmadi and Parast[51]
6. Righi et al.[52]
7. Ali et al.[53]
8. Matarrita-Cascante et al.[54]
9. Reyes and Nof[55]
10. Meerow et al.[56]
11. Modica and Reggiani[57]
12. Meerow and Newell[58]
13. Tukamuhabwa et al.[59]
14. Xu et al.[60]
15. Sanchez et al.[61]
16. Roberta et al.[62]
17. Ifejika et al.[63]
18. Ponis and Koronis[64]
19. Patriarca et al.[65]
20. Olsson et al.[66]
21. Bakkensen et al.[67]

The definitions included in these reviews were analyzed manually. For consistency with the search criteria (see above), two definitions from the field of psychology were excluded from the sample. In addition, two definitions synthesized by Xu et al.[60] and one by Ifejika et al.[63] from original sources were retained in the sample.

One hundred and twenty-six repetitions were eliminated (equivalent to 33% of the total samples). This relatively high share of repetitions indicates good coverage of the field within the bounds of the chosen criteria. The overview of the sample (see the Online Appendix) retains the first definition encountered in the included reviews (in the order listed above), and this definition is referenced under the relevant review. Table 1 gives an overview of the process of elimination and the consequences for inclusion and exclusion in the sample.

As shown in Table 1, the process resulted in a nonrepresentative sample of 251 unique definitions of resilience, covered by

TABLE 2 Excerpt of the analysis of definitions of resilience (see full sample in the Online Appendix)

Ref.	Author	Definition	System type	Performance	Uncertain conditions	Resilient properties
	From Ref. 49					
1	Bodin and Wiman (2004)	The speed at which a system returns to equilibrium after displacement, irrespective of oscillations, indicates the elasticity (resilience).	Unspecified/ generic	Equilibrium	Displacement	Return speed
2	Holling (1973)	The measure of the persistence of systems and the ability to absorb change and disturbance still maintain the same relationships between state variables.	Ecological systems	Relationships between state variables	Change, disturbance	Persistence, absorption
3	Walker et al. (2004)	The capacity of a system to absorb a disturbance and reorganize while undergoing change and retaining the same function, structure, identity, and feedback.	Ecological systems	Function, structure, identity, and feedback	Disturbance	Absorption, reorganization

TABLE 3 Overview of system types in the sample by number and share of total sample

System type	Number	Share
Supply chains	66	26%
Unspecified/generic	46	18%
Socio-ecological systems	36	14%
Organizations/firms	31	12%
Technical systems	26	10%
Urban systems	25	10%
Economic systems	12	5%
Ecological systems	7	3%
Tourism	2	1%
Total	251	100%

literature reviews—outside the subject areas of psychology, nursing, and medicine. In the Online Appendix, giving a complete overview, definitions are organized as in Table 2.

As shown, definitions are organized under the literature review in which they are included, and numbered in parenthesis for reference. The references to the original authors, as they appeared in the review, are listed in the second column. The definitions are listed in the third column. The fourth column "System type" contains our classification of the system type (Table 3). The remaining columns contain the three variable types shown in Figure 3. This classification was done manually, as shown in Table 2, using the definitions of the three variable types described in the previous section.

Turning to the distribution of the literature within these categories, 50% of the definitions in the sample specify all three variable types in Figure 3, while 46% specify two variable types. Four percent specify a single variable type, and 1% no variable types. Specifically, 67% specify one or more performance variables, while 91% specify one or more uncertain condition variables. 92% specify one or more resilient properties. Building on the column 4 in Table 2, the definitions in the sample were categorized into nine system types, as shown in Table 3.

Analyzing conceptual distinctions in the sample, guided by Figure 3, we searched for key distinctions in the sample in terms of resilience "*of what,*" "*to what,*" and "*how.*" Within each category in Figure 3, we used a combination of automated and manual text analysis. The frequency of terms was first ranked automatically within each of the three variables types in Figure 3. Conceptually related terms were grouped manually, working from most to least frequently occurring terms. Through multiple iterations, the category of "other" was gradually minimized (but not eliminated) through aggregation or disaggregation of preliminary categories. Following Cohen and Lefebvre,[68] any bottom-up classification based on similarities and differences between objects (concepts, in our case) is not "objective" or "universal." Alternative breakdowns of the same data, and at alternative levels of aggregation, thus remain both possible and valid. Thus, Tables 3–6 represent one possible set of classifications. The results of the analysis are detailed below.

4 | RESULTS

In the following, we identify key distinctions within the three variable types shown in Figure 3, classifying the performance, uncertain conditions, and resilient properties defined in the literature.

4.1 | Performance variables in the literature: resilience of what?

One hundred and fifty-two definitions in the sample specify one or more performance variables, that is, resilience "*of what.*" Table 4 gives an overview of these variables and their categorization.

As shown in Table 4, the literature specifies a wide range of performance variables. The majority of the resilience literature includes positive performance variables related to "system function," specifying, for example, the maximization, retention, or restoration of "normal operations" (133) or "acceptable service level" (139). This category accounts for half of the performance variables in the sample. "Loss" minimization

TABLE 4 Resilience "of what": overview of performance variables in the sample

Category	Common performance variables	Number[a]	Share[a]
Function	System function, output, service, requirements, operations, capacity, ability	76	50%
State	System state, state space, equilibrium, situation, regime	36	24%
Structure	System structure, components, relationships between variables, feedbacks, connectedness, persist, sustain	18	12%
Degradation	System degradation, deterioration, vulnerability, damage	7	5%
Loss	Loss minimization, devastation, destruction, harm, outages	7	5%
Identity	System identity, definition	4	3%
Growth	Growth, growth path/trajectory, development pathway	4	3%
Behavior	System behavior	3	2%
Control	Control	3	2%
Others	For example, mobility, thriving, competitive advantage, strength	14	9%

[a] Number and share sum to more than 152 and 100%, respectively, as some definitions specify variables in more than one category.

TABLE 5 Resilience "to what": overview of uncertain conditions in the sample

Category	Common condition variables	Number[a]	Share[a]
Disruption	Disruption, interruption, disturbance, perturbation, shock, accident	122	53%
Change	Change, shift, alteration, discontinuity	37	16%
Event	Event, incident, occurrence	31	13%
Damage	Damage, disaster, emergency, catastrophe, harm, trauma, destruction, misfortune, negative impacts, accidents	26	11%
Adversity	Adversity, stress, strain, challenge, problem, attack, crisis	29	13%
Risk	Hazard, danger, risk, threat	18	8%
Uncertainty	Uncertainty, unpredictability, surprise, the unexpected	7	3%
Turbulence/variation	Variation, oscillation, turbulence	6	3%
Failure	Failure, faults, breakdowns	6	3%
Others	Displacement, uncertain demands, compromised nodes, mistakes	18	8%

[a] Number and share sum to more than 230 and 100%, respectively, as some definitions specify variables in more than one category.

TABLE 6 Resilience "how": overview of resilient properties in the sample

Category	Common resilient properties	Number[a]	Share[a]
Recovery	Recover, return, self-righting, reconstruction, bounce back, restore, resume, rebuild, re-establish, repair, remedy	122	53%
Absorption	Absorb, tolerate, resist, sustain, withstand, endure, counteract	82	35%
Adaptation	Adapt, reorganize, transform, adjust, re-engineer, change, flexibility, self-renewal, innovation	67	29%
Reaction	Respond, react, alertness, recognition, awareness	20	9%
Improvement	Improve, grow	18	8%
Prevention	Prevent, avoid, circumvent	17	7%
Minimal/graceful deterioration	Minimal, restricted, acceptable, contained, graceful deterioration/degradation	17	7%
Anticipation	Anticipate, predict, plan, prepare	15	6%
Coping	Coping, cope	15	6%
Survival	Survival, persistence	12	5%
Mitigation	Mitigation, manage consequences	7	3%
Others	Learning, management, action, resourcefulness	26	11%

[a] Number and share sum to more than 232 and 100%, respectively, as some definitions specify variables in more than one category.

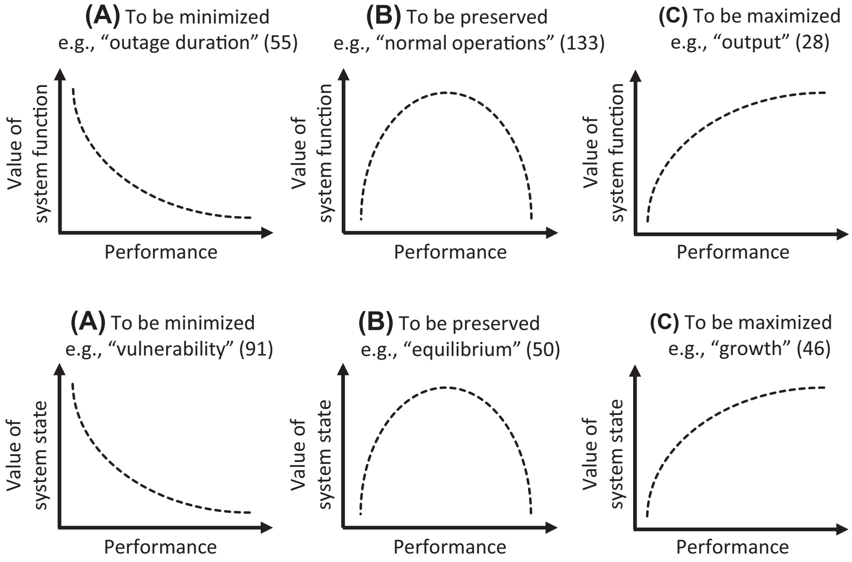

FIGURE 5 Key distinctions between performance variables (references to Online Appendix in parenthesis)

is a negative equivalent, that is, systems whose function is to minimize or prevent loss or harm, for example, "effects of disasters" (8) or "avoid maximum potential losses" (26).

The second largest category specifies performance variables referring to the "state" of the system, often using systems theoretical terms to specify an "equilibrium" (50), an "original state" (192), "desired state" (187), or "state space" (186) of the system itself, to be retained, restored, returned to, etc. The third and fourth largest categories are likewise related to the state of the system itself: These specify various aspects of the "structure" of the system (to be preserved) or "degradation" (to be minimized). These categories include, for example, the preservation of "relationships between state variables" (2) or the ability to "sustain shocks without completely deteriorating" (41), respectively. In the same vain, system "identify" likewise specifies inward-looking performance measures (e.g., (3) in Table 2).

Coupling these observations with system type suggests an underlying distinction between systems that are *ends in themselves*, and systems that are *means to higher ends*. A higher share of the literature on the former, for example, socio-ecological systems (8) or ecological systems (42), specifies performance variables related to system *identity*, *structure*, and *degradation* than systems serving higher ends, for example, technical systems (245) and supply chains (209).

In summary, Figure 5 illustrates two key distinctions between performance variables referring to (a) the *function* of the system versus the *state* of the system and (b) performance variables to be *minimized*, *preserved*, or *maximized*.

4.2 | Uncertain conditions in the literature: resilience to what?

Turning now to the uncertain conditions to which a system is to be resilient, 230 definitions in the sample specify one or more condition variables, that is, resilience "*of what.*" Table 5 gives an overview of these variables and their categorization.

As shown in Table 5, the resilience literature contains a wide range of uncertain conditions, including, for example, "stress" (182), "disasters" (176), "external shocks" (42), "crises" (24), and "turbulent change" (46). Among condition variables, the sample contains both temporary/singular events, change to new permanent states, and continuous fluctuation. (106) distinguishes between "major mishap" and "continuous stress," while (19) distinguishes between "disruptive event" and "continuous stress." (44) distinguishes between "change" and "disturbance." A conceptually interesting outlier, (243), defines supply chain resilience as "[…] not only as the ability to maintain control over performance variability in the face of disturbance but also a property of being adaptive and capable of sustained response to sudden and significant shifts in the environment in the form of uncertain demands." Here, changing performance requirements (demands) are themselves included as an uncertain condition.

The sample specifies both internal and external conditions, that is, both uncertain conditions within system boundaries and in the surrounding environment. (93) specifies "external events" only, but most definitions making this distinction include both. For example, (13) and (31) include "external" as well as "internal" disruptions. As shown in Table 5, the majority of definitions in the sample specify negative conditions, for example, "stress" and "disasters" (57), "shock" (170) and "cyber attacks" (59). However, the sample contains examples of favorable (or neutral) conditions, for example, "alteration" (145), "change" (113), "trends" (150), and "surprises" (169).

Figure 6 summarizes the key distinctions between condition variables in the sample referring to events, change, turbulence and variability and favorable, neutral and negative conditions.

4.3 | Properties of resilient systems in the literature: resilience how?

The 232 definitions in the sample specify one or more resilient properties, that is, the "*how*" of resilience. Table 6 gives an overview of these variables and their categorization.

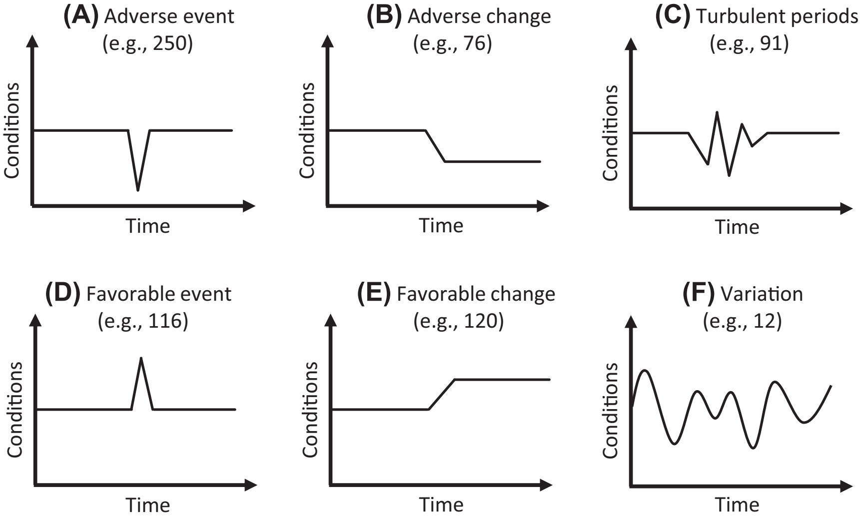

FIGURE 6 Key distinctions between uncertain conditions (references to Online Appendix in parenthesis)

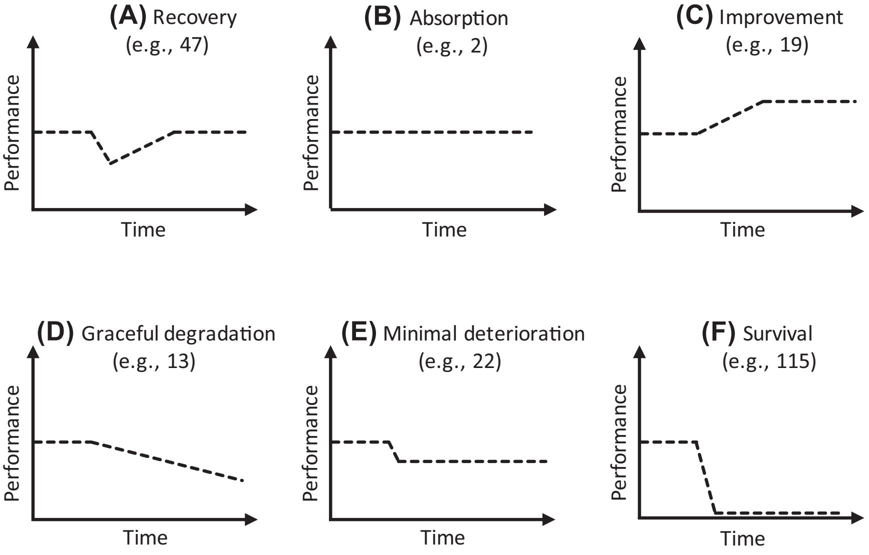

FIGURE 7 Key distinctions between resilient properties (references to Online Appendix in parenthesis)

The literature proposes a wide range of properties of resilient systems right across the risk-response chain. The literature includes examples of both resilience to causes, consequences, and both. For example, (89) includes both prevention and mitigation, (162) defines resilience as "[…] a spectrum, ranging from avoidance of breakdown to a state where transformational change is possible," and (95) specifies "An ability not just to recover from hits but to avoid problems altogether." (103) includes both the period before and after a disturbance when defining as follows: "Resilience is the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances […]." (96) includes "anticipation" as a property of resilient systems: "First, a reactive capacity of the company to resist an external event; second, a more active capacity to anticipate events and thus open new development pathways." However, elsewhere (100) by the same author defines resilience as "[…] an organization's ability to adjust to harmful influences rather than to shun or resist them." In addition, (44) includes only capabilities applied "[…] during and after the event," but not before.

As shown in Table 6, a recurring distinction in the literature is the ability of a system to absorb, resist, or withstand uncertain conditions, and the ability of the system to react, adapt, or change in various ways. This dichotomy is reflected in the sample under many names, for example, "dynamic" versus "static" (27), "proactive" versus "passive" (29), "reactive" versus "active" (96), "resist" versus "change" (47), and "stability" versus "flexibility" (38). (27), for example, states that: "Static economic resilience is the capability of an entity or system to continue its functionality like producing when faced with a severe shock. Dynamic economic resilience is defined as the speed at which a system recovers from a severe shock to achieve a steady state." (29) makes a similar distinction: "The sum of the passive survival rate (reliability) and proactive survival rate (restoration) of a system." (38) distinguishes between "[…] a balance of stability and flexibility." (67) distinguishes between "[…] resisting or changing to reach and maintain acceptable functioning." As shown in Table 6, the majority refer to various forms of "recovery." (35), for example, specifies the return to the "[…] original state or an adjusted state based on new requirements." This is followed by the ability to absorb, tolerate, or resist uncertain conditions. (103), for example, refers to the ability to "sustain required operations."

While variants of recovery and absorption are most common, the literature also includes improved performance in response to uncertain conditions, in addition to survival and persistence of the system itself, as shown in Table 6. In addition, as shown, 8% of definitions fall under the "improvement" (20) category, specifying some offensive capability to bounce forward (Figure 4) under uncertain conditions. Among these, (19) refers to the ability to "[…] improve functioning despite the presence of adversity," (46) specifies "[…] the capacity for an enterprise to survive, adapt, and grow in the face of turbulent change," while (65) specifies a return to "the original or a more efficient state," post disruption. This category is not evenly distributed across the literature, being twice as prevalent in supply chain resilience, and with no examples in technical or urban systems. The distinction between bounce back and bounce forward in the literature seems to reflect the value of a system's status quo, that is, whether the best that can be expected from a system is its continued operation (e.g., urban transportation networks (58)) or whether change is, in fact, necessary for expected system performance or survival (e.g., firms, industries, technologies, and institutions (28)).

An additional vein of the resilience literature allows for minimal, acceptable, or graceful deterioration of performance. (15), for example, specifies "acceptable degradation," (34) and (52) specify "minimum level of service" during interruptions, while (70) allows for "[…] a given percentage of pre-disaster operations."

In summary, Figure 7 shows the key distinctions between resilient properties in the literature, including recovery, absorption, improvement, in addition to two forms of degradation and survival.

5 | CONCLUSION AND IMPLICATIONS

This paper clarifies the key distinctions of resilience concept and their implications for engineering systems. This paper analyzes 251 definitions in the resilience literature and identifies a number of key distinctions. Analyzing the resilience literature from three angles, we ask; resilience *of what*, *to what*, and *how?*

In answer to the first question, *of what?*, the literature distinguishes a wide range of performance variables be (a) minimized, (b) preserved, or (c) maximized, and further distinguishes between systems that are (a) means to higher ends and (b) systems that are ends in themselves. In answer to the second question, *to what?*, the literature specifies a range of positive and negative uncertain conditions both within and without system boundaries. These include (a) adverse events, (b) adverse change, (c) turbulence, (d) favorable events, (e) favorable change, and (f) variation. Finally, in answer to the third question, *how?*, the literature distinguishes properties right across the risk-response chain, including: (a) recovery, (b) absorption, (c) improvement, (d) graceful degradation, (e) minimal deterioration, and (f) survival.

The key distinctions in the resilience literature outline a morphology of resilient systems, suggesting answers to three principal design questions, which must be asked of any engineering system: Resilience of what, to what, and how? In this light, no "best" definition of resilience exists independently of the answers to these questions. These, in turn, depend on at least three more fundamental questions about the system in question: Is it a means or an end in itself, is the status quo a "best case" to be defended or a baseline for improvement, and finally, is the existence of the unknown ultimately a good or a bad thing, or both?

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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