International Journal of Disaster Risk Reduction 96 (2023) 103893

Contents lists available at ScienceDirect

International Journal of Disaster Risk Reduction

journal homepage: www.elsevier.com/locate/ijdrr

A resilience glossary shaped by context: Reviewing resilience-related terms for critical infrastructures

Andrea Mentges [1], Lukas Halekotte [*,1], Moritz Schneider, Tobias Demmer, Daniel Lichte

German Aerospace Center (DLR), Institute for the Protection of Terrestrial Infrastructures, Rathausallee 12, 53757, Sankt Augustin, Germany

A R T I C L E I N F O

Keywords:
Resilience definition
Critical infrastructures
Terminology
Resilience capacities
Performance curve

A B S T R A C T

We present a comprehensive resilience glossary, comprising a set of 93 definitions of resilience-related terms used in the context of critical infrastructures. The definition and use of many of these terms, as well as the term resilience itself, shows an enormous variability in the literature. Therefore, we draw from the diverse pool of published definitions, integrate multiple contrasting views, compare the individual terms, and provide references to adjoining or contesting views, to create a clear resilience terminology. This terminology outlines a specific understanding of resilience which supports the effective assessment and management of the resilience of critical infrastructures. The two central elements of this understanding are that (1) resilience is the ability of a system to deal with the impacts of unspecific and possibly unforeseen disruptive events, and that (2) this ability comprises three pillar capacities whose quality can be extracted from performance curves.

1. Introduction

1.1. Background

Sometimes, failure is inevitable. For more than 50 years, this notion pushed scientists from various fields to study the ability of systems and individuals to deal with sudden negative impacts [1]. Today, understanding this ability - famously known under the name resilience - is more relevant than ever. Resilience can help critical infrastructures to master challenges posed by various global changes, such as globalization, digitalization, and the growing number of extreme weather events [1–4]; and thus, protect the essential services and assets our societies rely on.

1.2. Motivation

The definition of resilience shows an enormous variability. The long history of the concept [5], paired with early and persistent disagreements on its best use (see, e.g., the differing perspectives of Holling [6] and Pimm [7]), and its adaptation and continuous development in various research fields (e.g., ecology [6–8], disaster management [9–11], or critical infrastructure protection [12,13]) have led to its diversification. As a result, the exact definition of resilience varies across domains [5,14] and within domains [15,16], in dependence on research focus (e.g., seismic resilience of communities [10], hurricane resilience of electric power systems [17], or

* Corresponding author.
E-mail addresses: andrea.mentges@dlr.de (A. Mentges), lukas.halekotte@dlr.de (L. Halekotte), moritz.schneider@dlr.de (M. Schneider), tobias.demmer@dlr.de (T. Demmer), daniel.lichte@dlr.de (D. Lichte).

[1] Co-first authors.

https://doi.org/10.1016/j.ijdrr.2023.103893
Received 7 February 2023; Received in revised form 14 June 2023; Accepted 25 July 2023
Available online 28 July 2023

urban climate change resilience [18]), and from author to author (see for example the extensive collection of definitions in Refs. [19–21]). Therefore, there is no one-size-fits-all definition of resilience [22] and concluding consensus about its definition has not been reached [23]. A clear definition is crucial, however, since the way we define resilience will shape the way we measure it [21]. The aim of this document is to compile, define, and distinguish terms that are used to describe the resilience of socio-technical systems, and in particular of critical infrastructures. The goal is to collect synonyms and carve out subtle differences among similar terms, as well as to provide references and resources to gain further insights about each term.

1.3. What has been done before

Other resilience glossaries have been published before. However, they are mostly not targeted at the context of critical infrastructures, but have a different focus, e.g., the Society for Risk Analysis glossary [24], the industry-centered glossary by DRI International [25], the informatics-centered glossary by Andersson and colleagues [26], or the ecological resilience glossary by the Resilience Alliance [27]. A recent study reviewed 17 definitions of terms which are described as contributing to infrastructure resilience [23]. Another recent work presented definitions for 25 terms which are used in the context of defining and measuring infrastructure resilience [28]. The unique aspect of this glossary is the emphasis on carving out and discussing the differences and similarities between various terms which are used in the context of infrastructure resilience.

1.4. Aim of the study

We define and distinguish more than 90 resilience-related terms in the context of critical infrastructures. Just like the term resilience, the exact meaning of many of these terms is disputable and changes depending on the research field. In this regard, we emphasize that we do not claim to have found the "right" definition nor that others' definitions are flawed. Instead, we built on previous work to find an integrated terminology, that comprises many resilience-related terms without duplications and as much distinctness between them as possible. The aim of this work is thus not to add yet another definition to the comprehensive, valuable work that has already been done to define resilience and its related concepts. Rather, we aim to bring the existing definitions together, integrate them, condense them, and obtain a consistent set of terms which are as clearly distinct from each other as possible. Therefore, in the following, we i) briefly summarize the status of resilience definition, ii) show that there are still contradictions, blurriness, and overlap between terms, iii) present a glossary of resilience-related terms based on existing literature, describing the meaning of each term and the differences between them, and iv) discuss the implications of our view on resilience for its quantification and management.

2. Current status of the resilience definition

The concept of resilience has been established in the context of critical infrastructures mainly in the past two decades and the number of related studies is still growing significantly [23].

2.1. Variability in terminology: resilience

The definition of resilience depends on the author. Several previous studies have compiled extensive lists of resilience definitions from numerous sources, concluding that the variation in definitions is high (e.g., Mottahedi and colleagues enumerate 28 definitions [23]; Wied and colleagues compare 251 definitions [19]; see also Refs. [20,21]). Due to the great number of definitions and the high variability among these definitions, the concept of resilience has been heavily criticized. It has been claimed, for instance, that the term has a "poor scientific status" in regard to its application in terrorism research [22], that it is "potentially disappointing to read too much into the term as a model and as a paradigm" [5], that the term is a buzzword [29], and might be used more broadly than it should [30]. In fact, it is not always clear what the term resilience refers to. Many authors describe resilience as an ability or capability of a system [30–35]. However, resilience is sometimes also understood as the process or outcome following the disruption of a system [36]; an understanding which allows a much easier assessment. Some authors state that both the "power or ability" (i.e., capacities) and the "action or act" (i.e., processes) are included in resilience [37]. In this context, Seager and colleagues [38] emphasize that "rooting resilience in action" helps in clarifying that resilience analysis goes beyond checking for system resources but requires an in-depth treatment of the actions or processes which lead to a resilient outcome. Other well-known definitions describe resilience not conceptually as a capacity or process, but as a measure, e.g., a speed, rate, or degree of something; for example, the definition of engineering resilience according to Pimm [7], which emphasizes the speed of recovery. However, several reviews of resilience definitions from the engineering and infrastructure context [19,21,23] show that most studies view resilience as a capacity. Here, we follow this view and interpret resilience as a capacity respectively a set of capacities. Importantly, these resilience capacities are directly associated with corresponding actions or processes - resilience is the ability to act resilient or "the capacity to execute the [resilience] processes" [38]. This means that we restrict our understanding of the term resilience to the capacity but emphasize that this capacity can only be understood by considering the associated processes.

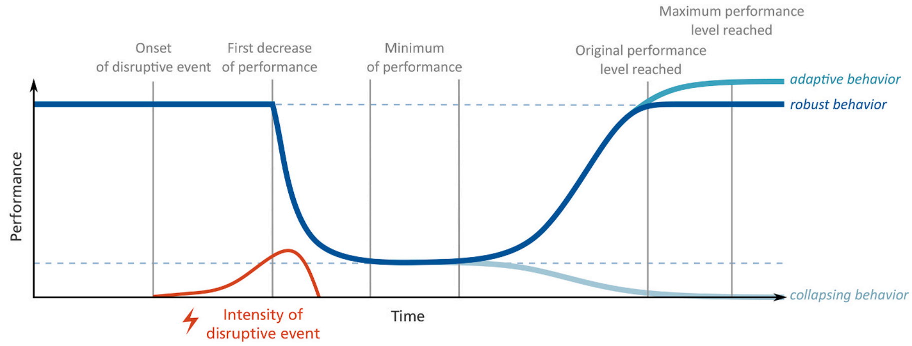
2.2. Variability in terminology: capacities

Resilience is an umbrella term, which comprises many different system capacities (sometimes termed components [20,39] or dimensions [10]). Most sources (see Ref. [19]) emphasize the ability to recover [40], some the ability to absorb [41], or learn [42–44]. Like for the term resilience itself, the definitions of its capacities are highly variable. For example, Carlson and colleagues' [20] definition of mitigation includes resistance and absorptivity while Ouyang and colleagues' [45] definition of resistance describes prevention and reduction. In addition, the grouping and number of resilience capacities varies across studies. For example, Béné and colleagues [36] distinguish absorptive, adaptive, and transformative capacity; Rehak and colleagues [39] distinguish robustness, recoverability, and adaptability; the MCEER's resilience framework "4R" comprises robustness, redundancy, resourcefulness, and rapidity [10]; and the Argonne National Laboratory's framework comprises preparedness, mitigation, response, and recovery [20].

Furthermore, the meaning of individual capacities also varies from author to author. An illustrative example is the adaptive capacity whose definition varies depending on, among others, the type of disruption which is considered, the time at which this capacity becomes relevant (i.e., during or after the disruption) as well as its effect (i.e., sustain performance or constrain performance loss [33, 36], restore performance [46], enhance performance [47], improve resilience [39,43]). For instance, Béné and colleagues [36] assume that the adaptive capacity of a system becomes important once the intensity of a disruption (in this case, a press disturbance) exceeds the system's absorptive capacity - adaptive capacity enables the maintenance of system functioning in the light of greater persistent disruptions. By contrast, other authors describe the adaptive capacity as the ability to draw lessons from past disruptions in order to improve the remaining resilience capacities, i.e., adaptive capacity plays out mainly after the restoration [39,43]. In this sense, if adaptability is high, resilience is a self-reinforcing ability.

2.3. Variability in terminology: phases

Similarly, there is considerable variation in terminology concerning the different phases a system goes through during the unfolding of a disruption. A popular way to illustrate this resilience cycle is via an idealized performance curve, which typically starts shortly before a single disruptive event and ends after the system has recovered from the associated impacts. The curve is conceptually divided into successive phases, which are named differently depending on the author (Fig. 1). Most authors name the phases in



Reference	Phases					
Klimek et al. 2019	Plan		Absorb		Recover	Adapt
Nan et al. 2014	Original steady phase		Disruptive phase		Recovery phase	New steady phase
Rehak et al. 2018	Crisis preparedness	Detection ability	Responsiveness		Recoverability	Adaptability
Jovanović et al. 2020	Understand risks	Anticipate/ prepare	Absorb/withstand		Respond/recover	Adapt/transform
Braun et al. 2020		Resist	Absorb		Adapt/Restore	Improve
Häring et al. 2017	Preparation and prevention		Absorption and response		Recovery	
Fischer et al. 2018	Prepare and prevent		Protect	Respond	Recover	
Taleb-Berrouane et al. 2019	Stability		Disruption effect	Reaction	Rehabilitation	Return to stability
Mishra et al. 2021	Pre-disturbance		Disturbance	Emergency	Restoration	Post-restoration
*Oboudi et al. 2019 **	Pre-disturbance		Disturbance progress	Post-disturbance	Restoration state	Post-restoration
Mottahedi et al. 2021	Initial normal state		Damage propagation	Disrupted state	System recovery process	Recovered state
Hossain et al. 2019	Stable original state / Reliability		Disruption / Vulnerability	Disrupted state	System recovery / Recoverability	
*Panteli et al. 2015 **	Resilient state		Event progress	Post-event degr. state	Restorative state	Post-restoration state

* use resilience as the dependent variable, instead of performance

Fig. 1. Resilience phases across studies using the performance curve. Depending on the author, the phases of the resilience cycle are called differently, emphasizing either the current state of the system, a resilience capacity that is important during the respective phase, or a resilience process that typically takes place at the time. However, the listed examples illustrate that start and end time points of the phases are largely consistent across studies.

accordance with the resilience process that takes place during that time [48–50]. Some refer to the resilience capacity that is thought to be most important during the corresponding time period [51]. Others distinguish the phases based on the state of the system or the progression of the disruption [23,52]. However, despite all these differences in the naming, among researchers using the performance curve for illustrative purposes, there is a consensus on the general order and duration of the phases (Fig. 1). It should, however, be noted that other ways to conceptualize the succession of resilience-constituting phases or processes exist, especially among frameworks which emphasize a system's ability to adapt. Notable examples in this regard are the adaptive cycle by Holling [53–55] and the approach by Park and colleagues which comprises the recursive phases of sensing, anticipating, adapting, and learning [38,56,57].

2.4. What's not resilience?

To understand the concept of resilience, it can be helpful to review its boundaries, i.e., what is *not* resilience. There are many different perspectives on where the resilience concept ends. Holling [6], the originator of the ecological resilience concept, emphasizes the difference between resilience and stability (similar to Ref. [44]), where stability is defined as the ability of a system to return to its original equilibrium state after a temporary disruption, and resilience "is the ability of systems to absorb change and disruption and still maintain the same relationships between […] state variables" [6]. Thus, Holling highlights the aspect of flexibility and transformability that is included in the resilience concept. While stability and resilience can be understood as complementary abilities of a system, other authors contrast resilience with its supposable opposite to illustrate the concept. Woods [58,59] sees resilience as the opposite of brittleness, with brittleness describing the sudden collapse of a system at or beyond its operating range, and resilience describing the ability to persist in the face of surprising disruptions (i.e., graceful extensibility). In social sciences, fragility is sometimes seen as the opposite of resilience [60,61]. Also, vulnerability is sometimes treated as the opposite of resilience [9] or can also be seen as the opposite of the resilience capacity robustness [23], since robustness is often measured as the inverse of the amount of performance loss [62], while vulnerability is often defined as the amount of performance loss [24,47,63]. In our view, there is no veritable opposite to the resilience concept. Instead, high resilience entails the absence or minimization of, among others, vulnerability, fragility, and inflexibility.

An important difference lies between resilience management and risk management. The differentiation and relationship between the two is vividly discussed [64–67], with opposing views ranging from refusing that resilience management adds anything new to existing risk practices to the believe that it represents a compulsory addition to the former. We see them as two complementary approaches for dealing with disruptions (see also Discussion section 4.1.3), which can benefit from each other in the joint goal of protecting infrastructures, as others have postulated before [57,68]. Risk management focuses on identifying and avoiding or reducing the impact of foreseeable specific threats [57,69]. While risk management might acknowledge the continuance of some residual risk, resilience management is explicitly motivated by the notion that neither are all risks predictable nor is all risk avoidable [57,66]. Thus, resilience management puts less emphasis on the reduction of individual risks, but focuses on a holistic increase of the ability to deal with disruptions as they emerge [70], emphasizing the time after the initial disruptive event, i.e., the recovery, learning, and adaption processes [71].

3. Glossary

The following glossary presents a consistent terminology, that integrates various aspects of resilience and provides a distinction between them. We decided to order the terms by topic, rather than alphabetically, in order to create a document which can be read from front to back and thus can also serve as a primer for scholars who are rather new to the topic. The glossary begins with a definition of basic terms, such as system, disruption, and risk (section 3.1); followed by terms that describe concepts which are important for system maintenance (section 3.2). In the following, we define both capacities that are important for traditional risk management (section 3.3) and capacities that are emphasized by resilience management (sections 3.4-3.6). The capacities are grouped according to the time when they become relevant, i.e., before the disruption (section 3.3), at the beginning of a disruption (section 3.4), during a disruption (section 3.5), and in-between disruptions (section 3.6). Finally, we compile terms related to resilience management (section 3.7) and analysis (section 3.8). Throughout the glossary, indentions point out the hierarchy of terms: left aligned terms are broader umbrella terms, which include the indented sub-terms grouped below them. Synonyms are included in the descriptions of the terms.

3.1. Basic terms

The following terms are the basis to understand the resilience-related concepts.

Term	Description
System	A set of components that act together as a whole to accomplish a specific function or set of functions [72,73]. System components can be, for example, machines and cables in technical systems, or individuals with specific responsibilities and tasks in socio-technical systems. We acknowledge that, for the general definition of a system, the need to perform a function might not be an absolutely necessary condition [74], but it is one which is very essential in the context of resilience, especially for infrastructure resilience [75]: Only if a desired or acceptable behavior or state can be defined, i.e., one in which a certain function is fulfilled, there is something to be maintained or restored and thus the system can show resilient behavior. Accordingly, our definition corresponds to a system which meets the fundamental requirements to be resilient.
System of systems	A set of systems, which act together in a specific context to achieve a common goal, which none of the constituent systems could reach on its own [76,77]. For example, a system of systems in the medical context is the health care system, where

(*continued on next page*)

(*continued*)

Term	Description
	the emergency treatment of patients relies on the interaction of several distinct systems, i.e., hospital management, power, traffic (road system), and communication systems.
Critical Infrastructure	A system whose purpose is providing essential or vital services to society [78–81], i.e., the infrastructure is critical in the sense that its failure or degradation results in a disruption of the fulfilment of a society's basic needs. Critical infrastructures have therefore also been referred to as "lifeline systems" [82] or "the backbone of a society" [83]. Other frequently acknowledged characteristics of critical infrastructures are that they are inherently complex [84] and that they are highly interdependent across different sectors [83,85] - e.g., many infrastructures depend on electrical power supply [85]. Despite the general agreement on the purpose of critical infrastructures (criticality to society), there is no general consensus on the precise definition of the term "critical infrastructure" (see Ref. [80] for a vast collection of definitions). Accordingly, there is also no commonly accepted standard for deciding which systems should be considered as critical infrastructures [86,87]. Nevertheless, illustrative lists of examples often include systems responsible for providing services like telecommunication, electrical power, health care, transportation, finance, transportation, water supply, emergency response, and government administration [83,86,79]. *Synonym:* Lifeline system, lifelines
Performance	The status of a system with regard to its designated function(s), i.e., how well a system's current behavior fulfills its purpose. The term "performance" is often used as a synonym for its quantitative representation, i.e., the measure of performance ("the vertical axis of a resilience curve" [13], see Fig. 1). In accordance with the different functions a system can serve, performance and its measures can refer to different things. For instance, in the context of infrastructures, Poulin and Kane [13] distinguish three different types of performance measures: Availability (e.g., number of functional pipes), productivity (e.g., water demand satisfied), and quality measures (e.g., water quality index). *Synonym:* Functionality [88] *Measured by*: Performance variable [19], performance measure [13], performance indicator, key performance indicator [89]
Hazard, threat	A potential state of the system or a situation which could cause damage or decrease functionality [24]. Although not limited to, "hazard" often refers to natural and unintentional sources of danger or risk, such as a fire hazard, environmental hazard, or accident hazard (safety-related); whereas "threat" more often refers to risks imposed by intentionally acting agents (security-related), i.e., a threat depends on intent and capability of the acting agents [90,91].
Exposure	The degree to which a system or an asset is subject to a risk source [24,92]. It is used in absolute, i.e., a system is either exposed or not exposed to a certain hazard or threat, as well as relative terms, i.e., a system can have a high or low exposure to a certain hazard or threat. For instance, in the context of disaster risk reduction, exposure can be expressed by the number of people, the situation of infrastructures, or the amount of property and other human assets which are present in a hazard-prone area and thus portray the potential for loss [93,94].
Stressor	All internal and external stimuli that cause stress and thereby lead the affected system to initiate an active reaction. Stressors can trigger disruptive events, and thus a loss of performance. The term "stressor" is well-defined and frequently used in psychology and ecology. For example, in humans, stressors such as prolonged noise can limit attention, which may lead to false decisions [95]. In contrast, in the context of infrastructure resilience, the usage of the term varies. Some authors see stressors as a synonym of disruptive events [24,96], whereas others define stressor as a stimulus that may trigger events, for example, climate change or increasing globalization [97]. The latter definition corresponds to the original definition of the term in psychology and is therefore reflected in this glossary. *Synonym:* Stress factor *Example:* Wind, climate change, scarcity of critical resources, material fatigue
Incident	An event or the occurrence of something with the potential for negative consequences (i.e., a potentially disruptive event). If the system in question constitutes a critical infrastructure, potential negative consequences correspond to disruptions of "the provision of an essential service" [81]. In the case of an incidence, a certain threat or hazard is realized which results in a specific exposure of the system. In contrast to a disruptive event, an incident does not necessarily lead to any negative consequences (e.g., the exposure could be zero or the system could fully resist or absorb the impact). The term is often further specified in order to highlight its type (e.g., poisoning incident, terrorist bombing incident, mass casualty incident) or severity (e.g., major, serious, catastrophic incident) [98,99]. Based on the cause of an incident, we can distinguish three general types of events [21,100]: Natural hazardous events, accidents, and attacks. *Synonym:* Event [19]
Natural hazardous event	An incidence that has a natural (non-human) source, i.e., it is neither directly caused by humans nor indirectly by a human-made system (safety-related). This involves climate- and weather-related (e.g., floods, storms, droughts), geophysical (e.g., earthquakes, volcanic eruptions) and biological (e.g., disease outbreaks, insect infestations) incidents [101]. *Synonym:* Natural accident [100], natural physical event [85]
Accident	An incidence that is directly or indirectly caused by humans but happens without planning, for instance, as a consequence of an unintentional or erroneous human action, a technical malfunction, or a system overload (safety-related). An accident usually, though not necessarily, has negative consequences such as damage, injury, or pollution [102]. *Synonym:* Normal accident [100,103]
Attack	An incidence that is caused by an intentional act (security-related). In contrast to a natural hazardous event or an accident, an attack is planned and executed by a responsive antagonist (e.g., a terrorist, criminal, or cyber-attacker) who proceeds in accordance with its own capabilities and with regard to a specific purpose/intent [104–106]. *Synonym:* Abnormal accident [100], malevolent event [21]
Disruptive event	An event that leads to negative consequences, i.e., a disruptive event is the cause of a loss of performance (see Fig. 1). In contrast to the more general term incident, this implies that there is an actual (i.e., non-zero) exposure to the event and that the system is not able to fully resist or absorb its impact. Comprises all sources of performance decrease, including, e.g., natural hazards, technical failures, human errors, extreme loads, and organizational issues, as well as intentional malicious attacks [71,107,108]. *Synonym:* Disturbance [7], adverse event [99], undesired event [21]

(*continued on next page*)

(*continued*)

Term	Description
Sudden-onset disruptive event	A disruptive event whose intensity builds up instantaneously [109], e.g., an earthquake or a tidal flood. In the context of resilience, many authors focus on such sudden-onset disruptive events [71,110]. It refers to one of the two extremes regarding the onset speed of disruptive events [111], the other extreme being included in the class of slow-onset disruptive events.
Slow-onset disruptive event	A disruptive event whose intensity increases over a longer period of time [109], e.g., deterioration of components or increasingly harsher conditions due to climatic changes. It should be noted that a slow-onset disruptive event can still lead to a sudden collapse of performance, e.g., when approaching a bifurcation or tipping point [112,113]. We propose that whether the onset of a disruptive event is considered slow or fast should depend on the time-scale of the considered system, i.e., if the intrinsic dynamics of the system are faster than the emergence of the event, the event should be referred to as slow-onset. *Synonym:* Gradual onset [111], creeping disruptive event [47], slow-onset changes or processes [114]
Pulse disturbance	A (sudden-onset) disruptive event of extremely short duration, such as a chemical spill [115]. It refers to one of the two extremes regarding the duration spectrum of disruptive events, the other extreme being the press disturbance. *Synonym:* Shock [116], acute disturbance [115]
Press disturbance	A disruptive event that shows lasting impact [115,116], such as a steady outflow of toxic chemicals. The term is mainly used in the ecological literature. *Synonym:* Adverse change [19], long-term change, chronic disturbance [115]
High Impact Low Probability (HILP) event	A disruptive event that is extreme, i.e., it is rare and causes severe consequences [117–120]. *Synonym:* Extreme event [118,121,122], high-impact rare (HR) event [123]
Disruption	A disruption is caused by a disruptive event and lasts as long as the performance of the system is decreased as a consequence of the event (i.e., a disruption is characterized by the performance drop in the resilience curve, see Fig. 1). The disruption ends when the system has recovered, i.e., it has returned to a normal operating state (see also restorative capacity in section 3.5). Thus, the disruption might last longer than the disruptive event (or be less persistent, e.g., if a system is able adapt to a long-lasting disruptive event). An important implication of this definition is that the manifestation of a disruption depends on the causing event (disruptive event) and on capacities of the affected system (i. e., its resilience and vulnerability). The proposed distinction between disruption and disruptive event is in line with the use of the terms in Refs. [39,124,125], to name a few. It should, however, be noted that the two terms are often used synonymously and sometimes even diametrical to our definition (see, e.g., the use of disruptive event in Ref. [126]).
Disaster	A disruption of the functioning of a community which tests or exceeds its capacity to cope with the situation using its own resources. It is characterized by severe and often widespread impacts on human well-being, e.g., death, disease, injury, and loss of property, essential services, or natural resources [94,127,128]. Although natural events (e.g., storms, floods, earthquakes) are the most common cause, disasters can also be human-induced (e.g., transport or industrial accidents) [101,129]. It is important to note that a disaster does not correspond to its triggering (disruptive) event [130] but is a function of the event and properties (vulnerability, exposure, capabilities) of the affected community and the involved actors (a disaster is a disruption not a disruptive event). Accordingly, there are physical, human, social, and organizational factors [83], as well as economic and political factors to a disaster [131].
Crisis	Similar to disaster (see above), it describes a disruption during which the core services provided by a system are endangered and/or its performance is already significantly affected. For instance, the temporary or partial breakdown of a critical infrastructure which exceeds known patterns can be denoted as a crisis. The terms disaster and crisis are often used interchangeable. However, the term crisis generally refers to a less severe situation, e.g., one without fatalities or the permanent loss of critical services [132]. Nevertheless, if not properly dealt with, a crisis can turn into a disaster [94]. Defining crisis as a disruption is in line with the view of "crisis as a process" as outlined in Ref. [133]. This view implies that the response to the causing event shapes the emerging crisis. The contrary view would be to consider crisis as the causing event (i.e., the incident or disruptive event), which would align with the view of "crisis as an event" [133].
Risk	The concept of risk describes "uncertain exposure to perceived harm" [91] or "the possibility of loss" [134]. It describes both the probability of a harmful effect occurring and the expected magnitude of the undesirable consequence [135]. Risk can be probabilistically formalized in different ways, for instance, as the product of probability and consequence [91] or, in the context of security, the product of threat, vulnerability, and consequence [136], where vulnerability describes the likelihood of a negative impact of the disruptive event. Independent of the applied metric, risk can generally be described as the result of its (three) essential determinants: The risk source (i.e., the hazard or threat), and the exposure and vulnerability of the system to this risk source [33,137].
Uncertainty	Uncertainty can be described as "any departure from the unachievable ideal of complete determinism" [138], i.e., when making decisions or taking action uncertainty is "inescapable" [139]. As such, it is more than the absence of knowledge [140]. The perceived degree of uncertainty is partially subjective, as it depends on the satisfaction with the existing knowledge [140]. In a socio-technical system, different sources of uncertainty can exist, for instance, in decision making, uncertainty can refer to the uncertain future state of the world as well as to the uncertainty regarding the behavior of different actors [141].
Epistemic uncertainty	A type of uncertainty which becomes deterministic over time as more data and/or knowledge are gathered. Thus, there is the possibility to reduce epistemic uncertainty by gathering more data or by refining models [138,142].
Aleatory uncertainty	A type of uncertainty where the modeler does not foresee the possibility of reducing it [142]. For example, the uncertainty associated with betting on the outcome of a single fair coin toss is aleatory [138]: Even though one might be perfectly familiar with the process and its possible outcomes, there is a 50% chance of losing. In general, natural and human systems usually involve some degree of aleatory uncertainty, e.g., due to erroneous or erratic behavior [142] or due to "the chaotic and unpredictable nature of natural processes" [138]. *Synonym:* Inherent randomness [143], variability uncertainty [138].
Deep uncertainty	Deep uncertainty refers to a high level of uncertainty, with only the extreme of "total ignorance" representing higher uncertainty [140]. The presence of deep uncertainty means that one is able to enumerate several plausible alternatives without being able to rank them in terms of likelihood [140]. Furthermore, deep uncertainty exists in situations where it is unclear or controversial which models are best suited to describe interactions among a system's variables, how to describe these variables using probability distributions, and/or which system states are desirable [144].

(*continued on next page*)

(*continued*)

Term	Description
Scenario	A scenario is a generally intelligible description of a possible situation in the future, based on a complex network of influence-factors [145]. This description comprises a sequence of events following a well-defined chronological order. Each identified scenario produces a set of consequences, which depends on the initiating event, the concerned critical infrastructure, and its geo-organizational context [146].

3.2. System maintenance

The following terms refer to system properties which are frequently used in the context of infrastructure maintenance.

Term	Description
Safety	Safety is a state of control over risk of harm or other undesirable outcomes imposed unintentionally (e.g., natural hazardous events, accidents) [24,147].
Security	Security is a state of control over risk of harm imposed intentionally by others [24] (e.g., terrorist attacks).
Reliability	The ability to meet an acceptable or the required performance level over extended periods of time [148], even under unfavorable operating conditions (involving disruptive events of any sort), e.g., "keeping the lights on" in a power system context [43]. In contrast to safety, reliability is always related to specifications regarding the required performance (what is acceptable?) [102]. *Synonym:* Business continuity (economics context, [149])
Sustainability	The term sustainability was first coined in the context of forestry, where it described an approach of not taking more resources out of the system than can be restored, such that a steady resource supply is guaranteed on the long term (see, e.g., Refs. [150,151] who refer to the book 'Sylvicultura Oeconomica' [152] by Hans Carl von Carlowitz published in 1713 as the first documented use of the term). In the context of social science, sustainable development is characterized as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [153], incorporating specifically the concepts of "needs", "intra-generational justice", and "limitations". Examples following the idea of sustainable development are circular economy, material and energy efficiency, end-of-life recovery, and environmental emissions [154,155]. Sustainability highlights the interconnectedness and interdependence of environmental, social, and economic aspects. The relation between sustainability and resilience is still under discussion [156]. Some authors argue that to achieve sustainability, high robustness, adaptation, and learning capacities are needed [154,155], and thus resilience is a part of the sustainability concept. However, it can also be argued the other way around, that resilience is the ultimate goal and sustainability contributes to reaching this objective, i.e., sustainability is a part of the resilience concept [156,157]. Finally, some authors view sustainability and resilience as two complementary concepts, which lack hierarchical order [156].
Resilience	Resilience is the ability of a system to deal with the impacts of unspecific and possibly unforeseen disruptive events. This ability depends on the availability and sophistication of a diverse set of skills and strategies, i.e., the resilience capacities. For example, resilience is enhanced by the capacity to anticipate, resist, absorb, respond to, and recover from negative impacts [20], carry out its original functions [43], and adapt in response to lessons learned from past experience or changed circumstances [33]. The core concept of resilience is "the recognition of our ignorance; not the assumption that future events are expected, but that they will be unexpected" [6]. The goal is thus to strengthen the system capacities to better deal with future events, whatever form they might take; i.e., without specifying the characteristics of the potential disruptive event in advance. Resilience is less a given, static characteristic of a system, but rather a set of skills and coping strategies that can be actively acquired [70]; this means resilience can change over time. Based on the above definition, resilience thus describes a set of various useful skills. In our view, resilience is therefore a synonym of "resilience capacities", while the associated "resilience processes" do not directly refer to the term resilience but to the manifestation of the resilience capacities in a specific situation (see Discussion section 4.1 for details). Resilience can be estimated through proxy indicators, as proposed by, e.g., Hollnagel [158] or Shirali and colleagues [159]. *Synonym:* Resilience capacities, resiliency [48], genotype of resilience [37]
General resilience	A type of resilience. General resilience presents the fundamental, underlying resilience capacities of a system [157,160]. It influences how well a system will be able to react in any circumstance. For example, general resilience describes the overall capacity of a city to persist in a rapidly and unpredictably changing world, without specifying what kind of disruptions occur [160].
Specified resilience	A type of resilience. Specified resilience describes the capacity of specific characteristics or functions of the system to handle specific types of disruptive events [157,160]. It is also described as the "resilience of what to what" [8] or as the resilience "regarding what" and "against what" [161], for example, the resilience of crop production to variation in rainfall, or a power system's total production against extreme wind. Specified resilience thus describes the reaction of the system to a specified class of stressors (or a single stressor), with regard to a number of specified performance indices (or a single performance index), in contrast to general resilience, which describes the reaction of the system as a whole to all imaginable stressors. It has been suggested that due to this restriction, specified resilience can be quantified, while general resilience is difficult to assess [8,160]. Accordingly, many instances of specified resilience can be found which often either explicitly specify the "to what" or "against what", e.g., seismic resilience [10], climate resilience [162], hurricane resilience [17], or flood resilience [163], or the "of what" or "regarding what", e.g., water resilience [164] or crop production resilience [165]. However, depending on how strictly the type of disruptive events is specified, this type of resilience conceptually approaches risk management; as resilience should in principle be indifferent towards the form of disruption.
Operational resilience	A particular view on the resilience of infrastructure systems which puts special emphasis on an operated system's ability to maintain the persistence of its function in the face of disruptive events [75,166,167]. It thus highlights the objective of system operation which is to "respond[s] to the demands placed on a system to provide the best possible function in any given situation" [75], which could imply adapting a system's structure or behavior in favor of ensuring system functioning. A way to quantify a system's operational resilience is via the performance degradation induced by disruptive events - systems with higher operational resilience are generally able to maintain a larger proportion of their original performance [166]. We consider operational resilience as an infrastructure operator's view on resilience where resilience is seen as a

(*continued on next page*)

(*continued*)

Term	Description
	"service-oriented" concept whose ultimate goal is "assuring functionality" of the whole system instead of protecting the integrity of single assets [168]. *Synonym:* Infrastructure resilience (at least, this is often implied in analyses regarding the resilience of infrastructures, especially in those using performance curves)
Engineering resilience	The terms engineering and ecological resilience were coined by Holling in order to distinguish between two different perspectives on resilience commonly applied in the ecological literature [169]. According to Holling, engineering resilience refers to the stability of a unique stable state which is composed of its resistance against disruptions and its speed of return to this equilibrium after a disturbance (not to be confused with "resilience engineering", see section 3.7). However, later on, engineering resilience has often been equated with the definition by Pimm [7] who states that resilience is simply the speed at which a system returns to its long-term equilibrium after a disruption (see, e.g., Ref. [170]), while resistance is another distinct aspect of a system (see also Ref. [171]). It is important to note that many (if not most) ecological - especially empirical - works use the term resilience in line with the definition by Pimm, i.e., they equate resilience with what we call rapidity in the context of infrastructure resilience (see, e.g., Refs. [115,172,173]). Nowadays, the term engineering resilience is sometimes used to refer to frameworks which estimate resilience based on a performance curve (such as in Fig. 1), i.e., frameworks which consider resilience as a result- or outcome-oriented concept (see, e.g., Refs. [15,16]). *Synonym:* Stability [6], resilience [7]
Ecological resilience	As for engineering resilience, the definition of ecological resilience is rooted in dynamical system theory. However, its central premise is the assumption that ecosystems are usually far from any stationary state and, moreover, better described by multi-stable complex systems [6], e.g., systems possessing more than one possible long-term behavior. In this context, ecological resilience has been equated with the capacity of a system to stay in its current basin of attraction, a capacity which is put together by several subcategories [174–176]. Generally speaking, ecological resilience is defined as "the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain the same function, structure, identity and feedbacks" [176]. This definition emphasizes the variability and intrinsic self-organizing capability of ecosystems which are necessary for its persistence [1,177]. In this regard, and in its understanding of resilience as an emergent system property or ability, the notion of ecological resilience has been very influential and shaped the way in which resilience is understood in various fields (see, e.g., Refs. [177,178]). *Synonym:* Resilience [6], systems resilience [163]
Social-ecological resilience	An extension of the ecological resilience perspective which has been developed in view of social-ecological systems [177,179], i.e., systems of inseparably intertwined social and ecological components [180]. According to the social-ecological perspective, resilience does not only concern a system's ability to persist (ecological resilience) but puts special emphasis on its adaptability and transformability [8,42,92]. In this sense, resilience is not seen as a static characteristic but as being subject to a dynamic process of continuous development (due to adaptation and transformation) which requires managing resilience for aspects like flexibility, anticipation (forward-looking perspective, e.g., Ref. [42]), and the enablement of social learning (e.g., Ref. [181]) - see Refs. [8,182] for illustrations of the dynamic nature of the concept. Today, engineering and social-ecological resilience are often referenced as the two central and opposing perspectives on resilience [15,16,183–185] or as the two endpoints of a spectrum of resilience interpretations [186], with the former referring to an understanding of resilience as the outcome following a disturbance (i.e., the return to an equilibrium) and the latter to a dynamic concept with the adaptive capacity as its centerpiece. While the social-ecological resilience perspective is quite popular among contemporary academic resilience definitions, practical applications often still rest upon an understanding reflecting the engineering resilience perspective [186]. *Synonym:* Adaptive resilience [183,184,187], complex adaptive systems resilience [163], socio-ecological resilience [188]
Community disaster resilience	The resilience of a community or any geographically bounded social unit (community resilience: resilience of which system), e.g., a neighborhood, city, county, region, or nation, to dangerous hazards and the corresponding disasters (disaster resilience: resilience to what), e.g., earthquakes, hurricanes, tsunamis, pandemics, or terrorist attacks [11,44,99,189]. Usually, the terms community resilience and disaster resilience are used synonymously, although they can refer to something slightly different, e.g., the disaster resilience of a particular infrastructure [88,190]. In accordance with the variability in the understanding of the resilience concept (e.g., rather complying with the engineering, ecological, or social-ecological perspective) and the diverse contexts of applications, a variety of measurement frameworks have been proposed [15,16,190,191]. An important aspect reflected in many frameworks is the understanding of resilience as a multidimensional concept [10,96,189,192]. Accordingly, its evaluation requires the incorporation of inputs from different domains and disciplines, e.g., health science, engineering, economics, and geography [193]. A particularly popular approach which allows the integration of multiple dimensions is a so-called composite indicator which combines a number of indicators which are assumed to be essential for building the required system capacities. *Synonym:* Community resilience [44], disaster resilience [193]
Resilience dimensions	Especially when applied to complex managed systems, such as critical infrastructures, cities, or communities, the concept of resilience incorporates multiple interrelated dimensions or domains which contribute to the overall resilience of the system [10,193–195]. Although the number of proposed dimensions varies [12,192,196], the most commonly applied dimensions, and the ones being considered the most essential, are still the four dimensions originally proposed in the seminal work by Bruneau and colleagues [10], i.e., the technical, organizational, social, and economic dimension (also known as the TOSE dimensions, see below).
Technical resilience	The technical dimension of resilience or the resilience of the engineered system. It refers to the resilience capacities or abilities of the physical system or the built environment [12]. *Synonym:* Technological resilience [23], infrastructure resilience [192,197]
Organizational resilience	The organizational dimension of resilience or the resilience of the owner organization of a system [23]. This includes all people involved in the management and maintenance of an organization, e.g., managers, personnel, and operators, and depends, for example, on their problem-solving mentality, training, experience, communication skills and problem-solving mentality as well as on the overall organizational culture and established management processes [194,198]. *Synonym:* Governance dimension of resilience [197]

(*continued on next page*)

(*continued*)

Term	Description
Social resilience	The social dimension of resilience or the resilience of the society in which the system exists [23]. It refers to the capabilities of social groups or communities to deal with the impacts of disruptive events [199].
Economic resilience	The economic dimension of resilience [12]. It refers to the ability of a system to minimize the financial losses associated with a disruptive event.
Hard resilience	Refers to structural, technical, mechanical, and cyber qualities and capacities of a system [200], i.e., the "hard" dimensions of resilience.
Soft resilience	Refers to resilience capacities related to community, and society, emphasizing human needs, behaviors, and relationships [200], i.e., the "soft" dimensions of resilience.
Fragility	A fragile system significantly decreases in performance when stressed beyond a certain level/threshold [201]. Fragile systems can be contrasted with robust or resilient systems, whereby consequences of disruptions are much less severe in the latter [202]. Fragility thus can be described as the lack of capacities and resources needed to provide basic functionality in the face of changes and disruptions [60,203]. In this context, it should be noted that a system's fragility generally depends on the considered stressor, i.e., a system can be robust to one set of disruptive events but fragile to another set ("robust yet fragile" [84]). Similar to the concept of resilience, the definition of fragility and its applications are still much debated [60,203].
Brittleness	Brittleness can be seen as a kind of fragility. A brittle system suddenly collapses when pushed past a threshold by disruptions [58], instead of adapting to the new circumstances, analogous to how materials under stress can experience brittle failure [59]. The term is coined and mainly used by Woods [58,59]. In the context of infrastructure resilience, it is not widely used. We searched for articles in web of science using the keywords "resilience AND brittle" and found 64 results. All but three were from the field of material science, construction mechanics, or ecology (date of search: 20.04.21, web of science). Two articles mention brittleness in the context of energy or transportation systems [204,205], but they lack a clear definition of brittleness. *Opposite*: Graceful extensibility [59]
Anti-fragility	The ability to benefit from stress, and potentially increase in performance in reaction to stress [201,202]. Anti-fragility has been proposed to be one out of a group of three possible system states, where robustness (defined as stress tolerance without decline in performance) and fragility are the other two optional system states [201]. As an example of anti-fragility, Verhulsta [206] presents the aviation industry, which is able to decrease the number of fatalities each year via analysis of and learning from past disruptions. The author contrasts this "antifragility" to "resilience", which in his definition is merely concerned with returning to the same state as before the disruption, without improvement. In contrast to graceful extensibility, anti-fragility thus describes systems which increase performance due to disruptions.
Vulnerability	Describes how much a system's performance could be reduced by a specific disruptive event, i.e., how strong the negative impacts of the disruptive event would be [24,47,63]. According to Zio [207], this "weakness" of a system comprises two aspects: (1) the susceptibility to destruction and (2) the incapacity to reestablish stable conditions. However, the definition of the term differs in other fields, e.g., in the security context, vulnerability refers to the likelihood of a negative impact of disruptive events [136], in socio-ecological systems, it describes the susceptibility to potential harm induced by changes and lack of adaptability [92], and in the field of disaster risk reduction, the term is heavily disputed [208]. While the exact relation between vulnerability and resilience is still discussed, there is consensus that resilience is one of several ways to reduce vulnerability [23,30,209]; another strategy is mitigation [30] or, more specifically, protection (one aspect of mitigation, see section 3.3).

3.3. Risk management strategies: minimizing known disruptions before they occur

These strategies aim to reduce the occurrence probability or impact of specific, known disruptions, and are thus part of the traditional risk management processes.

Term	Description
Risk management	A process that establishes, examines, weighs, and conducts plans and actions to identify and monitor hazards/threats, and to avoid them or reduce their impacts, such that the system continues to function (business continuity) [29,99]. Focus on high-risk disruptive events, such as foreseeable, single, sudden, high-probability, or high-intensity disruptions. *Includes*: Prevention, mitigation, protection, and absorptive capacity measures (see below and section 3.4; e.g., dams, floodways, early warning systems [99])
Mitigation	Reducing the risk due to future disruptions, by targeting the probability of occurrence and/or by minimizing the associated negative consequences of a disruptive event [30,210,211]. Mitigation is sometimes seen as part of resilience, e.g., Ouyang and colleagues assign mitigation to the resistant capacity [45]. We propose that based on the determinant of risk (source, exposure, vulnerability) which is targeted, three different classes of mitigation strategies can be distinguished: Prevention, avoidance, and protection (see below and Fig. 4). While we suppose that this distinction is particular helpful to classify different mitigation measures, it should be noted that often a single measure cannot exclusively be assigned to one of the three classes. *Includes*: Prevention, avoidance, protection *Synonym:* Risk reduction [24,91]
Prevention	Reducing risk by targeting the risk source (hazard/threat). In general, prevention can be achieved by manipulating the properties of the risk source (e.g., reducing the probability of severe weather events by climate mitigation), by removing it altogether, or by intercepting the pathway from the risk source towards the realization of a disruptive event [24]. The main scope of prevention is reducing the probability of the occurrence of specific disruptive events [63,107,45]. It should, however, be noted that preventive measures can also target the severity of occurring events (which would affect consequence rather than probability). Some authors use the term prevention to entitle one of the phases within the resilience cycle (e.g., Refs. [39,63]). The reasoning behind this assignment can be different. For instance, Fischer and colleagues [63] incorporate risk-based approaches in their resilience framework (their definition of prevention corresponds to what we would refer to as prevention plus avoidance). By contrast, considerations by Rehak and colleagues [212,213] express a rather different (less risk-focused) understanding of the term prevention. They argue that building resistance

(*continued on next page*)

(*continued*)

Term	Description
	is a preventive measure since it enables a system to "prevent the occurrence of a disruptive event" (i.e., "prevent" negative consequences due to an incident). While we share a similar understanding of the term resistance (we see it as a synonym for robustness, see section 3.4), we do not consider the process of building resistance as a part of prevention, but as a protective (see below) or adaptive (see section 3.6) measure which strengthens a system's absorptive capacity. *Synonym:* Hazard intervention [214] *Example:* Routine maintenance, climate mitigation (actions to reduce greenhouse gas emissions to limit global warming, climate adaptation could in contrast refer to avoidance or protection measures [101]), regulate/prohibit gun possession to prevent gun violence
Avoidance	Reducing risk by reducing the exposure to the corresponding risk source, e.g., not carrying out the process that may lead to the hazard [24, 91] or by avoiding places or areas where exposure is expected to be high [215]. While the main focus of avoidance is minimizing the potential for negative consequences due to disruptive events, it also affects the probability of incidents becoming (severe) disruptive events in the first place (there is no disruptive event without exposure). *Example:* Evacuating a building in case of a pending emergency in order to avoid human casualties, not building a facility within an earthquake- or flood-prone area, not moving to a region where drinking water is scarce, removing the risk of armed robbery by paying employees via electronic banking rather than cash [91]
Protection	Reducing risk by reducing the vulnerability of a system, i.e., reducing the impact or consequence in case of a certain exposure to a certain disruptive event (a realized threat) by adjusting system properties [107,216]. This could also mean reducing the probability that an event leads to any negative consequences (i.e., "preventing" an event/incidence from becoming a disruptive event [212]). One way of achieving protection is by preparing contingency and crisis plans which can be utilized in the event of an emergency, crisis, or disaster situation [57, 168]. Accordingly, protection provides a linkage to reactive response measures which are part of crisis or disaster management (see below). In contrast to absorption (resilience-related, see section 3.4), many protection measures are clearly targeted to specific, identified disruptions, for example elevating buildings to reduce the chance that they will be flooded or moving electrical transmission lines underground to better resist wind and ice loads [210]. Nevertheless, since protection directly targets the system or its capacities, it is the mitigation strategy which is most closely connected to resilience - it exhibits some overlap with the absorptive capacity respectively with measures for its enhancement (see below and section 4.1.3). *Example:* Building dams or walls, carrying a shield or an umbrella
Acceptance	Risks can only be mitigated up to a certain point [91] - "no matter which actions we take, risk can never be truly removed from any situation or activity" [139]. Acceptance describes the informed decision to accept the remaining or residual risk [215,216]. Accordingly, it is primarily concerned with judging identified (i.e., known) risks [24]: A risk is deemed to be either acceptable or unacceptable, in the latter case, it has to be (further) mitigated.
Crisis management	All processes which aim at repelling the emergence and reducing the impact of crises and disasters, i.e., crisis management usually involves multiple actors with different responsibilities, e.g., policy makers, risk managers, system operators, or technicians [217]. Although the scope of crisis management is sometimes focused on the crisis response [133], most definitions follow a broader understanding of crisis management which incorporates activities before, during, and after the emergence of a crisis [218–220]. These pre-crisis, during-crisis, and post-crisis phases are often further specified to highlight the different tasks which are addressed over the course of the full crisis management cycle, e.g., risk assessment, prevention, preparedness, response, recovery, and learning [221]. Traditionally, crisis management has been deeply rooted in risk management as it heavily relied on analyzing, preventing, and preparing response plans/routines and special organizations for known and/or expected situations/scenarios, i.e., this applies to rather recurrent crises, like floods, earthquakes, or partial infrastructure failures, which follow familiar patterns to a certain degree [217] or simply the most recent severe crisis [222]. However, this risk-based approach to crisis management is of limited use for informing actors on how to handle formerly unknown, unprecedented crises [222,223]. As a consequence, many authors have claimed that a holistic crisis management should incorporate both risk-based and resilience-based management approaches [57,132,217]. *Synonym:* Disaster management (we do not distinguish between crisis and disaster management as the broad understanding of crisis management involves both preventing incidents from becoming crises and crises from becoming disasters), catastrophe management

3.4. Absorptive capacity: at the beginning of a disruption

This capacity aims to limit the immediate impact of disruptive events on the system. The following table contains sub-capacities or design principles that contribute to the absorptive capacity.

Term	Description
Absorptive Capacity	The capacity of a system to reduce the initial adverse effects of and to continue to function after a disruptive event [24,224]. Absorptive capacities aim to ensure persistence of the system [36]. Absorptive capacity includes aspects that manifest automatically or with little effort [41,146,211], in contrast to restorative and adaptive capacity. In contrast to protection, absorption measures are scenario-unspecific and strengthen the general, overall ability of the system to withstand any disruptive event. Perfectly successful absorption is reflected in the performance curve by the absence of a decline [19]. *Synonym:* Static economic resilience [30], absorbability [225], capacity to absorb (in line with the consideration in Ref. [38] of "rooting resilience in action") *Associated process*: Absorption *Includes*: Robustness, redundancy, diversity, resourcefulness, situation awareness, monitoring, and modularity *Example:* Safety margin, excess, or buffer capacity [33,211], usage of back-up electricity generators, stockpiling critical materials, as well as importing goods that are in short supply within the affected region, and reserve margins [211]
Robustness	The ability of a system to withstand the immediate impact of a disruptive event. Measures to enhance robustness decrease the impact of disruptive events and are put into place prior to an event [41,43]. Robustness is one of the most frequently used terms to describe resilience capacities [23,28]. Robustness can be described by how much of its performance a system can maintain after a disruptive event [23,24,47]. Thus, the robustness against a specific disruptive event can be quantified by the minimum performance after the event [46], e.g., at least 80% of households have continued power supply after an earthquake [62], or, more generally, by the magnitude of a disruptive event divided by the magnitude of the induced initial performance loss [226].

(*continued on next page*)

(*continued*)

Term	Description
	Synonym: Resistance [20], survivability [23] *Example:* Levees that prevent damage by hurricanes to a chemical plant [41]
Redundancy	The number of alternate pathways for the system mechanics to operate [41] or how many independent parts of the system can carry out the same function and thus can replace a part that breaks down to ensure functionality of the system [227]. Redundancy increases the absorptive capacity of a system [23]. *Example:* A back-up communication system, purchasing input resources from multiple suppliers [41]
Diversity	Multiplicity of forms and behaviors [155] including variability in the response to disruptions [228]. Diversity is strongly related to redundancy but aims at avoiding correlated failure of different - possibly redundant - parts of a system [35]. Often referred to as response diversity in ecological/biological contexts [228,229] where it is sometimes seen as one aspect of functional redundancy [164,230]. Similar to redundancy, diversity is an essential design principle for developing resilient infrastructures [4]. Diversity comprises for example equipment diversity, human diversity, and software diversity [4]. *Example:* Buying components from several manufactures, usage of different protocols for the control of devices [4]
Resourcefulness	The ability of system operators to skillfully manage a disruption as it unfolds. It includes identifying problems, prioritizing what should be done, and communicating decisions to the people who will implement them [43,227]. Implementing these priorities inherently requires the availability of financial and technical resources. In contrast to robustness and redundancy, resourcefulness depends primarily on people, not technology [43]. Sometimes, resourcefulness is seen as a part of the restorative capacity [23]. In fact, if resourcefulness is high, this can increase both absorptive and restorative capacity [231]. We rather assign resourcefulness to the absorptive capacity, i.e., targeting an ongoing disruption, acting on a much shorter time scale, and implying short-term, temporary changes to the system. It should be noted that what we classify as resourcefulness is referred to as adaptive capacity or adaptability by some authors (see, e.g., Refs. [23,33,41]). In contrast, we define adaptability as the ability for a long-term adaptation, which implies implementing lasting changes in the system to prevent future negative impacts (see section 3.6). *Synonym:* Inherent resilience [30] *Example:* Good decision-making skills of the system manager, finding new substitutes for critical materials in short supply [211]
Situation awareness	"Knowing what's going on", building on perception, comprehension, and projection. Perception is the recognition of cues in the environment, comprehension means analyzing the meaning of the multiple pieces of information, and projection describes making predictions about the status in the near future [95,232]. Situation awareness increases the short-term ability to deal with acute hazards. Thus, in contrast to anticipation, situation awareness aims to identify the current situation and immediately pending events. It might be argued that situation awareness per definition is concerned with identifying specific disruptions, and thus is not a resilience capacity, but part of risk management. However, the ability to recognize that 'something is going on' and correctly assess and judge this observation's implications on the system is a resilience capacity, as it allows an entity to respond to a formerly unknown and unexpected situation and learn from this process. *Example:* Automated processes in navigation systems to avoid collisions of ships [32] *Synonym:* Situational awareness [233] (Note: We prefer the use of the term "situation awareness" to stress that it is the situation one aims to be aware of, and not something else whose perception could be affected by situational conditions)
Monitoring	Monitoring typically describes the continuous/continuing collection of data that informs of the current condition of a system [61]. For example, monitoring systems in water distribution networks regularly check water quality [234], and railway monitoring systems capture the speed, weight, acceleration, and acoustic emissions of trains [235]. Therefore, monitoring can help with the detection of hazards and handling of ongoing disruptions [235,236]. Furthermore, monitoring (or sensing) is an essential process for informing adaptive actions [38,57]. In contrast to situation awareness, monitoring is not necessarily directed outwards, but emphasizes perceiving the current status and performance of the internal processes of the system. In this sense, monitoring can also refer to the monitoring of a system's own resilience status (see resilience monitoring in section 3.7) which builds the basis for practices like operative resilience management (see section 3.7). *Synonym:* Observing, sensing [237] *Example:* Predictive maintenance strategies based on condition-based monitoring [238]
Modularity	Modularity refers to system design and describes the extent to which a system is distributed into local rather self-contained compartments or modules [157,239]. Similarly, in the context of network theory, modularity "refers to the extent to which there are subsets of densely connected nodes that are loosely connected to other subsets of nodes" [239]. A modular or compartmentalized design allows to maintain residual functionality when parts of a system fail [224] and to contain the spread of disturbances [157]. *Synonym:* Localized capacity [224] *Example:* Operating electrical distribution based on multiple microgrids [118,240], compartmentalization of forested areas due to networks of firebreaks [157,241]

3.5. *Restorative capacity: during the disruption*

This capacity becomes important once the immediate effects of a disruptive event have manifested and the system is progressing towards reverting these effects. The following table contains sub-capacities or design principles that contribute to the restorative capacity.

Term	Description
Restorative capacity	The capacity of the system to re-establish performance as quickly as possible after a disruptive event. The vast majority of resilience definitions emphasize restorative capacity as a central aspect of resilience [23]. It refers to actions that are carried out to revert the effects of the disruption, e.g., sending repair teams out, repairing components by using spare parts, ordering missing spare parts. It is enhanced by contingency plans, competent emergency operations, and the means to get the right people and resources to the right places [43]. Restorative capacity is high if performance is restored quickly and with little resources [45]. In contrast to resourcefulness which often comprises temporary measures to reduce the initial adverse effects of a

(*continued on next page*)

(*continued*)

Term	Description
	disruption, restorative capacity typically comprises lasting changes to the system. Moreover, restorative capacity always refers to resolving negative effects of a disruption which manifested in the system, whereas resourcefulness is also concerned with limiting potential secondary implications of a disruptive event and thus enabling fast recovery of performance (Note: A high resourcefulness therefore can improve a system's restorative capacity). The majority of studies define recovery as the return to a normal state of operation, as opposed to few studies which define it as the return to the original state (pre-disruption) of operation [23]. In general, we prefer the use of the notion 'normal state' or 'desired state' as it comprises the possibility of differing pre- and post-disruption performance levels (see Fig. 1). Although it should be noted that what is a normal or desired state (and what not) is system-specific and thus needs to be defined before assessments targeting the restorative capacity are carried out. *Synonym:* Rapid recovery [43], restorability [225], capacity to restore *Associated process*: Restoration, recovery, rehabilitation *Includes*: Rapidity, recoverability, graceful degradability *Example:* High number of spare parts in stock
Recoverability	Ability of a system to restore its performance and resilience capacities after a disruption [23], for example, in the case of high recoverability, 100% of the original performance are restored. *Synonym:* Repairability [224]
Rapidity	How fast a system restores its performance after a disruption. This can for example be quantified by the slope of the performance [23, 46], e.g., 10% of performance restored per day; or full restoration within 3 days after earthquake [62]. *Synonym:* Recovery slope, engineering resilience [176], resilience after Pimm [7,171] *Example:* Fast recovery due to small distance to repair team
Graceful degradability	The ability of a resilient system to decrease in performance slowly instead of abruptly, when the system capacities needed to cope with a disruption are exceeded [19]. This enables the system to temporarily operate in a safe but degraded state, and thus can help to return to normal operation after the disruption [2]. It is also defined as the ability of a system to return to an acceptable state after a disruption, as opposed to a perfectly robust system which would return to the optimum state [26]. *Synonym:* Weak robustness [26,242] *Associated process*: Graceful degradation, graceful deterioration [19] *Example:* Switch to safe operation mode during an emergency, use of adjustable speed limits on highways [38]

3.6. *Adaptive capacity: in-between disruptions*

We base our proposed distinction of resilience into three main capacities on two main arguments: (1) Each capacity should be associated with one stage within the resilience cycle in which its associated process is dominant, and (2) each capacity should have a unique effect on the system's ability to deal with disruptive events, which can be extracted from performance curves (see Discussion section 4.1.1). However, other plausible frameworks exist which organize the different capacities according to other classification criteria. The variation in interpretations is particularly high for the adaptive capacity. Some authors use the term adaptive capacity to describe temporary actions which prevent system failure [23], however, as this is mainly concerned with buffering the impacts of a present disruption, we refer to this as resourcefulness and group it under absorptive capacity (aims at keeping the initial impact low). Others note that adaptive capacities and restorative capacities work in parallel during the recovery period (e.g., visible in Fig. 1 in Ref. [50]) and can therefore only be distinguished based on the underlying mechanism (not based on information gained from analyzing the performance curve or based on the time when the associated process takes place, see Fig. 1 in this document) - with the adaptive capacity being defined as the endogenous ability of the system to adjust itself during the recovery phase and the restorative capacity as the exogenous ability to be repaired by external actions during this phase [41,46]. In our understanding, both endogenous and exogeneous ability would be included in the restorative capacity since both aim at restoring performance ("it is not straightforward to distinguish their effects on system performance" [46]). Another interpretation is that the adaptive capacity differs from other capacities in allowing a system to maintain function during particularly severe disruptive events which require adjustments to the current practices [30,211], whereby the maintenance of function can refer to both absorbing or restoring performance. Accordingly, we would assign parts of this ability to the absorptive and restorative capacity.

All of these interpretations describe the adaptive capacity as a situational skill, i.e., the ability to skillfully manage an ongoing disruption in order to minimize performance loss (what we refer to as absorptive capacity) or restore performance afterwards (what we refer to as restorative capacity). In contrast, we see the adaptive capacity as a strategic skill, which is focused on learning from past, successfully overcome disruptions (in line with definitions proposed in, e.g., Refs. [39,43]). As such, the associated process (adaption) mainly takes place in between disruptions and has no direct effect on the performance curve. Instead, the adaption takes effect in the other two resilience capacities, i.e., if being successful, it strengthens both the absorptive and restorative capacity of a system (see table below for more details).

The following table contains sub-capacities or design principles that contribute to the adaptive capacity. These capacities play out under normal operation of the system and in-between disruptions, not only during disruptions.

Term	Description
Adaptive capacity	The adaptive capacity of a system describes its ability to change itself to deal with future disruptions [39,43]. It also means implementing changes in the current practices or policies, and to learn from disruptions, e.g., through revising plans, modifying procedures, and introducing new tools, technologies, and training exercises needed to improve before the next crisis [43,56,243]. Thus, the adaptive capacity of a system is mainly determined by the social component (human actions), less by technical characteristics [176]. If adaptive capacity is high, the performance of the system might increase compared to the performance before the disruption [47], or

(*continued on next page*)

(*continued*)

Term	Description
	stay the same even though pressure on the system increases [36]. However, most importantly, as a follow-up to the disruption, the resilience itself will increase in a highly adaptive system [39]. The adaptive capacity is a uniquely powerful resilience capacity, whose impact shows in the development of the other resilience capacities, i.e., absorptive and restorative capacity. Compared to absorptive and restorative capacity, adaptive capacity is usually not focused on the current disruption but aims to increase the ability of the system to deal with future disruptions [39,43]. For instance, while the restorative capacity is concerned with re-instating a previous level of performance, and thus overcoming the effects of a current disruption (e.g., by repairing a broken component), adaptive capacity aims to increase the ability to cope with future disruptions by making changes to the current practices (e.g., by using a new material to build future components to be more robust to certain impacts). Only in the case of lasting press disturbances whose intensity is too strong to be fully absorbed, the adaptive capacity is engaged in dealing with an ongoing disruption, i.e., it enables the system to adjust to the new conditions [36]. However, in our understanding, this adjustment is mediated via the absorptive capacity: Adaption strengthens the absorptive capacity which then enables the system to absorb the impact of the press disturbance. Because of the central role the adaptive capacity plays in system resilience, some authors even see resilience as a synonym of adaptability [44]. *Synonym:* Adaption capacity, adaptability, adaptivity, re-adjust ability [243], capacity to adapt *Associated process*: Adaption, adaptation, process of learning [8] *Includes*: Anticipative capacity, capacity to prepare, flexibility, and graceful extensibility *Example:* High awareness that something might go wrong and frequent updates of emergency plans based on recent events [146]
Anticipative capacity	The ability of a system or an organization to forecast future risks [33]. In a review of more than 25 definitions of resilience, only three explicitly included the ability to anticipate disruptions [23]. In contrast to situation awareness, anticipative capacity is not concerned with the current situation and near future, but with events that happen in the medium-to-long term. Anticipation goes beyond prediction and includes analysis of the appropriate course of action in a potential future event [244]. *Associated process:* Anticipation
Capacity to prepare	The ability of a system to take appropriate measures in advance to meet potential adverse events [33]. For instance, in a critical infrastructure, an important constituent of preparedness could be an established crisis management which is flexible enough to be applicable in various different scenarios. Some authors assign preparation or planning to a separate stage of the resilience cycle, instead of including it in adaption (see Fig. 1 or Ref. [69]). We assume that both adaption and preparation take place in-between disruptions and that preparation is only one nuance of adaption. In contrast to avoidance, prevention, and protection (see section 3.3), preparation does not aim to change the risk associated with or impact of a specific disruption, but accepts the risk and strengthens the social and intellectual ability to learn from past disruptions and take appropriate actions. For illustration, consider the following simple example: On a construction site, from time to time, bricks accidently fall and cause head injuries of workers. In this case, the falling brick is the disruptive event, and resulting injury of a worker is the impact of that event. Prevention could mean to check every day whether any bricks have loosened, reducing the probability of a brick falling (i.e., reducing the probability of the event happening by targeting the risk source). Avoidance could mean using machines instead of workers in areas where bricks are particular likely to fall (i.e., reducing the exposure of workers). Protection could mean distributing helmets to the workers, thereby reducing the severity of the injury (i.e., reducing the immediate impact of the disruption). In contrast, preparation would accept that it is not completely avoidable that workers might get injured for various reasons and therefore hire a doctor to treat injuries on site, enabling the workers to quickly return to work (i.e., accepting the possibility of disruptions and their immediate effects, but preparing the system to better deal with these impacts). *Synonym:* Planning capacity *Associated process*: Preparation, planning *Example:* Fast planning processes [107], dynamic adaptive policy pathways [245], emergency drills
Flexibility	The ability of a system to cope with environmental changes [242] or changes in the acceptable level of performance [26]. Flexibility is closely related to graceful extensibility (see below) as it captures the degree to which a system can be changed and extended in comparison to its original design [26]. It entails changing the internal processes of the system. While recoverability describes the ability to return to an initial acceptable level of performance, flexibility describes the ability of the system to change its criteria of what an acceptable performance level is (see Fig. 4 in Ref. [26] for an illustration). *Synonym:* Sustained adaptability [26,58] *Example:* Adaption of a company to new limit values set by politics, or step-wise digitalization of an organization
Graceful extensibility	The ability of a system to continuously adapt to increasing stress, as opposed to a brittle system which suddenly collapses if a disruptive event leaves the range of events the system was originally designed to handle [58,59,246]. The term was coined by Woods, who describes the term as a blend of graceful degradation and software extensibility [246], with software extensibility describing a principle in software engineering where the need for future software extensions is already considered early on in the design process. Thus, graceful extensibility describes the ability of the system to shift into a new "regime of performance", i.e., transform, invoking new resources, responses, relationships, and priorities. If graceful extensibility is low, the system loses its ability to adapt to new circumstances when stress continuous to increase [246]. Woods describes graceful extensibility as one of multiple conceptual perspectives on resilience [58]. In contrast, we view graceful extensibility as one aspect of the adaptive capacity which specifically targets circumstances where challenges change and grow. The difference to the concept of antifragility is that an antifragile system would not only continue to function in reaction to stress, but even improve its performance [117]. *Opposite*: Brittleness [246] *Associated process:* Graceful extension
Transformation ability	In contrast to adaptability, which describes incremental changes, transformation ability describes the ability to undergo profound changes to the system's primary structure or functions. For example, high transformation ability could help a region move from an agrarian to a resource extraction economy [36]. In principle, transformability denotes an extreme expression of the capacity to adapt. Sustaining resilience over the long term requires the process of transformation in order to meet changing circumstances which challenge a system's adaptive capacity [38]. *Synonym:* Transformability, ability to transform *Example:* Move from fossil to renewable energy sources, e.g., in the power supply network or the road infrastructure *Associated process:* Transformation

3.7. Management processes targeting resilience

The following terms describe management strategies that are related to the goal of increasing resilience-related capacities of a system.

Term	Description
Resilience management	In contrast to traditional risk management, which hardens the system against specific, known threats [33,64], resilience management accepts that not all risks are predictable or identifiable in advance, i.e., "surprise is the new normal" [29,135] and not all risks can be avoided [33]. Therefore, emphasis lies less on prevention and solution of individual, foreseeable crises, but more on learning from and adapting to unwanted circumstances in general. Thus, resilience management is less concerned with the prevention and protection of individual risks, but aims at a holistic increase of the capacities to deal with disruptions as they emerge [70]. In this regard, resilience management is deeply interwoven with adaptive processes and should put special emphasis on sustaining the corresponding adaptive capacity. Also, resilience management explicitly includes multiple, slow-onset, low-probability, and low-intensity disruptions. The main subject of resilience management are the resilience capacities or capabilities [78]. In second instance, resilience management is a part of performance management, as the aim of resilience is to enable a system to perform well in the face of various disruptions [247]. Resilience management typically includes the quantification and evaluation of resilience, as well as the selection, prioritization, and implementation of options for improving resilience [47]. Some authors highlight that resilience management can benefit from approaches inspired by traditional risk management, such as broadly identifying, judging, and classifying potential disruptions, assessing their probabilities and the uncertainty associated with them [248]. Similarly, risk management can benefit from resilience management, e.g., measures that are taken to protect the system from unspecified disruptions (e.g., extending the security margin) will always also increase protection for some specific, known disruptions (e.g., against impacts of extreme weather).
Operational resilience management	Resilience management based on quantitative measures that capture and implement the concept of resilience [69], i.e., operationalize it or "put it into practice" [8,170,249]. Several frameworks to operationalize resilience management exist, e.g., Refs. [3,78,250]. Operationalization of resilience needs to be done in advance - before the system is damaged and undesired consequences occur [200].
Operative resilience management	Resilience management on a short time scale, i.e., "live" and under operation of the respective system [251,252]. Operative resilience management is based on continuously updated, quickly changing information. Operative resilience management can thus be seen as the opposite of strategic resilience management [253,254]. While operational resilience management emphasizes the applicability of the resilience framework, operative resilience management emphasizes the short time scale on which decisions to improve resilience capacities are made. As such, operative resilience management focuses on managing the current status of resilience capacities in one specific situation.
Strategic resilience management	Strategic management describes planning on how to reach long-term goals, in contrast to operative management which takes place on shorter time-scales [253,254]. For resilience management, this implies focusing on general resilience, i.e., the part of resilience that describes the general ability to deal with disruptions, independent of the current situation. *Synonym:* General resilience management
Resilience engineering	A kind of resilience management. The term "resilience engineering" was coined by Hollnagel, who describes it as a process that makes a system more resilient by applying four cornerstones of resilience [158]: anticipation, monitoring, responding (i.e., absorptive capacity), and learning (i.e., adaptive capacity). Resilience engineering enhances a system's ability to maintain functionality under varying conditions (including disruptions) [255]. According to Hollnagel, resilience engineering, in contrast to what he refers to as traditional safety management, not only analyzes "what went wrong" but also focuses on understanding how a system functions under normal conditions ("things that go right") [256]. Thus, following this definition, resilience engineering aims to identify technologies which support resilience, such as self-healing materials or energy-self-sufficient, automated sensor networks [29]. It should however be mentioned that the concept of resilience engineering is heavily criticized by some, e.g., that it is based on a wrong representation of what is common practice in safety management [257,258] or that it hardly represents something new when compared to the theory of high reliability organizations [259].
Resilience by design	An approach where resilience is built into the system during the design phase, e.g., by explicitly optimizing resilience design principles (see below) like diversity and cohesion [155]. The term is used mainly by practitioners. For example, the City of Los Angeles conducted a "resilience by design" program to increase seismic resilience, which enforced mandatory retrofits of pre-1980 buildings and stronger standards for newly built telecommunication towers [260]. Other examples come from the field of green engineering, which maximizes intrinsic characteristics to reduce or eliminate the potential negative effects from disruptions [261,262]. While related approaches like risk-based design [263] or safety-guided design [102] aim at mitigating known risks, resilience by design is mainly concerned with building capacities which enable the system to flexibly deal with potentially unexpected events, which includes the capacity to adapt to changing conditions and to restore performance once failure was inevitable. In contrast to resilience management, resilience by design is not a continuous, active process throughout the life cycle of a system, but it lays the foundation for it. *Synonym:* Inherent resilience [262], resilience-based design [263]
Design principles	Design principles describe potential sources of resilience and thus can help build and maintain resilience [157,224]. Well-known general design principles for resilient systems include for example diversity, redundancy, modularity, subsidiarity, buffer storages, geographical dispersion [4], cohesion [155], feedbacks, monitoring, leadership, and trust [157]. *Synonym:* Resilience principles [224]
Resilience-building system properties	Design principles are an abstract representation of potential sources of resilience [32,224]. For example, in a particular system, the general principle diversity might refer to supplier diversity, consumer diversity, energy source diversity, software diversity, employee diversity, etc. Accordingly, in order to improve the resilience of an actual system, the abstract principles need to be transferred into practical implications [32] which are associated with specific resilience-building system properties. *Synonym:* Resilience resources [118,264]

(*continued on next page*)

(*continued*)

Term	Description
Resilience monitoring	Monitoring in general means the continuous and systematic collection of data on specified indicators to track progress towards achievement objectives and use of allocated funds [61]. Data collection methods and tools may include document reviews, observations, surveys, focus group interviews, and key informant interviews [235,265]. Resilience monitoring should be used to inform management and stakeholders of the status of resilience capacities [266], based on suitable resilience indicators or indices (see section 3.8).

3.8. Resilience analysis

The following terms are frequently used in evaluation and interpretation of resilience and its effects on system performance.

Term	Description
Resilience processes	The resilience processes describe the resilient behavior of the system, which results from its resilience capacities. The resilience processes thus show how the resilience capacities are realized or "put into action" at one point in time, shaped by uncertainty, the currently present circumstances, and the recent past of the system. As such, the resilience processes should not be confounded with resilience itself, where the resilience capacities are the drivers or causes and the processes are the actions that follow from them. The quality of resilience processes can be inferred based on performance-based resilience indices, such as the area under the performance curve, the residual performance, or the disruption duration [13,37]. *Synonym:* Phenotype of resilience [37], resilience actions [38] *Example:* Absorption, restoration, adaption
Resilience cycle	Conceptual sequence of phases in the unfolding of a disruption, in which some capacities and actions are more important than others (see resilience phases in Fig. 1). Typically, it includes a preparation/prevention phase, an absorption/response phase, a recovery phase [39,47,63]. After the recovery phase, an adaption phase might take place, during which the system learns from the disruption and integrates the lessons learned, making it more resilient towards the next disruption [39]. For simplicity, the resilience cycle assumes that disruptions do not overlap, and that the main effects of a disruption on the functioning of the system accumulate in a single, concise time span. It is clear, however, that the resilience capacities can only in part be mapped to the phases. For example, learning [23] and anticipation are needed throughout the entire cycle, not only in their respective phases. *Synonym:* Crisis management cycle [221]
Performance curve	Typically refers to the curve of performance over time [231,236,267–270] or "the transient performance following a disturbance" [271]. It is often illustrated in a conceptualized, simplified manner as a typical "bathtub shape", i.e., a straight line, followed by a steep decrease, a pronounced, longer increase and return to the previous level (see Fig. 1). It further builds the basis for many quantitative infrastructure resilience analyses (see, e.g., Ref. [13]). In this context, a suitable choice of performance indicator(s) (and thus performance curves) is decisive since it heavily affects the outcome of such analyses. To avoid confusion, we advocate to use the term "performance curve" instead of the frequently used term "resilience curve", as the dependent variable is usually performance, not resilience. *Synonym:* Resilience curve [13]
Risk curve	Risk curves summarize system risk in terms of the likelihood of experiencing different levels of performance degradation in disasters as a function of that performance degradation [62].
Fragility curve	Shows the probability of failure or the probability of exceeding certain damage levels in dependence on a hazard characteristic [269,272,273]. To date, it's mostly used in the context of natural hazards [273]. *Example*: Damage probability against peak ground acceleration of earthquakes [272], failure probability of power system components as a function of wind speed or rain intensity [269] *Synonym:* Impact function, vulnerability curve [85]
Indicator	Indicators are quantitative, qualitative, or semi-quantitative measures which are used to describe a characteristic of a system, for example resilience [87], different components of risk [274,275], social vulnerability [276], or sustainability [262]. Indicators are used in decision making, in building consensus, and to explore the processes underlying certain phenomena [276].
Resilience indicator	Resilience indicators are typically derived based on interviews and estimate certain resilience capacities or constituents which are assumed to be essential within the respective context, such as top management commitment, learning culture, risk awareness, and flexibility [159,193,256,277].
Key performance indicator (KPI)	Key Performance Indicators (KPIs) measure how well a system performs or functions [89,278]. For example, the operational performance of a power grid could be measured using the KPIs "supplied customers" [48] (a measure of productivity) or the "maximum frequency deviation" [279] (a measure of power quality, see definition of "performance" in section 3.1).
Key risk indicator (KRI)	Key Risk Indicators (KRIs) estimate the possible exposure or loss, i.e., the possibility of future negative effects on the system [89]. When a KRI reaches an unacceptable value, this can be a signal that countermeasures must be taken to reduce negative impacts on the system [278]. A single indicator can serve both as a KPI and a KRI. For instance, in a power grid, the "maximum frequency deviation" not only measures power quality but, if it crosses a certain threshold, also initiates counteracting measures like load shedding or the disconnection of generators [279,280].
Index	An index aggregates several indicators, to summarize a complex phenomenon [276,281]. To this end, indices usually put several measures in relation to each other, often by using ratios. For example, in economics, an index usually relates a price or quantity to a reference standard. The choice of the aggregation model strongly impacts the robustness and reliability of an index [276], as well as the conclusions that are gained applying it [282]. *Synonym:* Composite indicator [276]
Resilience index	Resilience indices combine several measures to estimate the resilience of a certain system. For example, the resilience index by Argyroudis and colleagues integrates information on the robustness and rapidity of assets for multiple hazards, depending on impact, fragility, and occurrence time [231]. The resilience index by Eldosouky and colleagues relates the resilience of a system to its maximum resilience, by estimating the probability that the system is able to transition from a critical back to a functioning

(*continued on next page*)

(*continued*)

Term	Description
	state [283]. A large variety of resilience indices describe resilience based on properties of the performance curve (see, for example, Refs. [10,30,33]). An alternative to performance- or outcome-based approaches (e.g., approaches using the performance curve) is to estimate resilience based on system characteristics which are assumed to build resilience (see, e.g., Refs. [15,193]), i.e., corresponding approaches do not rely on the occurrence of a disruptive event but focus on the system's potential to deal with potential events. Most common within the diverse family of corresponding approaches (see, e.g., Refs. [12,15,196,282] for some extensive reviews) are resilience composite indicator frameworks which integrate measurable information from various sources (e.g., survey data, demographic data, expert opinion) and aggregate/combine them, often following a specific conceptual hierarchy (see, e.g., Refs. [49,277,284]), to obtain indices displaying the resilience of a system based on different, e.g., variables [39], themes [209], system functions [126], and/or phases of the resilience cycle [49].

4. Discussion and conclusion

As we have highlighted throughout this document, the term resilience "is used in different ways by different people" [285] - i.e., there are different understandings, "meanings" [286], "conceptual perspectives" [58], "interpretations" [287], "types" [288], or "manifestations of resilience" [289]. The reason for the persistent coexistence of different resilience understandings is manifold but can be attributed to three main causes: (1) the history of the concept, (2) the variety of applications, and (3) the preferred degree of specificity. First (1), resilience is rooted in multiple distinct fields, such as psychology, engineering, and ecology [5] and has followed different "developing traditions of resilience theorizing" [290]. Therefore, individual understandings of resilience can differ on account of "how the term emerged" [290] in the respective field or community. Second (2), the application context affects which perspective from the "family of related ideas" [291] will be most suitable to approach the resilience analysis and thus will also shape the preferred resilience definition. Accordingly, whether resilience will be seen as robustness, as rebounding, as graceful extensibility, or as sustained adaptability [58], or a combination thereof, depends on the system under examination, the function this system serves, the stressors which threaten its function, the actors which influence the system, and the response options these actors have [161,292]. Third (3), there are different opinions on the aspired specificity of the resilience concept or on "whether a narrow or a broad definition of the term 'resilience' is preferable" [161]. Much of this dispute centers around the question whether the ambiguity of resilience is something which should be overcome in favor of creating a more specific and practical concept ("the definition of resilience has become so broad as to render it almost meaningless" [293]), or whether it is something which should be embraced in order to foster interdisciplinary exchange (resilience as "a boundary object or a bridging concept" [294]) and "methodological pluralism" [295]. Resilience definitions of the latter type often incorporate multiple aspects and allow for adaptation to different circumstances or application contexts [285].

The present glossary represents an integrated terminology of resilience-related terms in the context of critical infrastructures. Since the exact meaning of many of the included terms is disputable, the compilation of a clear and consistent set of terms required some critical choices regarding the conceptual strands we follow. This selection process was inevitably shaped by our aim of targeting critical infrastructures. Regarding its specificity, our understanding of resilience falls somewhere in between a specific and a broad definition. On the one hand, it needed to be specific enough to build the conceptual basis for applying resilience in practice, i.e., it should communicate a clear and consistent understanding of the resilience concept (what is its scope and where are its boundaries) and include clear definitions of terms which provide guidance when operationalizing the concept (e.g., when assessing, building or managing resilience). On the other hand, it needed to be broad enough to cover the variety of different contexts in which infrastructure resilience is applicable. The class of critical infrastructures comprises a variety of highly complex socio-technical systems which incorporate technical, social, economic and, organizational dimensions. Furthermore, infrastructures face a diversity of disruptive events of different origin (e.g., natural or human-caused) and form (e.g., pulse or slow-onset press disturbances). Accordingly, infrastructure resilience can strongly benefit from interdisciplinary approaches and methodological openness. We therefore aimed for a description of resilience which is as inclusive as possible and as specific as necessary, i.e., it incorporates clear definitions of many different aspects we consider important for infrastructure resilience. In order to clarify some of the choices we made to create a consistent and inclusive glossary, we conclude this document with discussing what is its centerpiece - our understanding of resilience.

4.1. Our understanding of resilience (why capacities?)

Our understanding of resilience combines aspects of the three arguably most fundamental and influential perspectives on resilience, namely, engineering resilience, ecological resilience, and social-ecological resilience (see section 3.2). First of all, the presented framework promotes the use of performance curves for assessing resilience (see section 4.1.1), which is rooted in the engineering resilience perspective (see, e.g., Refs. [15,296]). An underlying assumption is that a system has a clearly definable desired state of performance, which it can leave and return to over the course of a disruption. This fits very well as our framework is intended to be applicable to critical infrastructures which, in their very essence [168], provide essential services to the public, i.e., the desired state can be defined as the state of maintained service.

The intended use of performance curves should, however, not be mistaken with the assumption that resilience can be extracted from a single performance curve, i.e., resilience is not the area under the performance curve, neither is it the minimum performance level and/or the slope of the recovery curve (see also Ref. [186] which points to the discrepancy between the most-common definitions and the use of resilience in practice). What can be seen in a performance curve is the outcome of the interplay between a disruptive event and the initiated system response which is shaped by the three resilience processes (absorption, restoration, and adaption). A resilience process does, however, only depict one manifestation of an underlying ability or capacity of the system - resilience itself, on the other hand, is this very capacity (or set of capacities) that enables the system to respond in a preferable way. This notion of resilience as the ability or capacity of a system is rooted in the ecological resilience perspective [6,176].

The incorporation of the adaptive capacity as one of three main constituents of resilience adds the social-ecological perspective to the framework [8,42,92]. This addition emphasizes that resilience is not a static trait but subject to permanent development. Accordingly, an effective manipulation of resilience also requires an understanding of how the modification of system attributes might affect the system's potential for further development - in addition to an understanding of how such changes would affect the current system dynamics. Overall, our understanding of resilience as the ability of a system which is comprised of a set of three capacities has important implications for how we imagine resilience can best be assessed (see the upcoming section 4.1.1), how resilience can be built into a system (see the upcoming section 4.1.2), and how resilience - and not risk - can be managed (see the upcoming section 4.1.3).

4.1.1. Why three capacities? (The role of performance curves)

The understanding of resilience as a set of a few essential pillar capacities is in line with the work by many other authors [33,39]. However, the naming and classification deviates from other frameworks which define their pillar capacities based on a different distinction criterion [10,20,36]. For instance, Béné and colleagues [36] distinguish three capacities - absorptive, adaptive, and transformative capacity - based on the level of change to the system which is required to respond to disruptive events of various intensities. Other frameworks, such as the ones presented in Refs. [21,33,41], use the same naming as we do, but describe a fundamentally different understanding of the adaptive capacity (see section 3.6). Some frameworks largely match our distinction, both in naming and meaning, but include an additional capacity [29,43], e.g., one which considers a system's ability to prepare or plan [29] or a system's resourcefulness [43] - both of which we consider to be sub-aspects of one of the three fundamental pillar capacities (see section 3.6 and 3.4).

So why do we choose this particular set of capacities? In principle, our three main capacities are chosen in a way that should ultimately enable us to verify the benefit and efficiency of implied resilience-enhancing measures. We therefore consider two requirements [10]: Firstly, the set of capacities should represent the ultimate goal of all resilience-enhancing measures (requirement I: goal-oriented approach) and, secondly, the choice of pillar capacities should facilitate measuring resilience (requirement II: measurability). In order to meet the first requirement, our capacities need to cover the entire scope of resilience, i.e., all aspects which distinguish a resilient from a less resilient system. We accomplish this by considering two capacities which cover the two essential aspects of coping with an emerging or ongoing disruption (and which are involved in most resilience frameworks) and complement them with a third more strategic capacity which puts special emphasis on the need for considering long-term development, change, and flexibility. The resulting set of capacities consists of (1) the capacity to keep the initial impact of an unspecific disruptive event as small as possible (absorptive capacity), (2) the capacity to recover fast and as completely as possible from disruptions (restorative capacity), and (3) the capacity to learn from disruptions and implement corresponding changes to the system and thus reduce the impact of future disruptive events (adaptive capacity). It should be noted that this set of multi-dimensional pillar capacities (each capacity includes multiple aspects) incorporates all essential aspects of the four conceptually different understandings of the term "resilience" outlined by Woods [58], which are *resilience as rebound*, *resilience as robustness*, *resilience as graceful extensibility* and

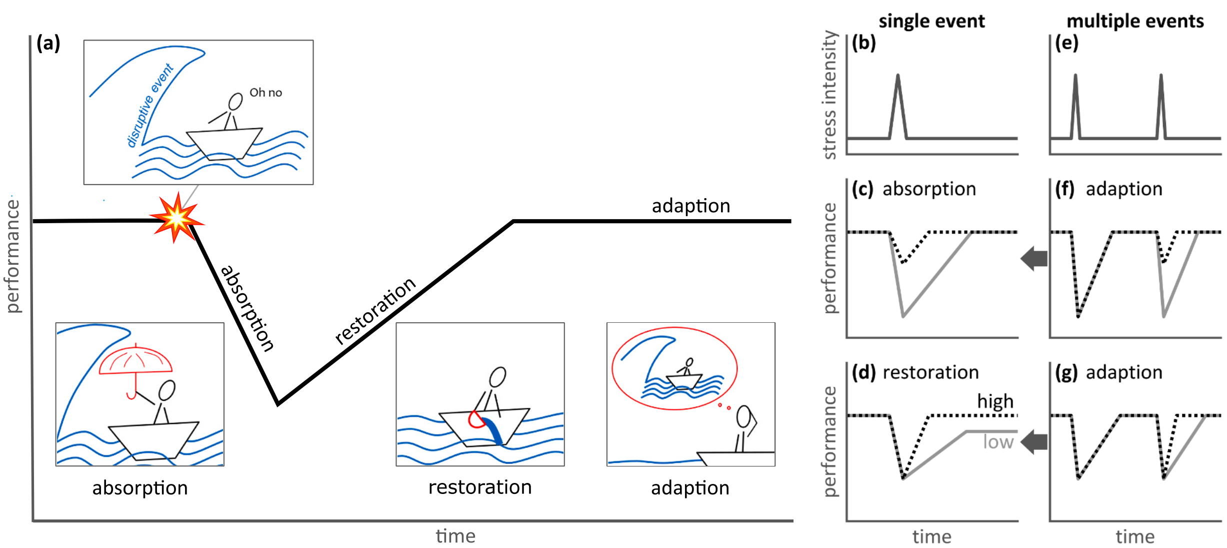


Fig. 2. Effect of the three essential resilience processes. (a) Visual representation of each process based on one exemplary disruptive event. For illustrative purposes it is helpful that each process can be associated with one stage within the resilience cycle - although in reality the different stages are likely to overlap in time. (b–g) Effect of the three processes on system performance. The effect is depicted in the case of a single disruptive event for absorption and restoration (b–d), and multiple disruptive events for adaption (e–g), in each case for a system with a higher (black dashed line) and a lower capacity (gray solid line).

resilience as sustained adaptability.

Furthermore, the three main capacities fulfil our second requirement, i.e., they build the basis for measuring resilience. In this regard, our main consideration was that, in order to assess all three capacities, each of them should be associated with a unique and distinguishable process which is involved in dealing with a disruptive event (see Fig. 2a). The improvement of each process should further have a clear imprint on performance curves (see right side of Fig. 2), e.g., if one of two systems is able to better absorb the same disruptive event, this should show in characteristic differences between the two corresponding performance curves. For absorption and restoration, some of the sub-aspects we assigned to the corresponding capacity (robustness in section 3.4, recoverability and rapidity in section 3.5) describe how an enhancement would affect the performance curve in the case of a single disruptive event: A better absorption leads to a smaller initial impact (robustness) and thus to higher minimal performance level (Fig. 2c); a better restoration increases the magnitude (recoverability) and rate (rapidity) of performance increase after a disruptive event (Fig. 2d). For adaption, the situation is less clear. In the literature, the net gain in performance over one resilience cycle (increase in performance relative to the performance level before the disruption) is sometimes considered a measure of adaption (see, e.g., Refs. [47,49,50]). We refuse this notion as we consider the optimization of system performance under normal or stress-free conditions as out of the scope of resilience (a net performance gain could nevertheless be an indication for the occurrence of adaption). In our understanding, adaption means learning to better deal with future disruptive events. We propose that this learning process can best be depicted as a change in the other two capacities, i.e., the adaptive capacity is a system's ability to adapt its two coping capacities (absorptive and restorative capacity). Accordingly, the impact of an enhanced adaption is not directly visible in a single resilience cycle but only shows in the longer-term development of the other two capacities and their associated processes, i.e., in an enhanced absorption or restoration in a future disruption (Fig. 2fg).

4.1.2. How to build resilience? (The role of principles)

The use of the three proposed pillar capacities facilitates the assessment of resilience based on performance curves. However, we emphasize here that the regulating screws, which need to be manipulated in order to boost resilience, are the properties of the managed system (the resilience-building system properties). Design or resilience principles (see section 3.7) can provide guidance for choosing appropriate resilience-building measures. We included the principles we believe to be of particular importance in the glossary. Some of them rather refer to "ends" [10] which describe what a resilient design should accomplish (e.g., robustness, rapidity, anticipative capacity) and some of them rather to "means" which describe how to accomplish these goals (e.g., redundancy, diversity, flexibility). However, all of them help to depict what makes a system resilient: The things a resilient system should have (resilience requires resources) and the processes it should perform (resilience requires actions [38]).

In the literature, design or resilience-building principles are often categorized into few distinct groups, in accordance with the capacity or the higher-level goal they promote [39,224]. We followed this approach and assigned each principle as a subcategory to one of three pillar capacities (see sections 3.4-3.6). However, this assignment is not entirely unambiguous. In fact, that a specific design principle concerns only one of the three capacities is rather the exception than the norm. For instance, a modular design might at first hinder the propagation of an initial harmful impact within a system and thus enhance absorption, but subsequently it can also promote building up the prior performance level - e.g., operating energy distribution grids within multiple smaller balancing areas (microgrids) allows an islanded operation during emergencies, which ultimately can also shorten restoration times [269]. We assume that the same holds true for most resilience-building principles and thus that most principles have several cause-effect-pathways (see Fig. 3 for our suggestion); although the actual relations will ultimately depend on the specifics of the system of interest.

In the actual implementation of resilience principles inter-dependencies can arise (see also Ref. [224]). In the example mentioned above, for instance, a modular design is a necessary condition for an islanded operation of the power grid which allows system operators to switch operation modes - from a global to a local balance between power supply and demand - in case of an emergency. The availability of multiple operation modes ultimately raises the number of options to skillfully handle a disruption. Accordingly, the improvement of modularity allows improving diversity and resourcefulness. Such dependencies are likely to occur since more technical principles, like redundancy or monitoring, can often build the foundation for more organizational principles, like resourcefulness

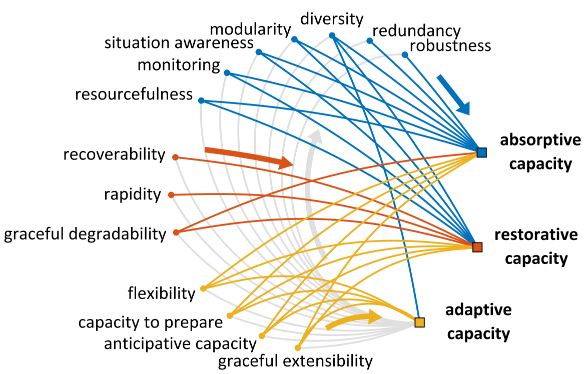


Fig. 3. Connection between resilience principles and the three resilience capacities. The colored edges denote which principle is assumed to affect which capacity. Gray edges in the background indicate that the adaptive capacity can take effect by altering any resilience-building system property.

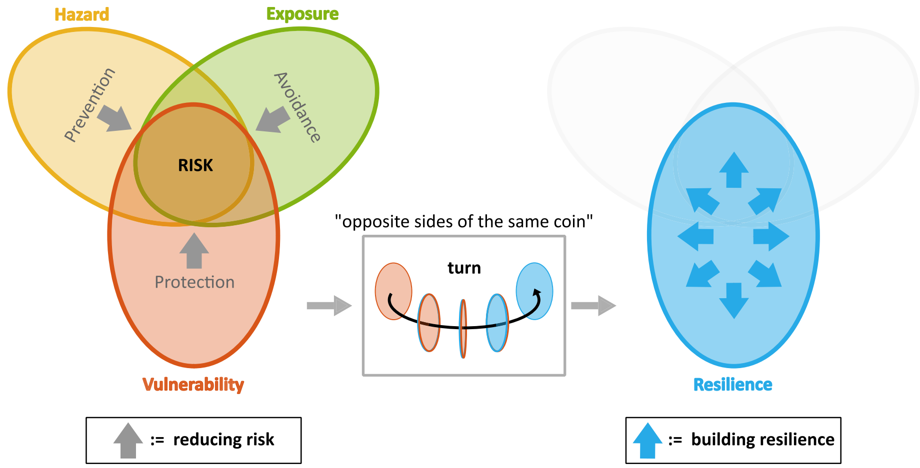


Fig. 4. Difference and overlap between reducing risk and building resilience. Each risk reducing strategies - prevention, avoidance, and protection (depicted by gray arrows) - aims at one of the three risk determinants at the point of expected risk, i.e., where hazard, exposure, and vulnerability are anticipated to come together. Building resilience shows some overlap with protection since the two measures act on "opposite sides of the same coin" [101], i.e., both concern capacities of the system. However, building resilience is independent from any expected risk and thus corresponding measures target the entirety of resilience capacities (depicted by blue arrows pointing at no particular direction). Illustration on the left side is based on Ref. [137]. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

and situation awareness. In fact, in order to build resilience, it is often not enough to add certain resources to a system since being resilient also requires the capacity to use these resources [38]. Furthermore, the interrelation between different principles can also involve trade-offs. For instance, building underground instead of overhead power transmission lines might improve the robustness of a power grid but, if damaged, also hampers its repairability [269]. In the end, we cannot expect simple cause-effect relationships between system design and system resilience - especially in complex dynamical systems such as critical infrastructures [84]. Therefore, building resilience always requires a holistic view on the entire system, otherwise one could overlook important trade-offs, dependencies, or synergies between different design objectives.

4.1.3. Where does it end? (The difference between building resilience and reducing risk)

To highlight the boundaries of the resilience concept and the scope of corresponding management efforts, it is helpful to consider the difference between approaches which aim for reducing risk and those which aim for building resilience. While answers to the question regarding the difference and relation between the two approaches heavily depend on the consulted author (see section 2.4), an important and widely accepted distinction criterion is the uncertainty or "knowability" associated with the events the two approaches aim to prepare for: While risk approaches help preparing for events which fall into a spectrum of known or familiar patterns, resilience approaches aim at enabling a system to effectively respond to any event, including those which are unexpected and unique [57,217]. In fact, it is the growing awareness of the latter class of events which caused the rising popularity of "resilience thinking" in critical infrastructure policies [168,297,298].

The difference in the targeted events has implications for the nature of strategies which can be followed to build resilience. We have proposed that mitigation or risk reducing strategies can be categorized based on the risk determinant they aim at (see section 3.3): Prevention aims at reducing the probability of severe hazards or threats, avoidance targets the exposure to these risk sources, and protection intends to reduce the vulnerability of the system (see left side of Fig. 4). Two of these three strategies, prevention and avoidance, are out of the scope of valid resilience-enhancing measures (see right side of Fig. 4) as they apply only to formerly known hazards or threats (see also Ref. [217]), i.e., prevention and avoidance are clearly and exclusively risk-based.

In contrast, the third risk-reducing strategy - protection - shows some overlap with approaches for enhancing resilience: Both aim to decrease the impact of disruptive events by implementing changes which strengthen system capacities, protection from the risk perspective (targeting the vulnerability against specific events), resilience enhancement from the resilience perspective (targeting the capacity to cope with any event) - we therefore depicted the two as acting on "opposite sides of the same coin" [101]. Resilience-enhancing measures that are taken to protect the system from unspecified disruptions (e.g., extending the security margin) will always also increase protection against some specific, known disruptions (e.g., against impacts of extreme weather) - i.e., improving resilience can be considered a valid risk-reducing strategy (as done, e.g., in Refs. [214,299]). In the same manner, it is reasonable to assume that protection measures which are taken with regard to specific threats, such as setting up disaster response plans or undertaking training for specific disaster scenarios, generally strengthens a system's ability to deal with unanticipated disruptions. Ultimately, the effectiveness of the two proactive measures will cumulate in the system's response to an emerging disruptive event. Nevertheless, the conceptual difference between the two opposing perspectives is reflected in a distinct methodological approach. As part of risk management, protection presents one mitigation option for meeting risks which are considered unacceptable (the other two options being prevention and avoidance). Accordingly, it will be incorporated in the process of weighing and prioritizing different risks, deciding which of the identified risks poses the greatest threat, what are their likelihoods of occurrence, and what are the most efficient ways to mitigate the most pending ones. Resilience management, on the other hand, is not concerned with treating specific risks, but with maintaining and enhancing the resilience capacities, i.e., the ability of the system to absorb, recover, and adapt to any type of stress under any circumstance. Enhancing resilience is thus the more holistic and system-centered approach to building system capacities, which includes a system's long-term development and its ability to improve itself (explicitly included due to the adaptive capacity). We therefore depicted resilience enhancement as pertaining the complete coin representing resilience, while protection only concerns the part of vulnerability which overlaps with the anticipated threat and exposure (see Fig. 4).

In the end, reducing risk and building resilience are conceptually distinct tasks which differ in scope and focus, but both share the common goal of keeping the negative impacts of disruptive events as mild as possible. Therefore, we strongly believe that the best way to go when aiming for safe and secure infrastructures is an R^2 approach which involves both efforts to reduce risk and efforts to build resilience (R^2 equals reducing risk times building resilience): Prevent and/or avoid known threats where possible (with reasonable effort), protect the system against the remaining risk, and build resilience in order to be prepared for unexpected or unpredicted events (prediction will inevitably fail sometimes). Such a holistic approach will be capable of dealing with both the known and unknown [57], and will target both the reduction of the probability of occurrence of events and the capability to deal with these events should they arise [300].

4.2. Conclusion (what is it good for?)

It has been argued that science "largely depends upon clear and commonly agreed upon definitions of concepts, and well-defined parameters" [301]. While we strongly support the use of clear definitions and the communication thereof, we are also aware that the field of resilience research is way too diverse and divided to be summarized in a unified glossary that pleases everyone. Instead, the goal of this glossary is to present an integrated and consistent terminology which displays one possible perspective on resilience - resilience from a viewpoint we believe is particularly helpful when striving for an operational and operative treatment of the resilience of critical infrastructures. In this regard, it can serve as an introduction for scholars which are new to the field and as a source for scholars sharing a similar scope in their work. By focusing on one specific perspective, this glossary can create a firm conceptual basis for transferring resilience from theory to practice, e.g., when figuring out how to measure, build, or manage resilience.

While we focus on presenting one perspective on resilience, we also paid tribute to the diversity and ambiguity surrounding the concept by drawing from a diverse pool of ideas developed in different disciplines, integrating different views where possible, and referring to adjoining or contesting views where necessary. In this way, we created entry points for scholars with a different understanding and/or background. Such entry points allow scholars to align the presented definitions with their own understanding and, if they disagree with part of the glossary, to easily adapt it to their needs. The background is that we intend to avoid depriving the resilience concept from being malleable, since its malleability makes much of the concept's appeal within and across disciplinary boundaries [286,302], which ultimately provides opportunities for transdisciplinary exchange and cooperation [287]. In the end, by focusing on one perspective while appreciating the diversity surrounding the concept, this glossary provides orientation in the sometimes confusing field of resilience terminology, it builds the conceptual basis for resilience applications, and it invites a wide group of people into using, discussing, adapting, and further developing the presented ideas.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgements

We thank the members of the department for resilience and risk methodology for their valuable input and the insightful discussions; Walaa Bashary, Jens Kahlen, Alexander Khanin, Ingo Schönwandt, and Dustin Witte. Furthermore, we thank Tobias Koch and Kostyantin Konstantynovski for their useful comments regarding an earlier version of this manuscript. Finally, we thank three anonymous reviewers for their constructive comments and suggestions.

References

[1] L.K. Comfort, A. Boin, C.C. Demchak, Designing Resilience: Preparing for Extreme Events, University of Pittsburgh Pre, 2010. https://books.google.de/books?id=ZN4LLw6YcmEC.
[2] Z. Bie, Y. Lin, G. Li, F. Li, Battling the extreme: a study on the power system resilience, Proc. IEEE 105 (7) (2017) 1253–1266, https://doi.org/10.1109/JPROC.2017.2679040.
[3] R.A. Caralli, J.H. Allen, P.D. Curtis, D.W. White, L.R. Young, Improving Operational Resilience Processes: the Cert Resilience Management Model, IEEE, 2010.
[4] P. Thier, C. Pot d'Or, Contribution of diversity to the resilience of energy systems - A literature review, in: Proceedings of the 30th European Safety and Reliability Conference and the 15th Probabilistic Safety Assessment and Management Conference, 2020.
[5] D.E. Alexander, Resilience and disaster risk reduction: an etymological journey, Nat. Hazards Earth Syst. Sci. 13 (11) (2013) 2707–2716, https://doi.org/10.5194/nhess-13-2707-2013.
[6] C.S. Holling, Resilience and stability of ecological systems, Annu. Rev. Ecol. Systemat. 4 (1) (1973) 1–23, https://doi.org/10.1146/annurev.es.04.110173.000245.
[7] S.L. Pimm, The complexity and stability of ecosystems, Nature 307 (5949) (1984) 321–326, https://doi.org/10.1038/307321a0.

[8] S. Carpenter, B. Walker, J.M. Anderies, N. Abel, From metaphor to measurement: resilience of what to what? Ecosystems 4 (8) (2001) 765–781, https://doi.org/10.1007/s10021-001-0045-9.
[9] W.N. Adger, T.P. Hughes, C. Folke, S.R. Carpenter, J. Rockström, Social-ecological resilience to coastal disasters, Science 309 (5737) (2005) 1036–1039, https://doi.org/10.1126/science.1112122.
[10] M. Bruneau, S.E. Chang, R.T. Eguchi, G.C. Lee, T.D. O'Rourke, A.M. Reinhorn, M. Shinozuka, K. Tierney, W.A. Wallace, D. von Winterfeldt, A framework to quantitatively assess and enhance the seismic resilience of communities, Earthq. Spectra 19 (4) (2003) 733–752, https://doi.org/10.1193/1.1623497.
[11] S.L. Cutter, L. Barnes, M. Berry, C. Burton, E. Evans, E. Tate, J. Webb, A place-based model for understanding community resilience to natural disasters, Global Environ. Change 18 (4) (2008) 598–606, https://doi.org/10.1016/j.gloenvcha.2008.07.013.
[12] D. Guo, M. Shan, E.K. Owusu, Resilience assessment frameworks of critical infrastructures: state-of-the-art review, Buildings 11 (10) (2021) 464, https://doi.org/10.3390/buildings11100464.
[13] C. Poulin, M.B. Kane, Infrastructure resilience curves: performance measures and summary metrics, Reliab. Eng. Syst. Saf. 216 (2021), 107926, https://doi.org/10.1016/j.ress.2021.107926.
[14] X. Xue, L. Wang, Liang, R.J. Yang, Exploring the science of resilience: critical review and bibliometric analysis, Nat. Hazards 90 (1) (2018) 477–510, https://doi.org/10.1007/s11069-017-3040-y.
[15] A. Asadzadeh, T. Kötter, P. Salehi, J. Birkmann, Operationalizing a concept: the systematic review of composite indicator building for measuring community disaster resilience, Int. J. Disaster Risk Reduc. 25 (2017) 147–162, https://doi.org/10.1016/j.ijdrr.2017.09.015.
[16] K. Rus, V. Kilar, D. Koren, Resilience assessment of complex urban systems to natural disasters: a new literature review, Int. J. Disaster Risk Reduc. 31 (2018) 311–330, https://doi.org/10.1016/j.ijdrr.2018.05.015.
[17] M. Ouyang, L. Dueñas-Osorio, Multi-dimensional hurricane resilience assessment of electric power systems, Struct. Saf. 48 (2014) 15–24, https://doi.org/10.1016/j.strusafe.2014.01.001.
[18] A. Brown, A. Dayal, C. Del Rumbaitis Rio, From practice to theory: emerging lessons from Asia for building urban climate change resilience, Environ. Urbanization 24 (2) (2012) 531–556, https://doi.org/10.1177/0956247812456490.
[19] M. Wied, J. Oehmen, T. Welo, Conceptualizing resilience in engineering systems: an analysis of the literature, Syst. Eng. 23 (1) (2020) 3–13, https://doi.org/10.1002/sys.21491.
[20] J.L. Carlson, R.A. Haffenden, G.W. Bassett, W.A. Buehring, M.J. Collins III, S.M. Folga, F.D. Petit, J.A. Phillips, D.R. Verner, R.G. Whitfield, Resilience: Theory and Application: ANL/DIS-12-1, 2012, https://doi.org/10.2172/1044521.
[21] B. Biringer, E. Vugrin, D. Warren. Critical Infrastructure System Security and Resiliency, CRC Press, 2013, https://doi.org/10.1201/b14566.
[22] S.H. Jore, Is resilience a good concept in terrorism research? A conceptual adequacy analysis of terrorism resilience, Stud. Conflict Terrorism 0 (0) (2020) 1–20, https://doi.org/10.1080/1057610X.2020.1738681.
[23] A. Mottahedi, F. Sereshki, M. Ataei, A. Nouri Qarahasanlou, A. Barabadi, The resilience of critical infrastructure systems: a systematic literature review, Energies 14 (6) (2021) 1571, https://doi.org/10.3390/en14061571.
[24] T. Aven, Y. Ben-Haim, H.B. Andersen, T. Cox, E.L. Droguett, M. Greenberg, S. Guikema, W. Kröger, O. Renn, K.M. Thompson, E. Zio, Society for Risk Analysis Glossary, 2018.
[25] DRI, DRI International Glossary for Resilience, Disaster Recovery Institute International, 2021. https://drii.org/resources/viewglossary.
[26] J. Andersson, V. Grassi, R. Mirandola, D. Perez-Palacin, A Conceptual Framework for Resilience: Fundamental Definitions, Strategies and Metrics. *Computing*, Advance online publication, 2020, https://doi.org/10.1007/s00607-020-00874-x.
[27] Resilience Alliance, Glossary. https://www.resalliance.org/glossary, 2021.
[28] T.J. Nipa, S. Kermanshachi, A. Pamidimukkala, Identification of resilience dimensions in critical transportation infrastructure networks, J. Leg. Aff. Dispute Resolut. Eng. Constr. 15 (2) (2023), https://doi.org/10.1061/jladah.ladr-870.
[29] I. Linkov, T. Bridges, F. Creutzig, J. Decker, C. Fox-Lent, W. Kröger, J.H. Lambert, A. Levermann, B. Montreuil, J. Nathwani, R. Nyer, O. Renn, B. Scharte, A. Scheffler, M. Schreurs, T. Thiel-Clemen, Changing the resilience paradigm, Nat. Clim. Change 4 (6) (2014) 407–409, https://doi.org/10.1038/nclimate2227.
[30] A. Rose, Economic resilience to natural and man-made disasters: multidisciplinary origins and contextual dimensions, Environ. Hazards 7 (4) (2007) 383–398, https://doi.org/10.1016/j.envhaz.2007.10.001.
[31] B. Cai, M. Xie, Y. Liu, Yonghong, Y. Liu, Yiliu, Q. Feng, Availability-based engineering resilience metric and its corresponding evaluation methodology, Reliab. Eng. Syst. Saf. 172 (2018) 216–224, https://doi.org/10.1016/j.ress.2017.12.021.
[32] E. Engler, M. Baldauf, P. Banys, F. Heymann, M. Gucma, F. Sill Torres, Situation assessment—an essential functionality for resilient navigation systems, J. Mar. Sci. Eng. 8 (1) (2020) 17, https://doi.org/10.3390/jmse8010017.
[33] R. Francis, B. Bekera, A metric and frameworks for resilience analysis of engineered and infrastructure systems, Reliab. Eng. Syst. Saf. 121 (2014) 90–103, https://doi.org/10.1016/j.ress.2013.07.004.
[34] M. Ouyang, Z. Wang, Resilience assessment of interdependent infrastructure systems: with a focus on joint restoration modeling and analysis, Reliab. Eng. Syst. Saf. 141 (2015) 74–82, https://doi.org/10.1016/j.ress.2015.03.011.
[35] J.P.G. Sterbenz, D. Hutchison, E.K. Çetinkaya, A. Jabbar, J.P. Rohrer, M. Schöller, P. Smith, Resilience and survivability in communication networks: strategies, principles, and survey of disciplines, Comput. Network. 54 (8) (2010) 1245–1265, https://doi.org/10.1016/j.comnet.2010.03.005.
[36] C. Béné, R.G. Wood, A. Newsham, M. Davies, Resilience: new utopia or new tyranny? Reflection about the potentials and limits of the concept of resilience in relation to vulnerability reduction programmes, 2012, IDS Working Papers (405) (2012) 1–61, https://doi.org/10.1111/j.2040-0209.2012.00405.x.
[37] T. Kanno, S. Koike, T. Suzuki, K. Furuta, Human-centered modeling framework of multiple interdependency in urban systems for simulation of post-disaster recovery processes, Cognit. Technol. Work 21 (2) (2019) 301–316, https://doi.org/10.1007/s10111-018-0510-2.
[38] T.P. Seager, P. Thomas, S.S. Clark, D.A. Eisenberg, J.E. Thomas, M.M. Hinrichs, R. Kofron, C.N. Jensen, L.R. McBurnett, M. Snell, D.L. Alderson, Redesigning resilient infrastructure research, in: I. Linkov, J.M. Palma-Oliveira (Eds.), NATO Science for Peace and Security Series C: Environmental Security, Resilience and Risk, Springer Netherlands, 2017, pp. 81–119, https://doi.org/10.1007/978-94-024-1123-2_3.
[39] D. Rehak, P. Senovsky, M. Hromada, T. Lovecek, Complex approach to assessing resilience of critical infrastructure elements, International Journal of Critical Infrastructure Protection 25 (2019) 125–138, https://doi.org/10.1016/j.ijcip.2019.03.003.
[40] H.-N.L. Teodorescu, Defining resilience using probabilistic event trees 35 (2) (2015) 279–290, https://doi.org/10.1007/s10669-015-9550-9.
[41] E.D. Vugrin, D.E. Warren, M.A. Ehlen, A resilience assessment framework for infrastructure and economic systems: quantitative and qualitative resilience analysis of petrochemical supply chains to a hurricane, Process Saf. Prog. 30 (3) (2011) 280–290, https://doi.org/10.1002/prs.10437.
[42] C. Folke, Resilience (republished), Ecol. Soc. 21 (4421) (2016), https://doi.org/10.5751/ES-09088-210444.
[43] NIAC, A Framework for Establishing Critical Infrastructure Resilience Goals Report: Final Report and Recommendations by the, National Infrastructure Advisory Council, 2010.
[44] F.H. Norris, S.P. Stevens, B. Pfefferbaum, K.F. Wyche, R.L. Pfefferbaum, Community resilience as a metaphor, theory, set of capacities, and strategy for disaster readiness, Am. J. Community Psychol. 41 (1) (2008) 127–150, https://doi.org/10.1007/s10464-007-9156-6.
[45] M. Ouyang, L. Dueñas-Osorio, X. Min, A three-stage resilience analysis framework for urban infrastructure systems, Structural Safety 36–37 (2012) 23–31, https://doi.org/10.1016/j.strusafe.2011.12.004.
[46] C. Nan, G. Sansavini, W. Kröger, H.R. Heinimann, A Quantitative Method for Assessing the Resilience of Infrastructure Systems, vol. 12, PSAM 2014 - Probabilistic Safety Assessment and Management, 2014.
[47] I. Häring, G. Sansavini, E. Bellini, N. Martyn, T. Kovalenko, M. Kitsak, G. Vogelbacher, K. Ross, U. Bergerhausen, K. Barker, I. Linkov, Towards a generic resilience management, quantification and development process: general definitions, requirements, methods, techniques and measures, and case studies, in: NATO Science for Peace and Security Series C: Environmental Security, Springer Netherlands, 2017, pp. 21–80, https://doi.org/10.1007/978-94-024-1123-2\textunderscore2.

[48] M. Braun, C. Hachmann, J. Haack, Blackouts, restoration, and islanding: a system resilience perspective, IEEE Power Energy Mag. 18 (4) (2020) 54–63, https://doi.org/10.1109/MPE.2020.2986659.
[49] A. Jovanović, P. Klimek, O. Renn, R. Schneider, K. Øien, J. Brown, M. DiGennaro, Y.[Y.] Liu, V. Pfau, M. Jelić, T. Rosen, B. Caillard, S. Chakravarty, P. Chhantyal, Assessing resilience of healthcare infrastructure exposed to COVID-19: emerging risks, resilience indicators, interdependencies and international standards, Environment Systems and Decisions 40 (2) (2020) 1–35, https://doi.org/10.1007/s10669-020-09779-8.
[50] P. Klimek, J. Varga, A.S. Jovanovic, Z. Székely, Quantitative resilience assessment in emergency response reveals how organizations trade efficiency for redundancy, Saf. Sci. 113 (2019) 404–414, https://doi.org/10.1016/j.ssci.2018.12.017.
[51] D. Rehak, P. Senovsky, S. Slivkova, Resilience of critical infrastructure elements and its main factors, Systems 6 (2) (2018) 21, https://doi.org/10.3390/systems6020021.
[52] N.U.I. Hossain, R. Jaradat, S. Hosseini, M. Marufuzzaman, R.K. Buchanan, A framework for modeling and assessing system resilience using a Bayesian network: a case study of an interdependent electrical infrastructure system, International Journal of Critical Infrastructure Protection 25 (2019) 62–83, https://doi.org/10.1016/j.ijcip.2019.02.002.
[53] L.H. Gunderson, C.S. Holling, Panarchy: Understanding Transformations in Human and Natural Systems, Island Press, 2002.
[54] C.S. Holling, The resilience of terrestrial ecosystems: local surprise and global change, in: W.C. Clark, R.E. Munn (Eds.), *Sustainable Development of the Biosphere* (292–317), Cambridge Univ. Pr, 1986.
[55] C.S. Holling, Understanding the complexity of economic, ecological, and social systems, Ecosystems 4 (5) (2001) 390–405, https://doi.org/10.1007/s10021-001-0101-5.
[56] D.L. Alderson, R.P. Darken, D.A. Eisenberg, T.P. Seager, P. Thomas, Surprise is inevitable: how do we train and prepare to make our critical infrastructure more resilient? Int. J. Disaster Risk Reduc. 72 (2022), 102800 https://doi.org/10.1016/j.ijdrr.2022.102800.
[57] J. Park, T.P.[T.P.] Seager, P.S.C. Rao, M. Convertino, I. Linkov, Integrating risk and resilience approaches to catastrophe management in engineering systems, Risk Anal. 33 (3) (2013) 356–367, https://doi.org/10.1111/j.1539-6924.2012.01885.x.
[58] D.D. Woods, Four concepts for resilience and the implications for the future of resilience engineering 141 (2015) 5–9, https://doi.org/10.1016/j.ress.2015.03.018.
[59] D.D. Woods, Resilience as graceful extensibility to overcome brittleness, in: M.-V. Florin, I. Linkov (Eds.), IRGC Resource Guide on Resilience, 2016, pp. 258–263.
[60] S.B. Manyena, S. Gordon, Bridging the concepts of resilience, fragility and stabilisation, Disaster Prev. Manag. 24 (1) (2015) 38–52, https://doi.org/10.1108/DPM-04-2014-0075.
[61] OECD, Glossary of Key Terms in Evaluation and Results Based Management, Organisation for Economic Co-operation and Development, Paris, 2002.
[62] M. Shinozuka, S.E. Chang, T.-C. Cheng, M. Feng, T.D. O'Rourke, M.A. Saadeghvaziri, X. Dong, X. Jin, Y [Yu] Wang, P. Shi, Resilience of Integrated Power and Water Systems, 2004.
[63] K. Fischer, S. Hiermaier, W. Riedel, I. Häring, Morphology dependent assessment of resilience for urban areas, 2071-1050, 10(6), 1800, https://doi.org/10.3390/su10061800, 2018.
[64] T. Aven, The call for a shift from risk to resilience: what does it, Mean? 1539-6924 39 (6) (2019) 1196–1203, https://doi.org/10.1111/risa.13247.
[65] A. Fekete, T. Hartmann, R. Jüpner, Resilience: on-going wave or subsiding trend in flood risk research and practice? WIREs Water 7 (1) (2020) e1397, https://doi.org/10.1002/wat2.1397.
[66] I. Linkov, C. Fox-Lent, L. Read, C.R. Allen, J.C. Arnott, E. Bellini, J. Coaffee, M.-V. Florin, K. Hatfield, I. Hyde, Hynes William, A. Jovanovic, R. Kasperson, J. Katzenberger, P.W. Keys, J.H. Lambert, R. Moss, P.S. Murdoch, J. Palma-Oliveira, D. Woods, Tiered approach to resilience assessment, Risk Anal. 38 (9) (2018) 1772–1780, https://doi.org/10.1111/risa.12991.
[67] I. Linkov, J.M. Palma-Oliveira, in: *NATO Science For Peace And Security Series C: Environmental Security. Resilience And Risk: Methods And Application In Environment, Cyber And Social Domains* (Igor Linkov, & José Manuel Palma-Oliveira, Springer Netherlands, 2017, https://doi.org/10.1007/978-94-024-1123-2.
[68] J. Johansson, H. Hassel, E. Zio, Reliability and vulnerability analyses of critical infrastructures: comparing two approaches in the context of power systems, Reliab. Eng. Syst. Saf. 120 (2013) 27–38, https://doi.org/10.1016/j.ress.2013.02.027.
[69] A.A. Ganin, E. Massaro, A. Gutfraind, N. Steen, J.M. Keisler, A. Kott, R. Mangoubi, I. Linkov, Operational resilience: concepts, design and analysis, Sci. Rep. 6 (2016), 19540, https://doi.org/10.1038/srep19540.
[70] R. Anholt, K. Boersma, From security to resilience: new vistas for international responses to protracted crises, in: B.D. Trump, M.-V. Florin, I. Linkov (Eds.), IRGC Resource Guide on Resilience (Volume 2): Domains of Resilience for Complex Interconnected Systems, EPFL International Risk, Lausanne, 2018.
[71] P. Gasser, P. Lustenberger, M. Cinelli, W. Kim, M. Spada, P. Burgherr, S. Hirschberg, B. Stojadinovic, T.Y. Sun, A review on resilience assessment of energy systems, Sustainable and Resilient Infrastructure 0 (0) (2019) 1–27, https://doi.org/10.1080/23789689.2019.1610600.
[72] L. Skyttner, General systems theory: problems, perspectives, practice, in: Problems, Perspectives, Practice, Chapter 2: Basic Ideas of General Systems Theory, second ed., World Scientific Publishing Company, 2006. http://ebookcentral.proquest.com/lib/dlr-ebooks/detail.action?docID=1681395.
[73] IEEE Std 610.12-1990. IEEE Standard Glossary of Software Engineering Terminology. Piscataway, NJ, USA. IEEE.
[74] A. Backlund, The definition of system, Kybernetes 29 (4) (2000) 444–451, https://doi.org/10.1108/03684920010322055.
[75] D.L. Alderson, G.G. Brown, W.M. Carlyle, 1539-6924, Operational models of infrastructure resilience 35 (4) (2015) 562–586, https://doi.org/10.1111/risa.12333.
[76] ISO, ISO/IEC/IEEE 15288:2015, 2018. https://www.iso.org/obp/ui/#iso:std:iso-iec-ieee:24748:-1:ed-1:v1:en.
[77] C.B. Nielsen, P.G. Larsen, J. Fitzgerald, J. Woodcock, J. Peleska, Systems of systems engineering, ACM Comput. Surv. 48 (2) (2015) 1–41, https://doi.org/10.1145/2794381.
[78] D. Lichte, F.S. Torres, E. Engler, Framework for operational resilience management of critical infrastructures and organizations, Infrastructure 7 (5) (2022) 70, https://doi.org/10.3390/infrastructures7050070.
[79] DHS, National Infrastructure Protection Plan (NIPP) 2013: Partnering for Critical Infrastructure Security and Resilience, U.S. Department of Homeland Security, 2013. http://www.dhs.gov/publication/nipp-2013-partnering-critical-infrastructure-security-and-resilience.
[80] CIPedia©. https://websites.fraunhofer.de/CIPedia/index.php/Critical_Infrastructure.
[81] Directive (EU), 2022/2557 of the European parliament and of the council of 14 december 2022 on the resilience of critical entities and repealing council directive 2008/114/EC. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32022L2557, 2022.
[82] T. McDaniels, S. Chang, K. Peterson, J. Mikawoz, D. Reed, Empirical framework for characterizing infrastructure failure, Interdependencies 13 (3) (2007) 175–184, https://doi.org/10.1061/(ASCE)1076-0342(2007)13:3(175), 1076-0342.
[83] F.C. Nick, N. Sänger, S. van der Heijden, S. Sandholz, Collaboration is key: exploring the 2021 flood response for critical infrastructures in Germany, Int. J. Disaster Risk Reduc. 91 (2023), 103710, https://doi.org/10.1016/j.ijdrr.2023.103710.
[84] D.L. Alderson, J.C. Doyle, Contrasting views of complexity and their implications for network-centric infrastructures, IEEE Trans. Syst. Man Cybern. Syst. Hum. 40 (4) (2010) 839–852, https://doi.org/10.1109/TSMCA.2010.2048027.
[85] E. Mühlhofer, E.E. Koks, C.M. Kropf, G. Sansavini, D.N. Bresch, A generalized natural hazard risk modelling framework for infrastructure failure cascades, Reliab. Eng. Syst. Saf. 234 (2023), 109194, https://doi.org/10.1016/j.ress.2023.109194.
[86] B. Arvidsson, J. Johansson, N. Guldåker, Critical infrastructure, geographical information science and risk governance: a systematic cross-field review, Reliability Engineering &amp\mathsemicolon System Safety 213 (2021), 107741, https://doi.org/10.1016/j.ress.2021.107741.
[87] Z. Yang, B. Barroca, A. Weppe, A. Bony-Dandrieux, K. Laffréchine, N. Daclin, V. November, K. Omrane, D. Kamissoko, F Benaben, H. Dolidon, J. Tixier, V. Chapurlat, Indicator-based resilience assessment for critical infrastructures - a review, 160, 106049, https://doi.org/10.1016/j.ssci.2022.106049, 2023.
[88] G.P. Cimellaro, A.M. Reinhorn, M. Bruneau, Framework for analytical quantification of disaster resilience, Engineering Structures 32 (11) (2010) 3639–3649, https://doi.org/10.1016/j.engstruct.2010.08.008.

[89] F.S. Torres, N. Kulev, B. Skobiej, M. Meyer, O. Eichhorn, J. Schafer-Frey, Indicator-based safety and security assessment of offshore wind farms, Resilience Week 2020 (2020) 26–33, https://doi.org/10.1109/RWS50334.2020.9241287.
[90] C. Bieder, K. Pettersen Gould (Eds.), SpringerBriefs in Applied Sciences and Technology. The Coupling of Safety and Security, Springer International Publishing, 2020, https://doi.org/10.1007/978-3-030-47229-0.
[91] C.L. Smith, D.J. Brooks, Security Science: the Theory and Practice of Security, Elsevier BH, 2013. http://www.sciencedirect.com/science/book/9780123944368.
[92] W.N. Adger, Vulnerability, Global Environmental Change 16 (3) (2006) 268–281, https://doi.org/10.1016/j.gloenvcha.2006.02.006.
[93] H. Kreibich, A.F. van Loon, K. Schröter, P.J. Ward, M. Mazzoleni, N. Sairam, G.W. Abeshu, S. Agafonova, A. AghaKouchak, H. Aksoy, C. Alvarez-Garreton, B. Aznar, L. Balkhi, M.H. Barendrecht, S. Biancamaria, L. Bos-Burgering, C. Bradley, Y. Budiyono, W. Buytaert, G. Di Baldassarre, The challenge of unprecedented floods and droughts in risk management, Nature 1–7 (2022), https://doi.org/10.1038/s41586-022-04917-5.
[94] UNISDR, 2009 UNISDR terminology on disaster risk reduction. https://www.undrr.org/publication/2009-unisdr-terminology-disaster-risk-reduction, 2009.
[95] M.R. Endsley, Toward a theory of situation awareness in dynamic systems, Human Factors 37 (1) (1995) 32–64, https://doi.org/10.1518/001872095779049543.
[96] M. Parsons, S. Glavac, P. Hastings, G. Marshall, J. McGregor, J. McNeill, P. Morley, I. Reeve, R. Stayner, Top-down assessment of disaster resilience: a conceptual framework using coping and adaptive capacities, International Journal of Disaster Risk Reduction 19 (2016) 1–11, https://doi.org/10.1016/j.ijdrr.2016.07.005.
[97] K. O'Brien, R. Leichenko, U. Kelkar, H. Venema, G. Aandahl, H. Tompkins, A. Javed, S. Bhadwal, S. Barg, L. Nygaard, J. West, Mapping vulnerability to multiple stressors: climate change and globalization in India, Global Environmental Change 14 (4) (2004) 303–313, https://doi.org/10.1016/j.gloenvcha.2004.01.001.
[98] C.J. Aylwin, T.C. König, N.W. Brennan, P.J. Shirley, G. Davies, M.S. Walsh, K. Brohi, Reduction in critical mortality in urban mass casualty incidents: analysis of triage, surge, and resource use after the London bombings on July 7, 2005, The Lancet 368 (9554) (2006) 2219–2225, https://doi.org/10.1016/S0140-6736(06)69896-6.
[99] National Academy of Sciences, Disaster Resilience: A National Imperative, The National Academies Press, 2012. http://www.nap.edu/catalog.php?record_id=13457.
[100] I.I. Mitroff, M.C. Alpaslan, Preparing for evil, Harvard Business Review 81 (4) (2003) 109–115, 124.
[101] IFRC, *World Disasters Report 2020: Come Heat Or High Water*. Geneva. International Federation of Red Cross and Red Crescent Societies, 2020. https://www.ifrc.org/document/world-disasters-report-2020.
[102] N.G. Leveson, Engineering a Safer World: Systems Thinking Applied to Safety, The MIT Press, 2016. https://library.oapen.org/handle/20.500.12657/26043.
[103] C. Perrow, Normal Accidents: Living with High Risk Technologies, Princeton University Press, 1999.
[104] G. Brown, M. Carlyle, J. Salmerón, K. Wood, Defending critical infrastructure, Interfaces 36 (6) (2006) 530–544, https://doi.org/10.1287/inte.1060.0252.
[105] Y.Y. Haimes, 1539-6924, On the Definition of Vulnerabilities in Measuring Risks to Infrastructures 26 (2) (2006) 293–296, https://doi.org/10.1111/j.1539-6924.2006.00755.x.
[106] E. Jenelius, J. Westin, Å.J. Holmgren, Critical infrastructure protection under imperfect attacker perception, International Journal of Critical Infrastructure Protection 3 (1) (2010) 16–26, https://doi.org/10.1016/j.ijcip.2009.10.002.
[107] I. Häring, S. Ebenhöch, A. Stolz, Quantifying resilience for resilience engineering of socio technical systems, European Journal of Security Research 1 (1) (2016) 21–58, https://doi.org/10.1007/s41125-015-0001-x.
[108] Z. Xu, J.E. Ramirez-Marquez, Y. Liu, Yu, T. Xiahou, A new resilience-based component importance measure for multi-state networks, Reliability Engineering & System Safety 193 (2020), 106591, https://doi.org/10.1016/j.ress.2019.106591.
[109] C.W. Zobel, L. Khansa, Quantifying cyberinfrastructure resilience against multi-event attacks, Decision Sciences 43 (4) (2012) 687–710, https://doi.org/10.1111/j.1540-5915.2012.00364.x.
[110] K.A. Klise, M. Bynum, D. Moriarty, R. Murray, A software framework for assessing the resilience of drinking water systems to disasters with an example earthquake case study 95 (2017), https://doi.org/10.1016/j.envsoft.2017.06.022, 420–431.
[111] K. Hewitt, I. Burton, The Hazardousness of a Place: A Regional Ecology ofDamaging Events, Department of Geography, University of Toronto, 1971.
[112] L. Dai, D. Vorselen, K.S. Korolev, J. Gore, Generic indicators for loss of resilience before a tipping point leading to population collapse, Science 336 (6085) (2012) 1175–1177, https://doi.org/10.1126/science.1219805.
[113] J. Gao, B. Barzel, A.-L. Barabási, Universal resilience patterns in complex networks, Nature 530 (7590) (2016) 307–312, https://doi.org/10.1038/nature16948.
[114] K. van der Geest, R. van den Berg, Slow-onset events: a review of the evidence from the IPCC special reports on land, oceans and cryosphere, Current Opinion in Environmental Sustainability 50 (2021) 109–120, https://doi.org/10.1016/j.cosust.2021.03.008.
[115] I. Donohue, H. Hillebrand, J.M. Montoya, O.L. Petchey, S.L. Pimm, M.S. Fowler, K. Healy, A.L. Jackson, M. Lurgi, D. McClean, N.E. O'Connor, E.J. O'Gorman, Q. Yang, Navigating the complexity of ecological stability, Ecology Letters 19 (9) (2016) 1172–1185, https://doi.org/10.1111/ele.12648.
[116] A.R. Ives, S.R. Carpenter, Stability and diversity of ecosystems, Science 317 (5834) (2007) 58–62, https://doi.org/10.1126/science.1133258.
[117] T. Aven, Implications of black swans to the foundations and practice of risk assessment and management, Reliability Engineering & System Safety 134 (2015) 83–91, https://doi.org/10.1016/j.ress.2014.10.004.
[118] M. Mahzarnia, M.P. Moghaddam, P.T. Baboli, P. Siano, A review of the measures to enhance power systems resilience, IEEE Systems Journal 14 (3) (2020) 4059–4070, https://doi.org/10.1109/JSYST.2020.2965993.
[119] A.J. Masys, Black swans to grey swans: revealing the uncertainty, Disaster Prevention and Management 21 (3) (2012) 320–335, https://doi.org/10.1108/09653561211234507.
[120] M. Panteli, C. Pickering, S. Wilkinson, R. Dawson, P. Mancarella, Power system resilience to extreme weather: fragility modeling, probabilistic impact assessment, and adaptation measures, IEEE Transactions on Power Systems 32 (5) (2017) 3747–3757, https://doi.org/10.1109/TPWRS.2016.2641463.
[121] M. Panteli, P. Mancarella, Modeling and evaluating the resilience of critical electrical power infrastructure to extreme weather events, IEEE Systems Journal 11 (3) (2015) 1733–1742, https://doi.org/10.1109/JSYST.2015.2389272.
[122] A. Umunnakwe, H. Huang, K. Oikonomou, K.R. Davis, Quantitative analysis of power systems resilience: standardization, categorizations, and challenges, Renewable and Sustainable Energy Reviews 149 (2021), 111252, https://doi.org/10.1016/j.rser.2021.111252.
[123] A. Gholami, T. Shekari, M.H. Amirioun, F. Aminifar, M.H. Amini, A. Sargolzaei, Toward a Consensus on the Definition and Taxonomy of Power System Resilience 2169–3536 (6) (2018) 32035–32053, https://doi.org/10.1109/ACCESS.2018.2845378.
[124] D. Rehak, J. Markuci, M. Hromada, K. Barcova, Quantitative evaluation of the synergistic effects of failures in a critical infrastructure system, International Journal of Critical Infrastructure Protection 14 (2016) 3–17, https://doi.org/10.1016/j.ijcip.2016.06.002.
[125] P.E. Roege, Z.A. Collier, J. Mancillas, J.A. McDonagh, I. Linkov, Metrics for energy resilience, Energy Policy 72 (2014) 249–256, https://doi.org/10.1016/j.enpol.2014.04.012.
[126] C. Fox-Lent, M.E. Bates, I. Linkov, A matrix approach to community resilience assessment: an illustrative case at Rockaway Peninsula, Environment Systems and Decisions 35 (2) (2015) 209–218, https://doi.org/10.1007/s10669-015-9555-4.
[127] IFRC, *What is a disaster?* International federation of red cross and red crescent societies. https://www.ifrc.org/what-disaster, 2022.
[128] United Nations General Assembly, Report of the Open-Ended Intergovernmental Expert Working Group on Indicators and Terminology Relating to Disaster Risk Reduction, 2016. https://www.preventionweb.net/files/50683_oiewgreportenglish.pdf.
[129] CRED, EM-DAT glossary: EM-DAT the international disaster database, Centre for Research on the Epidemiology of Disasters (2022). https://www.emdat.be/Glossary.
[130] P. O'Keefe, K. Westgate, B. Wisner, Taking the naturalness out of natural disasters, Nature 260 (5552) (1976) 566–567, https://doi.org/10.1038/260566a0.

[131] C. Kuhlicke, M.M. de Brito, B. Bartkowski, W. Botzen, C. Doğulu, S. Han, P. Hudson, A.N. Karanci, C.J. Klassert, D. Otto, A. Scolobig, T.M. Soares, S. Rufat, Spinning in circles? A systematic review on the role of theory in social vulnerability, resilience and adaptation research, Global Environmental Change 80 (2023), 102672, https://doi.org/10.1016/j.gloenvcha.2023.102672.
[132] A. Boin, A. McConnell, Preparing for critical infrastructure breakdowns: the limits of crisis management and the need for resilience, Journal of Contingencies and Crisis Management 15 (1) (2007) 50–59, https://doi.org/10.1111/j.1468-5973.2007.00504.x.
[133] T.A. Williams, D.A. Gruber, K.M. Sutcliffe, D.A. Shepherd, E.Y. Zhao, Organizational response to adversity: fusing crisis management and resilience research streams, Academy of Management Annals 11 (2) (2017) 733–769, https://doi.org/10.5465/annals.2015.0134.
[134] P.F. O'Neill, Building resilience through risk analysis, in: Igor Linkov & José Manuel Palma-Oliveira, NATO Science for Peace and Security Series C: Environmental Security. Resilience and Risk: Methods and Application in Environment, Cyber and Social Domains, Springer Netherlands, 2017, pp. 451–468, https://doi.org/10.1007/978-94-024-1123-2_17.
[135] UNDRR, Global Assessment Report on Disaster Risk Reduction (GAR), 2019 (5th), https://gar.undrr.org/sites/default/files/reports/2019-05/full_gar_report.pdf.
[136] W.L. McGill, B.M. Ayyub, M. Kaminskiy, Risk Analysis for Critical Asset Protection 27 (5) (2007) 1265–1281, https://doi.org/10.1111/j.1539-6924.2007.00955.x, 1539-6924.
[137] A. Lavell, M. Oppenheimer, C. Diop, J. Hess, R. Lempert, J. Li, R. Muir-Wood, S. Myeong, S. Moser, K. Takeuchi, Kuniyoshi, O.D. Cardona, S. Hallegatte, M. Lemos, C. Little, A. Lotsch, E. Weber, Climate Change: New Dimensions in Disaster Risk, Exposure, Vulnerability, and Resilience, Cambridge University Press, 2012, pp. 25–64, https://doi.org/10.1017/CBO9781139177245.004.
[138] W.E. Walker, P. Harremoës, J. Rotmans, J.P. van der Sluijs, M. van Asselt, P. Janssen, M.P. Krayer von Krauss, Defining uncertainty: a conceptual basis for uncertainty management in model-based decision support, Integrated Assessment 4 (1) (2003) 5–17, https://doi.org/10.1076/iaij.4.1.5.16466.
[139] F. Wu, B.D. [Benjamin D. Trump, Modest doubt is called the beacon of the wise"—Incorporating uncertainty in risk analysis from Shakespeare to today 43 (5) (2023) 871–874, https://doi.org/10.1111/risa.14139, 1539-6924.
[140] W.E. Walker, R. Lempert, J. Kwakkel, Deep uncertainty, 395–402, https://doi.org/10.1007/978-1-4419, 2013.
[141] E.S. Quade, Analysis for Public Decisions, third ed., 1989 (North-Holland).
[142] A.D. Kiureghian, O. Ditlevsen, Aleatory or epistemic? Does it matter? Structural Safety 31 (2) (2009) 105–112, https://doi.org/10.1016/j.strusafe.2008.06.020.
[143] H.M.D. Kabir, A. Khosravi, M.A. Hosen, S. Nahavandi, Neural Network-Based Uncertainty Quantification: A Survey of Methodologies and Applications 2169–3536 (6) (2018) 36218–36234, https://doi.org/10.1109/ACCESS.2018.2836917.
[144] R.J. Lempert, S.W. Popper, S.C. Bankes, Shaping the Next One Hundred Years: New Methods for Quantitative, Long-Term Policy Analysis, RAND, 2003. https://www.ebook.de/de/product/2567224/robert_j_lempert_steven_w_popper_steven_c_bankes_shaping_the_next_one_hundred_years_new_methods_for_quantitative_long_term_policy_analysis.html.
[145] J. Gausemeier, A. Fink, O. Schlake, Scenario management, Technological Forecasting and Social Change 59 (2) (1998) 111–130, https://doi.org/10.1016/S0040-1625(97)00166-2.
[146] R. Setola, V. Rosato, E. Kyriakides, E. Rome, Managing the complexity of critical infrastructures, in: Studies in Systems, Decision and Control, vol. 90, Springer International Publishing, 2016, https://doi.org/10.1007/978-3-319-51043-9.
[147] P. Maurice, M. Lavoie, A. Chapdelaine, H.B. Bonneau, L. Ellison, Safety and safety promotion: conceptual and operational aspects, Chronic Diseases in Canada 18 (4) (1997) 179–186.
[148] J. Beyza, P. Gil, M. Masera, J.M. Yusta, Security Assessment of Cross-Border Electricity Interconnections, vol. 201, Reliability Engineering & System Safety, 2020, 106950, https://doi.org/10.1016/j.ress.2020.106950.
[149] BCI, Good Practice Guidelines 2013: A Guide to Global Good Practice in Business Continuity, Business Continuity Institute, 2013. https://www.thebci.org/uploads/assets/uploaded/5c0205f3-a9ff-4f81-9695c3813b674a3b.pdf.
[150] U. Grober, Die Entdeckung der Nachhaltigkeit: Kulturgeschichte eines Begriffs, Antje Kunstmann, 2013.
[151] E.A. Spindler, The History of Sustainability the Origins and Effects of a Popular Concept, vols. 9–31, 2013, https://doi.org/10.1007/978-3-8349-7043-5_1.
[152] H.-C. von Carlowitz, Sylvicultura Oeconomica: Hausswirthliche Nachricht und Naturmäßige Anweisung zur Wilden Baum-Zucht, Johann Friedrich, 1713.
[153] WECD, Our common future: report of the world commission on environment and development. https://sustainabledevelopment.un.org/content/documents/5987our-common-future.pdf, 1987.
[154] acatech, Resilience-by-design Strategie Für Die Technologischen Zukunftsthemen, 2014.
[155] J. Fiksel, Designing resilient, sustainable systems, Environmental Science & Technology 37 (23) (2003) 5330–5339, https://doi.org/10.1021/es0344819.
[156] D. Marchese, E. Reynolds, M.E. Bates, H. Morgan, S.S. Clark, I. Linkov, Resilience and sustainability: similarities and differences in environmental management applications, Science of the Total Environment 613–614 (2018) 1275–1283, https://doi.org/10.1016/j.scitotenv.2017.09.086.
[157] S.R. Carpenter, K.J. Arrow, S. Barrett, R. Biggs, W.A. Brock, A.-S. Crépin, G. Engström, C. Folke, T.P. Hughes, N. Kautsky, C.-Z. Li, G. McCarney, K. Meng, K.-G. Mäler, S. Polasky, M. Scheffer, J. Shogren, T. Sterner, J.R. Vincent, A. de Zeeuw, General resilience to cope with extreme events, Sustainability 4 (12) (2012) 3248–3259, https://doi.org/10.3390/su4123248.
[158] E. Hollnagel, Epilogue: rag - the resilience assessment grid, in: Ashgate Studies in Resilience Engineering. Resilience Engineering in Practice: A Guidebook, Ashgate, 2011, pp. 316–337.
[159] G.A. Shirali, I. Mohammadfam, V. Ebrahimipour, A new method for quantitative assessment of resilience engineering by PCA and NT approach: a case study in a process industry, Reliability Engineering & System Safety 119 (2013) 88–94, https://doi.org/10.1016/j.ress.2013.05.003.
[160] B.H. Walker, L. Pearson, A resilience perspective of the SEEA, Ecological Economics 61 (4) (2007) 708–715, https://doi.org/10.1016/j.ecolecon.2006.04.010.
[161] L.A. Tamberg, J. Heitzig, J.F. Donges, A modeler's guide to studying the resilience of social-technical-environmental systems, Environmental Research Letters 17 (5) (2022), 55005, https://doi.org/10.1088/1748-9326/ac60d9.
[162] H. Kahiluoto, J. Kaseva, J. Balek, J.E. Olesen, M. Ruiz-Ramos, A. Gobin, K.C. Kersebaum, J. Takác, F. Ruget, R. Ferrise, P. Bezak, G. Capellades, C. Dibari, H. Mäkinen, C. Nendel, D. Ventrella, A. Rodríguez, M. Bindi, M. Trnka, Decline in climate resilience of European wheat, Proceedings of the National Academy of Sciences 116 (1) (2019) 123–128, https://doi.org/10.1073/pnas.1804387115.
[163] K. McClymont, D. Morrison, L. Beevers, E. Carmen, Flood resilience: a systematic review, Journal of Environmental Planning and Management 63 (7) (2020) 1151–1176, https://doi.org/10.1080/09640568.2019.1641474.
[164] N.P. Simpson, C.D. Shearing, B. Dupont, 'Partial functional redundancy': an expression of household level resilience in response to climate risk, Climate Risk Management 28 (2020), 100216, https://doi.org/10.1016/j.crm.2020.100216.
[165] M. Zampieri, C.J. Weissteiner, B. Grizzetti, A. Toreti, M. van den Berg, F. Dentener, Estimating resilience of crop production systems: from theory to practice, Science of the Total Environment 735 (2020), 139378, https://doi.org/10.1016/j.scitotenv.2020.139378.
[166] D.L. Alderson, G.G. Brown, W.M. Carlyle, Assessing and improving operational resilience of critical infrastructures and other systems, in: A. Newman, J. Leung (Eds.), Bridging Data and Decisions, INFORMS, 2014, pp. 180–215, https://doi.org/10.1287/educ.2014.0131.
[167] HSC, National Strategy for Homeland Security, Homeland Security Council, Washington, D.C, 2007. https://www.dhs.gov/national-strategy-homeland-security-october-2007.
[168] L. Petersen, D. Lange, M. Theocharidou, Who cares what it means? Practical reasons for using the word resilience with critical infrastructure operators, Reliability Engineering & System Safety 199 (2020), 106872, https://doi.org/10.1016/j.ress.2020.106872.
[169] C.S. Holling, Engineering Resilience versus Ecological Resilience: Engineering within Ecological Constraints, National Academies Press, 1996, pp. 31–44, https://doi.org/10.17226/4919.
[170] H. Herrera, From metaphor to practice: operationalizing the analysis of resilience using system dynamics modelling, Systems Research and Behavioral Science 34 (4) (2017) 444–462, https://doi.org/10.1002/sres.2468.

[171] S.L. Pimm, I. Donohue, J.M. Montoya, M. Loreau, Measuring resilience is essential if we are to understand it, Nature Sustainability 2 (10) (2019) 895–897, https://doi.org/10.1038/s41893-019-0399-7.
[172] D.L. Hoover, A.K. Knapp, M.D. Smith, Resistance and resilience of a grassland ecosystem to climate extremes, Ecology 95 (9) (2014) 2646–2656, https://doi.org/10.1890/13-2186.1.
[173] H. Hillebrand, S. Langenheder, K. Lebret, E. Lindström, Ö. Östman, M. Striebel, Decomposing multiple dimensions of stability in global change experiments, Ecology Letters 21 (1) (2018) 21–30, https://doi.org/10.1111/ele.12867.
[174] V. Dakos, S. Kéfi, Ecological resilience: what to measure and how, Environmental Research Letters 17 (4) (2022), 43003, https://doi.org/10.1088/1748-9326/ac5767.
[175] C. Mitra, J. Kurths, R.V. Donner, An integrative quantifier of multistability in complex systems based on ecological resilience, Scientific Reports 5 (1) (2015), 16196, https://doi.org/10.1038/srep16196.
[176] B. Walker, C.S. Holling, S.S. Carpenter, A. Kinzig, Resilience, adaptability and transformability in social- ecological systems, Ecology and Society 9 (2) (2004).
[177] C. Folke, Resilience: the emergence of a perspective for social\textendashecological systems analyses, Global Environmental Change 16 (3) (2006) 253–267, https://doi.org/10.1016/j.gloenvcha.2006.04.002.
[178] M. Zampieri, Reconciling the ecological and engineering definitions of resilience, Ecosphere 12 (2) (2021), e03375, https://doi.org/10.1002/ecs2.3375.
[179] C. Folke, R. Biggs, A.V. Norström, B. Reyers, J. Rockström, Social-ecological resilience and biosphere-based sustainability science, Ecology and Society 21 (3) (2016), https://doi.org/10.5751/es-08748-210341.
[180] F. Berkes, D. Jolly, Adapting to climate change: social-ecological resilience in a Canadian western arctic community, Conservation Ecology 5 (2) (2002), https://doi.org/10.5751/es-00342-050218.
[181] S.L. Cutter, Resilience to what? Resilience for whom? The Geographical Journal 182 (2) (2016) 110–113, https://doi.org/10.1111/geoj.12174.
[182] T. Elmqvist, E. Andersson, N. Frantzeskaki, T. McPhearson, P. Olsson, O. Gaffney, K. Takeuchi, Kazuhiko, C. Folke, Sustainability and resilience for transformation in the urban century, Nature Sustainability 2 (4) (2019) 267–273, https://doi.org/10.1038/s41893-019-0250-1.
[183] B.-J. Jesse, H.U. Heinrichs, W. Kuckshinrichs, Adapting the theory of resilience to energy systems: a review and outlook, Energy, Sustainability and Society 9 (1) (2019) 27, https://doi.org/10.1186/s13705-019-0210-7.
[184] X. Liu, D. Li, M. Ma, B.K. Szymanski, H.E. Stanley, J. Gao, Network resilience, Physics Reports 971 (2022) 1–108, https://doi.org/10.1016/j.physrep.2022.04.002.
[185] D. Butler, R. Farmani, G. Fu, S. Ward, K. Diao, M. Astaraie-Imani, A new approach to urban water management: safe and sure, Procedia Engineering 89 (2014) 347–354, https://doi.org/10.1016/j.proeng.2014.11.198.
[186] N.L. Engle, Adaptive capacity and its assessment, Global Environmental Change 21 (2) (2011) 647–656, https://doi.org/10.1016/j.gloenvcha.2011.01.019.
[187] J. Simmie, R. Martin, The economic resilience of regions: towards an evolutionary approach, Cambridge Journal of Regions, Economy and Society 3 (1) (2010) 27–43, https://doi.org/10.1093/cjres/rsp029.
[188] R. Cretney, Resilience for whom? Emerging critical geographies of socio-ecological resilience, Geography Compass 8 (9) (2014) 627–640, https://doi.org/10.1111/gec3.12154.
[189] C.G. Burton, A validation of metrics for community resilience to natural hazards and disasters using the recovery from hurricane katrina as a case study, Annals of the Association of American Geographers 105 (1) (2014) 67–86, https://doi.org/10.1080/00045608.2014.960039.
[190] H. Cai, N.S.N. Lam, Y. Qiang, L. Zou, R.M. Correll, V. Mihunov, A synthesis of disaster resilience measurement methods and indices, International Journal of Disaster Risk Reduction 31 (2018) 844–855, https://doi.org/10.1016/j.ijdrr.2018.07.015.
[191] A. Ostadtaghizadeh, A. Ardalan, D. Paton, H. Jabbari, H.R. Khankeh, Community disaster resilience: a systematic review on assessment models and tools, PLoS Currents 7 (2015), https://doi.org/10.1371/currents.dis.f224ef8efbdfcf1d508dd0de4d8210ed ecurrents.dis.f224ef8efbdfcf1d508dd0de4d8210ed.
[192] S.L. Cutter, C.G. Burton, C.T. Emrich, Disaster resilience indicators for benchmarking baseline conditions, Journal of Homeland Security and Emergency Management 7 (1) (2010), https://doi.org/10.2202/1547-7355.1732.
[193] S.L. Cutter, The landscape of disaster resilience indicators in the USA, Natural Hazards 80 (2) (2016) 741–758, https://doi.org/10.1007/s11069-015-1993-2.
[194] A. Pagano, I. Pluchinotta, R. Giordano, U. Fratino, Integrating “hard” and “soft” infrastructural resilience assessment for water distribution systems, 2018, Complexity (2018) 1–16, https://doi.org/10.1155/2018/3074791.
[195] J. Qin, M. Faber, Resilience informed integrity management of wind turbine parks, Energies 12 (2019) 2729, https://doi.org/10.3390/en12142729.
[196] R. Cantelmi, G. Di Gravio, R. Patriarca, Reviewing qualitative research approaches in the context of critical infrastructure resilience, Environment Systems and Decisions 41 (3) (2021) 341–376, https://doi.org/10.1007/s10669-020-09795-8.
[197] A. Opdyke, A. Javernick-Will, M. Koschmann, Infrastructure hazard resilience trends: an analysis of 25 years of research, Natural Hazards 87 (2) (2017) 773–789, https://doi.org/10.1007/s11069-017-2792-8.
[198] L. Gover, L. Duxbury, Inside the onion: understanding what enhances and inhibits organizational resilience, The Journal of Applied Behavioral Science 54 (4) (2018) 477–501, https://doi.org/10.1177/0021886318797597.
[199] W.N. Adger, Social and ecological resilience: are they related? Progress in Human Geography 24 (3) (2000) 347–364, https://doi.org/10.1191/030913200701540465.
[200] J.H. Kahan, A.C. Allen, J.K. George, An operational framework for resilience, Journal of Homeland Security and Emergency Management 6 (1) (2009), https://doi.org/10.2202/1547-7355.1675.
[201] N.N. Taleb, R. Douady, Mathematical Definition, Mapping, and Detection of (Anti)Fragility, 2012.
[202] T. Aven, 1539-6924, The Concept of Antifragility and Its Implications for the Practice of Risk Analysis 35 (3) (2015) 476–483, https://doi.org/10.1111/risa.12279.
[203] OECD, Concepts and Dilemmas of State Building in Fragile Situations, Part II, from Fragility to Resilience, OECD Journal on Development, 2008.
[204] P. Dias, Is toughness a better metaphor than resilience? Civil Engineering and Environmental Systems 32 (1–2) (2015) 68–76, https://doi.org/10.1080/10286608.2015.1016922.
[205] J.O. Gomes, D.D. Woods, P.V. Carvalho, G.J. Huber, M.R. Borges, Resilience and brittleness in the offshore helicopter transportation system: the identification of constraints and sacrifice decisions in pilots' work, Reliability Engineering & System Safety 94 (2) (2009) 311–319, https://doi.org/10.1016/j.ress.2008.03.026.
[206] E. Verhulsta, Applying systems and safety engineering principles for antifragility, Procedia Computer Science 32 (2014) 842–849, https://doi.org/10.1016/j.procs.2014.05.500.
[207] E. Zio, Challenges in the vulnerability and risk analysis of critical infrastructures, Reliability Engineering & System Safety 152 (2016) 137–150, https://doi.org/10.1016/j.ress.2016.02.009.
[208] S.B. Manyena, The concept of resilience revisited, Disasters 30 (4) (2006) 434–450, https://doi.org/10.1111/j.0361-3666.2006.00331.x.
[209] H.-T. Jhan, R. Ballinger, A. Jaleel, K.-H. Ting, 2071-1050, Development and application of a Socioeconomic Vulnerability Indicator Framework (SVIF) for Local Climate Change Adaptation in Taiwan 12 (4) (2020), https://doi.org/10.3390/su12041585, 1585.
[210] NIBS, Natural Hazard Mitigation Saves: 2019 Report. US Global Change Research Program, 2019. https://www.nibs.org/files/pdfs/NIBS_MMC_MitigationSaves_2019.pdf.
[211] A. Rose, N. Dormady, Advances in analyzing and measuring dynamic economic resilience, in: B.D. Trump, M.V. Florin, I. Linkov (Eds.), IRGC Resource Guide onResilience (vol. 2): Domains of resilience for complex interconnected systems, CH: EPFL International Risk Governance Center, Lausanne, 2018.
[212] D. Rehak, M. Hromada, T. Lovecek, Personnel threats in the electric power critical infrastructure sector and their effect on dependent sectors: Overview in the Czech Republic 127 (2020), 09257535, https://doi.org/10.1016/j.ssci.2020.104698, 104698.
[213] D. Rehak, L. Flynnova, S. Slivkova, Concept of resistance in the railway infrastructure elements protection, in: O. Prentkovskis, I. Yatskiv, P. Skačkauskas, R. Junevičius, P. Maruschak (Eds.), TRANSBALTICA XII: Proceedings of the 12th International Conference TRANSBALTICA, September 16-17, 2021, Springer, Vilnius, Lithuania, 2022, pp. 419–428, https://doi.org/10.1007/978-3-030-94774-3_41.

[214] J. Birkmann, O.D. Cardona, M.L. Carreño, A.H. Barbat, M. Pelling, S. Schneiderbauer, S. Kienberger, M. Keiler, D. Alexander, P. Zeil, T. Welle, Framing vulnerability, risk and societal responses: the MOVE framework, Natural Hazards 67 (2) (2013) 193–211, https://doi.org/10.1007/s11069-013-0558-5.
[215] BBK, Schutz Kritischer Infrastrukturen - Risiko- und Krisenmanagement: Leitfaden für Unternehmen und Behörden, Bundesamt für Bevölkerungsschutz und Katastrophenhilfe, Bonn, 2011.
[216] DIN EN ISO 22300:2018 , Security and Resilience - Vocabulary, DIN Deutsches Institut für Normung e.V., Berlin, 2018 (ISO 22300:2018), German Version EN ISO 22300:2018 22300.
[217] A. Boin, P.'. Hart, S. Kuipers, The crisis approach, in: H. Rodríguez, W. Donner, J.E. Trainor (Eds.), Handbooks of Sociology and Social Research, Springer International Publishing, 2018, pp. 23–38, https://doi.org/10.1007/978-3-319-63254-4_2.
[218] L.J. Branicki, Covid-19, ethics of care and feminist crisis management, Gender, Work & Organization 27 (5) (2020) 872–883, https://doi.org/10.1111/gwao.12491.
[219] J. Bundy, M.D. Pfarrer, C.E. Short, W.T. Coombs, Crises and crisis management: integration, interpretation, and research development, Journal of Management 43 (6) (2017) 1661–1692, https://doi.org/10.1177/0149206316680030.
[220] T. Christensen, P. Lægreid, L.H. Rykkja, Organizing for crisis management: building governance capacity and legitimacy, Public Administration Review 76 (6) (2016) 887–897, https://doi.org/10.1111/puar.12558.
[221] C. Pursiainen, The Crisis Management Cycle, Routledge, 2017, https://doi.org/10.4324/9781315629179.
[222] A. Boin, P. 't Hart, Organising for effective emergency management: lessons from Research1, Australian Journal of Public Administration 69 (4) (2010) 357–371, https://doi.org/10.1111/j.1467-8500.2010.00694.x.
[223] P. Lagadec, A new cosmology of risks and crises: time for a radical shift in paradigm and practice, Review of Policy Research 26 (4) (2009) 473–486, https://doi.org/10.1111/j.1541-1338.2009.00396.x.
[224] S. Jackson, T.L.J. Ferris, Resilience principles for engineered systems, Systems Engineering 16 (2) (2013) 152–164, https://doi.org/10.1002/sys.21228.
[225] H. Xu, Y. Li, L [Lin] Wang, Resilience assessment of complex urban public spaces, International Journal of Environmental Research and Public Health 17 (2) (2020) 524, https://doi.org/10.3390/ijerph17020524.
[226] K. Meyer, A mathematical review of resilience in ecology, Natural Resource Modeling 29 (3) (2016) 339–352, https://doi.org/10.1111/nrm.12097.
[227] N. Kumar, V. Poonia, B.B. Gupta, M.K. Goyal, A novel framework for risk assessment and resilience of critical infrastructure towards climate change, Technological Forecasting and Social Change 165 (2021), 120532, https://doi.org/10.1016/j.techfore.2020.120532.
[228] T. Elmqvist, C. Folke, M. Nyström, G. Peterson, J. Bengtsson, B. Walker, J. Norberg, Response diversity, ecosystem change, and resilience, Frontiers in Ecology and the Environment 1 (9) (2003) 488–494, https://doi.org/10.1890/1540-9295(2003)001[0488:RDECAR]2.0.CO;2.
[229] A.S. Mori, T. Furukawa, T. Sasaki, Response diversity determines the resilience of ecosystems to environmental change, Biological Reviews 88 (2) (2013) 349–364, https://doi.org/10.1111/brv.12004.
[230] H. Kahiluoto, J. Kaseva, K. Hakala, S.J. Himanen, L. Jauhiainen, R.P. Rötter, T. Salo, M. Trnka, Cultivating resilience by empirically revealing response diversity, Global Environmental Change 25 (2014) 186–193, https://doi.org/10.1016/j.gloenvcha.2014.02.002.
[231] S.A. Argyroudis, S.A. Mitoulis, L. Hofer, M.A. Zanini, E. Tubaldi, D.M. Frangopol, Resilience assessment framework for critical infrastructure in a multi-hazard environment: case study on transport assets, The Science of the Total Environment 714 (2020), 136854, https://doi.org/10.1016/j.scitotenv.2020.136854.
[232] C. Mutzenich, S. Durant, S. Helman, P. Dalton, Updating our understanding of situation awareness in relation to remote operators of autonomous vehicles, Cognitive Research: Principles and Implications 6 (1) (2021) 9, https://doi.org/10.1186/s41235-021-00271-8.
[233] N.A. Stanton, P.R.G. Chambers, J. Piggott, Situational awareness and safety, Safety Science 39 (3) (2001) 189–204, https://doi.org/10.1016/S0925-7535(01)00010-8.
[234] N. Sankary, A. Ostfeld, Incorporating operational uncertainty in early warning system design optimization for water distribution system security, Procedia Engineering 186 (2017) 160–167, https://doi.org/10.1016/j.proeng.2017.03.222.
[235] C. Ngamkhanong, S. Kaewunruen, B. Costa, State-of-the-Art review of railway track resilience monitoring, Infrastructures 3 (1) (2018) 3, https://doi.org/10.3390/infrastructures3010003.
[236] A. Jovanović, P. Klimek, A. Choudhary, e. al, Analysis of Existing Assessment Resilience Approaches, Indicators and Datasources: Usability and Limitations of Existing Indicators for Assessing, Predictingand Monitoring Critical Infrastructure Resilience, 2018.
[237] T.C. Sharkey, S.G. Nurre Pinkley, D.A. Eisenberg, D.L. Alderson, In search of network resilience: an optimization-based view, Networks 77 (2) (2021) 225–254, https://doi.org/10.1002/net.21996.
[238] N. Yodo, T. Afrin, O.P. Yadav, Di Wu, Y. Huang, Condition-based monitoring as a robust strategy towards sustainable and resilient multi-energy infrastructure systems, Sustainable and Resilient Infrastructure 8 (sup1) (2023) 170–189, https://doi.org/10.1080/23789689.2022.2134648.
[239] R. Biggs, M. Schlüter, D. Biggs, E.L. Bohensky, S. BurnSilver, G.l. Cundil, V. Dakos, T.M. Daw, L.S. Evans, K. Kotschy, A.M. Leitch, C. Meek, A. Quinlan, C. Raudsepp-Hearne, M.D. Robards, M.L. Schoon, L. Schultz, P.C. West, Toward principles for enhancing the resilience of ecosystem services, Annual review of environment and resources 37 (2012) 421–448, https://doi.org/10.1146/annurev-environ-051211-123836.
[240] K.P. Schneider, F.K. Tuffner, M.A. Elizondo, C.-C. Liu, Y. Xu, D. Ton, Evaluating the feasibility to use microgrids as a resiliency resource, IEEE Transactions on Smart Grid 8 (2) (2017) 687–696, https://doi.org/10.1109/TSG.2015.2494867.
[241] A. Kharrazi, Y. Yu, A. Jacob, N. Vora, B.D. Fath, Redundancy, diversity, and modularity in network resilience: applications for international trade and implications for public policy, Current Research in Environmental Sustainability 2 (2020), 100006, https://doi.org/10.1016/j.crsust.2020.06.001.
[242] H. Schmeck, C. Müller-Schloer, E. Çakar, M. Mnif, U. Richter, Adaptivity and self-organization in organic computing systems, ACM Transactions on Autonomous and Adaptive Systems 5 (3) (2010), https://doi.org/10.1145/1837909.1837911.
[243] S.S.H. Toroghi, V.M. Thomas, A framework for the resilience analysis of electric infrastructure systems including temporary generation systems, Reliability Engineering & System Safety 202 (2020), 107013, https://doi.org/10.1016/j.ress.2020.107013.
[244] G. Pezzulo, M.V. Butz, C. Castelfranchi, R. Falcone, Introduction: anticipation in natural and artificial cognition, in: G. Pezzulo, M.V. Butz, C. Castelfranchi, R. Falcone (Eds.), The Challenge of Anticipation: A Unifying Framework for the Analysis and Design of Artificial Cognitive Systems, Springer, 2008.
[245] M. Haasnoot, J.H. Kwakkel, W.E. Walker, J. ter Maat, Dynamic adaptive policy pathways: a method for crafting robust decisions for a deeply uncertain world, Global Environmental Change 23 (2) (2013) 485–498, https://doi.org/10.1016/j.gloenvcha.2012.12.006.
[246] D.D. Woods, The theory of graceful extensibility: basic rules that govern adaptive systems, Environment Systems and Decisions 38 (4) (2018) 433–457, https://doi.org/10.1007/s10669-018-9708-3.
[247] T. Aven, S. Thekdi, *The Importance of resilience-based Strategies in risk analysis, and vice versa* (IRGC resource guide on resilience, in: Domains of Resilience for Complex Interconnected Systems) vol. 2, EPFL International Risk Governance Center (IRGC), 2018.
[248] T. Aven, How some types of risk assessments can support resilience analysis and management, Reliability Engineering & System Safety 167 (2017) 536–543, https://doi.org/10.1016/j.ress.2017.07.005.
[249] R.A. Caralli, J.H. Allen, D.W. White, L.R. Young, N. Mehravari, P.D. Curtis, CERT Resilience Management Model,Version 1.2, 2016. http://www.cert.org/resilience/.
[250] S. Schauer, M. Latzenhofer, S. König, S. Rass, Conceptual Approach towards a Combined Risk and Resilience Framework for Interdependent Infrastructures, Research Publishing Services, 2021, https://doi.org/10.3850/978-981-18-2016-8_584-cd.
[251] L. Jaroš, M. Starý, L. Brezková, A stochastic approach to the operative control of flood flows through a reservoir, Journal of Hydrology and Hydromechanics 64 (1) (2016) 91–96, https://doi.org/10.1515/johh-2016-0012.
[252] M.S. Thibodeaux, E. Favilla, Organizational effectiveness and commitment through strategic management, Industrial Management & Data Systems 96 (5) (1996) 21–25, https://doi.org/10.1108/02635579610123307.
[253] L. Dvorakova, J. Kronych, A. Mala, Treasury management in strategic and operative corporate management, in: Z. Ndaba, T. Mokoteli (Eds.), Proceedings of the 5th International Conference on Management, Leadership and Governance (Icmlg 2017), Acad Conferences Ltd, 2017, pp. 119–127. https://www.webofscience.com/wos/woscc/full-record/WOS:000404892000016.

[254] M. Klumpp, S. Bioly, A. Mai, Operative sustainable logistics management simulation, Conference Proceedings (2010) 378–382.
[255] A.M. Madni, S. Jackson, Towards a conceptual framework for resilience engineering, IEEE Systems Journal 3 (2) (2009) 181–191, https://doi.org/10.1109/JSYST.2009.2017397.
[256] E. Hollnagel, Prologue: the scope of resilience engineering, in: Ashgate Studies in Resilience Engineering. Resilience Engineering in Practice: A Guidebook, Ashgate, 2011, pp. 30–41.
[257] T. Aven, A risk science perspective on the discussion concerning Safety I, Safety II and Safety III, Reliability Engineering & System Safety 217 (2022), 108077, https://doi.org/10.1016/j.ress.2021.108077.
[258] N. Leveson, Safety III: A Systems Approach to Safety and Resilience, MIT Engeneering Systems Lab, 2020.
[259] T.K. Haavik, Debates and politics in safety science, Reliability Engineering & System Safety 210 (2021), 107547, https://doi.org/10.1016/j.ress.2021.107547.
[260] L. Jones, M. Aho, Resilience by design, The Bridge 49 (2019). https://www.nae.edu/212175/Resilience-by-Design.
[261] P.T. Anastas, J.B. Zimmerman, Design through the 12 principles of green engineering, Environmental Science & Technology 37 (5) (2003) 94A–101A, https://doi.org/10.1021/es032373g.
[262] J. Fiksel, Sustainability and resilience: toward a systems approach, Sustainability: Science, Practice and Policy 2 (2) (2006) 14–21, https://doi.org/10.1080/15487733.2006.11907980.
[263] J. Park, T.P.[T.P.] Seager, P.S.C. Rao, t, Lessons in risk- versus resilience-based design and managemen 7 (3) (2011) 396–399, https://doi.org/10.1002/ieam.228, 15513777.
[264] L. Richards, For whom money matters less: social connectedness as a resilience resource in the UK, Social Indicators Research 125 (2) (2016) 509–535, https://doi.org/10.1007/s11205-014-0858-5.
[265] World Bank Group, Operational Guidance for Monitoring and Evaluation (M&E) in Climate and Disaster Resilience-Building Operations, 2017. Washington, D. C, http://documents.worldbank.org/curated/en/692091513937457908/Operational-guidance-for-monitoring-and-evaluation-M-E-in-climate-and-disaster-resilience-building-operations.
[266] C. Béné, T. Frankenberger, S. Nelson, Design, Monitoring and Evaluation of Resilience Interventions: Conceptual and Empirical Considerations, Institute of Development Studies, 2015. https://opendocs.ids.ac.uk/opendocs/handle/20.500.12413/6556.
[267] D.K. Mishra, M.J. Ghadi, A. Azizivahed, L. Li, J. Zhang, A review on resilience studies in active distribution systems, Renewable and Sustainable Energy Reviews 135 (2021), 110201, https://doi.org/10.1016/j.rser.2020.110201.
[268] M.H. Oboudi, M. Mohammadi, M. Rastegar, Resilience-oriented intentional islanding of reconfigurable distribution power systems, Journal of Modern Power Systems and Clean Energy 7 (4) (2019) 741–752, https://doi.org/10.1007/s40565-019-0567-9.
[269] M. Panteli, P. Mancarella, The grid: stronger, bigger, smarter? Presenting a conceptual framework of power system resilience, IEEE Power and Energy Magazine 13 (3) (2015) 58–66, https://doi.org/10.1109/MPE.2015.2397334.
[270] M. Taleb-Berrouane, F. Khan, Dynamic resilience modelling of process systems, Chemical Engineering Transactions 77 (2019), https://doi.org/10.3303/CET1977053.
[271] G. Sansavini, Engineering resilience in critical infrastructures, in: Igor Linkov & José Manuel Palma-Oliveira, NATO Science for Peace and Security Series C: Environmental Security. Resilience and Risk: Methods and Application in Environment, Cyber and Social Domains, Springer Netherlands, 2017, pp. 189–203, https://doi.org/10.1007/978-94-024-1123-2_6.
[272] I. Kilanitis, A. Sextos, Integrated seismic risk and resilience assessment of roadway networks in earthquake prone areas, Bulletin of Earthquake Engineering 17 (1) (2019) 181–210, https://doi.org/10.1007/s10518-018-0457-y.
[273] M.T. Schultz, B.P. Gouldby, J.D. Simm, J.L. Wibowo, Beyond the Factor of Safety: Developing Fragility Curves to Characterize System Reliability, Fort Belvoir, 2010, https://doi.org/10.21236/ADA525580 vol. A.
[274] A. Fekete, U. Nehren, Assessment of social vulnerability to forest fire and hazardous facilities in Germany, International Journal of Disaster Risk Reduction 87 (2023), 103562, https://doi.org/10.1016/j.ijdrr.2023.103562.
[275] N. Thanvisitthpon, Statistically validated urban heat island risk indicators for UHI susceptibility assessment, International Journal of Environmental Research and Public Health 20 (2) (2023) 1172, https://doi.org/10.3390/ijerph20021172.
[276] E. Tate, Social vulnerability indices: a comparative assessment using uncertainty and sensitivity analysis, Natural Hazards 63 (2) (2012) 325–347, https://doi.org/10.1007/s11069-012-0152-2.
[277] K. Storesund, N.K. Reitan, J. Sjöström, B. Rød, F. Guay, R. Almeida, M. Theocharidou, Novel methodologies for analysing critical infrastructure resilience, in: S. Haugen, A. Barros, C. van Gulijk, T. Kongsvik, J.E. Vinnem (Eds.), Safety and Reliability - Safe Societies in a Changing World, CRC Press, 2018, pp. 1221–1229, https://doi.org/10.1201/9781351174664-154.
[278] E. Engler, D. Göge, S. Brusch, ResilienceN - a multi-dimensional challenge for maritime infrastructures: otpornost - višedimenzionalni izazov za pomorsku infrastrukturu, Naše More 65 (2) (2018) 123–129, https://doi.org/10.17818/NM/2018/2.8.
[279] D. Groß, S. Bolognani, B.K. Poolla, F. Dörfler, Increasing the resilience of low-inertia power systems by virtual inertia and damping, in: Proceedings of IREP'2017 Symposium, 2017. Symposium conducted at the meeting of International Institute of Research and Education in Power System Dynamics (IREP), https://www.research-collection.ethz.ch/bitstream/handle/20.500.11850/232185/2/paper64s0a4badi.pdf.
[280] J. Kruse, B. Schäfer, D. Witthaut, Revealing drivers and risks for power grid frequency stability with explainable AI, Patterns 2 (11) (2021), 100365, https://doi.org/10.1016/j.patter.2021.100365.
[281] A. Hawken, G.L. Munck, Cross-national indices with gender-differentiated data: what do they measure? How valid are they? Social Indicators Research 111 (3) (2013) 801–838, https://doi.org/10.1007/s11205-012-0035-7.
[282] L.A. Bakkensen, C. Fox-Lent, L.K. Read, I. Linkov, 1539-6924, Validating Resilience and Vulnerability Indices in the Context of Natural Disasters 37 (5) (2017) 982–1004, https://doi.org/10.1111/risa.12677.
[283] A. Eldosouky, W. Saad, N. Mandayam, Resilient critical infrastructure: bayesian network analysis and contract-Based optimization, Reliability Engineering & System Safety 205 (2021), 107243, https://doi.org/10.1016/j.ress.2020.107243.
[284] F.D. Petit, G.W. Bassett, R. Black, W.A. Buehring, M.J. Collins, D.C. Dickinson, e. al, Resilience Measurement Index: an Indicator of Critical Infrastructure Resilience, 2013. www.osti.gov/bridge.
[285] K. de Bruijn, J. Buurman, M. Mens, R. Dahm, F. Klijn, Resilience in practice: five principles to enable societies to cope with extreme weather events, Environmental Science & Policy 70 (2017) 21–30, https://doi.org/10.1016/j.envsci.2017.02.001.
[286] F.S. Brand, K. Jax, Focusing the meaning(s) of resilience: resilience as a descriptive concept and a boundary object, Ecology and Society 12 (1) (2007). https://www.jstor.org/stable/26267855.
[287] S. Moser, S. Meerow, J. Arnott, E. Jack-Scott, The turbulent world of resilience: interpretations and themes for transdisciplinary dialogue, Climatic Change 153 (1) (2019) 21–40, https://doi.org/10.1007/s10584-018-2358-0.
[288] T.M. Logan, T. Aven, S.D. Guikema, R. Flage, Risk science offers an integrated approach to resilience, Nature Sustainability 5 (9) (2022) 741–748, https://doi.org/10.1038/s41893-022-00893-w.
[289] A. Wieland, M. Stevenson, S.A. Melnyk, S. Davoudi, L. Schultz, Thinking differently about supply chain resilience: what we can learn from social-ecological systems thinking, International Journal of Operations & Production Management 43 (1) (2023) 1–21, https://doi.org/10.1108/IJOPM-10-2022-0645.
[290] J.L. Davidson, C. Jacobson, A. Lyth, A. Dedekorkut-Howes, C.L. Baldwin, J.C. Ellison, N.J. Holbrook, M.J. Howes, S. Serrao-Neumann, L. Singh-Peterson, T. F. Smith, Interrogating resilience: toward a typology to improve its operationalization, Ecology and Society 21 (2) (2016). http://www.jstor.org/stable/26270410.
[291] R. Westrum, A typology of resilience situations, in: D. Woods, N. Leveson, E. Hollnagel (Eds.), Resilience Engineering: Concepts and Precepts, first ed., CRC Press, 2006, pp. 55–65, https://doi.org/10.1201/9781315605685-8.
[292] J. Bergström, R. van Winsen, E. Henriqson, On the rationale of resilience in the domain of safety: a literature review, Reliability Engineering & System Safety 141 (2015) 131–141, https://doi.org/10.1016/j.ress.2015.03.008.

[293] R.J.T. Klein, R.J. Nicholls, F. Thomalla, Resilience to natural hazards: how useful is this concept? Environmental Hazards 5 (1) (2003) 35–45, https://doi.org/10.1016/j.hazards.2004.02.001.
[294] J.A. Baggio, K. Brown, D. Hellebrandt, Boundary object or bridging concept? A citation network analysis of resilience, Ecology and Society 20 (2) (2015). https://www.jstor.org/stable/26270178.
[295] L. Olsson, A. Jerneck, H. Thoren, J. Persson, D. O'Byrne, Why resilience is unappealing to social science: theoretical and empirical investigations of the scientific use of resilience, Science Advances 1 (4) (2015), e1400217, https://doi.org/10.1126/sciadv.1400217.
[296] N. Yodo, P. Wang, Engineering resilience quantification and system design implications: a literature survey, Journal of Mechanical Design 138 (11) (2016), https://doi.org/10.1115/1.4034223.
[297] OECD, Good Governance for Critical Infrastructure Resilience, Organisation for Economic Co-operation and Development, 2019. https://www.oecd-ilibrary.org/governance/good-governance-for-critical-infrastructure-resilience_02f0e5a0-en.
[298] C. Pursiainen, E. Kytömaa, From European critical infrastructure protection to the resilience of European critical entities: what does it mean? Sustainable and Resilient Infrastructure 0 (0) (2022) 1–17, https://doi.org/10.1080/23789689.2022.2128562.
[299] G. O'Brien, P. O'Keefe, J. Rose, B. Wisner, Climate change and disaster management, Disasters 30 (1) (2006) 64–80, https://doi.org/10.1111/j.1467-9523.2006.00307.x.
[300] A. Jovanović, F. Quintero, A. Choudhary, Use of safety-related indicators in resilience assessment of Smart Critical Infrastructures (SCIs), in: Safety and Reliability - Theory and Applications, CRC Press, 2017, p. 162, https://doi.org/10.1201/9781315210469-139.
[301] P.J. Blokland, G.L. Reniers, The concepts of risk, safety, and security: a fundamental exploration and understanding of similarities and differences, in: C. Bieder, K. Pettersen Gould (Eds.), SpringerBriefs in Applied Sciences and Technology. The Coupling of Safety and Security, Springer International Publishing, 2020, pp. 9–16, https://doi.org/10.1007/978-3-030-47229-0_2.
[302] S. Meerow, J.P. Newell, M. Stults, Defining urban resilience: a review, Landscape and Urban Planning 147 (2016) 38–49, https://doi.org/10.1016/j.landurbplan.2015.11.011.