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# On the quantitative resilience assessment of complex engineered systems

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ABSTRACT

Recent years have seen the increasing complexity of engineered systems. Complexity and uncertainty also exist in engineered systems' interactions with human operators, managers, and the organization. Resilience, focusing on a system's ability to anticipate, absorb, adapt to, and recover from disruptive situations, can provide an umbrella concept that covers reliability and risk-based thinking to ensure these complex systems' safety. This paper discusses the quantitative aspects of the notion of resilience. Like the quantitative risk assessment framework, a generic framework should be developed for quantitative resilience assessment. This paper proposes a framework based on a triplet resilience definition consisting of disruption, functionality, and performance. Uncertainty treatment is also considered. The proposed framework aims to answer the question of "resilience of what to what" and how it can be quantitively assessed.

## 1. Introduction

Resilience is a popular word in the VUCA (Volatility, Uncertainty, Complexity, and Ambiguity) world. The criticality of being resilient is becoming evident during the COVID-19 pandemic. As people are now well aware, no matter how good our risk management program is, we still have to handle the residue risk of highly uncertain events (e.g., natural hazards, terrorist attacks, pandemics, and economic crises). People are eager to develop resilient cities and societies (Banai, 2020; Trundle, 2020; Yang and Wang, 2020). Engineered systems are the cornerstone of a city. We can never build up a resilient city without resilient engineered systems. An immediate question would be, "how can we manage and improve the resilience of an engineered system?". Drucker (1954) has already provided a clue to answer this question via his famous quote - "If you can't measure it, you can't manage it.". Therefore, this article is concerned with developing a quantitative way of expressing the resilience of an engineered system.

Resilience assessment (e.g., Bergstrom et al., 2015; Linkov and Florin, 2016; Zio, 2018; Sharma et al., 2020) is a relatively new scientific field. The idea that resilience is a system property arose from various disciplinary perspectives that include: ecology (Holling, 1973), infrastructure and community (Koliou et al., 2018; Sharma et al., 2018), human and organization (Sutcliffe and Vogus, 2003; Weick and Sutcliffe, 2007); system safety (Hollnagel, 2014), risk analysis (Aven, 2019) and others. Woods (2015) grouped the various uses of the label "resilience" into four primary concepts: i) resilience = rebound; ii) resilience = robustness; iii) resilience = graceful extensibility (i.e., the opposite of brittleness); and iv) resilience = architectures for sustained adaptability. Zio (2018) combined these concepts to formulate a comprehensive resilience definition as a system's ability to anticipate, absorb, adapt to disruptions, and recover and learn from failures and accidents. This definition is generic and applicable to many time frames from the pre-design stage until the system has been operated and encountered both success and failure. Cottam et al. (2019) surveyed the literature on the resilience of engineered systems from 1996 to 2018. They found that the literature defining and quantifying resilience in the engineering domain is inadequate compared to the studies in which resilience is defined qualitatively.

Resilience assessment can be supplemented and improved by considering risk. Resilience and risk are inherently related (Logan et al., 2022). Aven (2017) linked resilience and risk. He stated that risk assessment could provide helpful information to the resilience assessment by considering the uncertainties of disruptions. We should not separate resilience assessment and risk analysis but develop holistic

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methods integrating resilience and risk-based thinking (Aven, 2019). Quantitative risk assessment follows a uniform framework that includes the following major steps (Crowl and Louvar, 2019):

1) Defining potential accident scenarios;
2) Estimating the accident consequences (including the impacts on people, environment, and property);
3) Assessing the accident probabilities; and
4) Evaluating the risk by combining the consequence and probabilities.

However, the existing literature does not provide a generic framework for quantitative resilience assessment similar to the one for quantitative risk assessment presented above. This paper aims to give some suggestions and contributions toward a conceptual framework for the quantitative resilience assessment of engineered systems. This paper views resilience as an umbrella concept embracing equipment reliability and risk control on socio-technical complex systems rather than a replacement methodology. Besides, we refer to conventional risk assessment (in which residue risk is not dealt with) in the remaining part of this paper.

The rest of this paper is organized as follows. Section 2 discusses the notion of resilience from a quantitative perspective. A quantitative definition of resilience is provided in Section 3. Section 4 proposes a general framework for quantitative resilience assessment.

## 2. Quantitative aspects of the notion of resilience

The subject of resilience has become a popular topic in recent years and has been extensively discussed at all levels of government and industry. Correspondingly, the literature on this subject has proliferated (e.g., Pasman et al., 2020; Mottahedi et al., 2021a,b). Nemeth and Herrera (2015) review the development of resilience engineering research and have found that patterns of adaptation and describing how they occur progressed well while resilience assessment was less investigated. Recent years have seen publication growth in system resilience assessment (Cheng et al., 2022). In these studies, the notion of "resilience" is proposed to characterize system performance change and recovery subject to various hazards and threats (termed as disruptions in resilience studies). Since one essential requirement for making resilience assessment an intelligible subject is a uniform and consistent usage of terms, this section starts sorting things out by distinguishing the meaning between varieties of these terms as they shall be used in the engineering context.

### 2.1. The distinction between resilience and reliability

Hollnagel (2011) defines resilience as "the intrinsic ability of a system to adjust its functioning before, during or following changes and disturbances so that it can sustain required operations under both expected and unexpected conditions". Reliability describing whether a system can work for a particular period, is an aspect of engineering uncertainty. Probability is used to represent this uncertainty. The usual engineering definition of reliability is "The probability that a system will perform a required function without failure under stated conditions for a stated period" (O'Connor et al., 2002). Therefore, the first distinction is "Resilience is about capability while reliability is about probability". The subject of interest in resilience and reliability assessment differs but is closely related. When viewing reliability as a system performance metric/indicator, it can be used to quantify system resilience. Fig. 1 gives such a representation.

Fig. 1 also indicates another distinction: resilience covers a more extensive operation phase of a system subject to disruption, while reliability covers the pre-failure and failure stages shown in the figure. In this sense, the reliability decrease rate can be used to indicate the absorption capability of a system subject to disruptions. Part of adaptation capability can also be characterized by reliability, particularly when human reliability is considered in the reliability assessment of a complex system.

### 2.2. The distinction between resilience and robustness

Some early studies on resilience confound resilience and robustness, in which resilience is defined as the ability to absorb perturbations (Alderson et al., 2013; Woods, 2015). In Oxford Learner's Dictionaries, robustness is defined as "the state of being strong and healthy" and its synonym is strength. With this definition, robustness is very close to reliability. The above-mentioned distinctions may also be applicable here. In an engineering context, robustness is defined as the system's ability to absorb or withstand disruptions. Therefore, robustness can be viewed as part of a system's resilience – the absorption capability.

Alderson and Doyle (2010) claim that robust control only works for cases where disruptions are well-modeled. Besides, increasing robustness to one set of disruptions may make a system vulnerable to disruptions outside this set (Hoffman and Woods, 2011). For example, digitalization and automation may make a system more robust to human error and vulnerable to cyber-attacks. Resilience can be improved by optimizing the trade-offs for complex adaptive systems concerning variations and constraints when facing various disruptions.

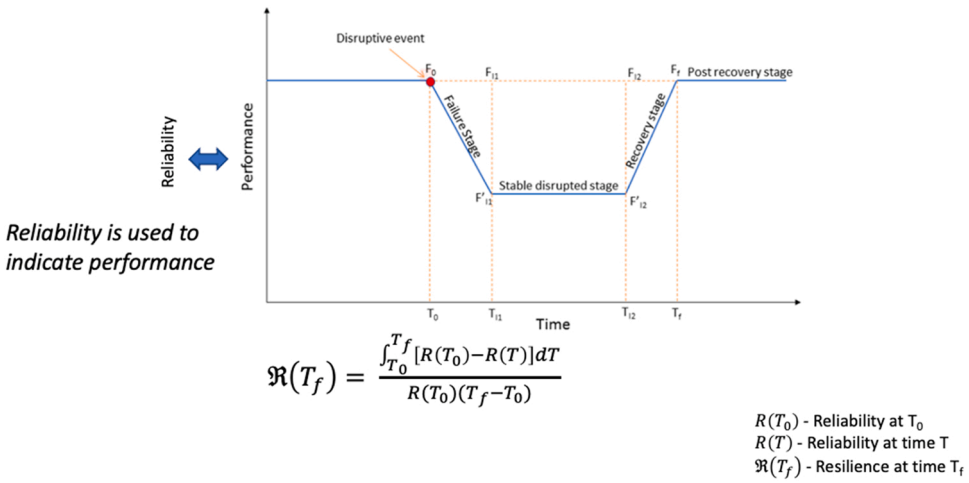


**Fig. 1.** The relationship between resilience and reliability.

### 2.3. The distinction between resilience and rebound

The Oxford Learner's Dictionary defines rebound as "to bounce back after hitting something". It is common for researchers to use the label resilience as rebound (Alderson and Doyle, 2010) as they view resilience from a narrow perspective focusing on recovery. This may be influenced by the fact that resilience is a concept that originated from material science and is measured by the tensile test (Dovstam, 1995). Limiting resilience to rebound would restrict people's thinking to responses to specific disruptions. This generates the risk of system brittleness when facing surprising disruptions and thus highlights a paradox about resilience (Woods, 2015). A resilient system should have the adaptation potential to handle surprises when internal and external factors vary. Therefore, resilience should have a broader scope than "rebound" for sustained adaptability and absorbability.

### 2.4. The distinction between resilience and risk

Publications in prestigious journals suggest that risk and resilience should be independently managed (Ganin et al., 2016; Linkov et al., 2018). The U.S. National Academy of Science defines resilience as "the ability to anticipate, prepare for, and adapt to changing conditions, and withstand, respond to, and recover rapidly from disruptions" (National Research Council, 2012). This definition makes the "risk" part of "resilience" since "prepare for", "withstand" and "respond to" are risk concepts (i.e., risk prevention and mitigation). Recently Logan et al. (2022) argued that the system's recovery is an essential consideration in consequence assessment as part of risk assessment if the long-term impact is accounted for. Thus, risk should have an equivalent scope to resilience. They also propose an integrated approach to link risk and resilience models. We support the statement that resilience and risk are interdependent and should not be managed separately, although the focus of resilience and risk assessment is different. Resilience assessment focuses on evaluating the system's ability to handle disruptions, while risk assessment focuses on the outcomes of being unable to handle disruptions.

## 3. Quantitative definition of resilience

In analyzing resilience, we attempt to envision how a system responds to and handles disruptions given specific system characteristics and configurations. In this paper, we exclude the anticipation phase of resilience, since at this stage we could not model the anticipation capability as part of the system resilience using existing performance curve-based mathematical models. We are working on a method to measure anticipation capability and its impact on absorption, adaption, and recovery.

Generally, resilience assessment answers the following questions:

1) What are possible disruptions to a system?
2) If the disruptions occur, what are their impacts on the system functionality?
3) How well can the system handle these disruptions while maintaining acceptable system performance?

The key terms in these questions are "disruption (D)", "functionality (F)", and "performance (P)". A triplet can be used to represent resilience.

$$\Re = (D, F, P)$$

Like the risk definition, uncertainty is another term that should be included. Uncertainties are associated with D, F, and P in terms of epistemic and aleatory uncertainties. For example, if we would assess the resilience of a chemical process plant to flooding (D), we should identify and analyze the impacts on the plant's functionality (F). Functionality is defined as the service that a system provides. A comprehensive functional analysis of physical, personnel and organizational entities accomplishing the system functionality needs to be conducted. Based on this functionality analysis, system performance (P) metrics can then be developed. Performance is measurement of functionality, which reflects changes in system functionality under disruptive conditions. It can be a single parameter representing the overall functionality (e.g., the production rate of this chemical process plant) or a list of parameters covering various aspects of the plant (e.g., safety, product quality, economic considerations, environmental considerations, sustainability (Pasman et al., 2020)). In this resilience assessment process, uncertainties exist in determining the predictability of the flooding (e.g., uncertain magnitude and frequency), survivability (e.g., the plant's varying response to the flooding), and recoverability (e.g., the availability of personnel and resources for emergency response).

## 4. Quantitative assessment framework

Fig. 2 gives the framework for quantitative resilience assessment. The following subsections describe the primary steps in this framework.

### 4.1. Define scope and context

This step first defines the scope of the assessment, including the following primary elements:

- **Goal of assessment**: the overall goal of resilience assessment is to evaluate the system's capability to handle disruptions. It may extend to the identification and evaluation of possible options for system resilience enhancement. Primary questions at this stage are:
  - Who will use the outcome of the assessment?
  - What information related to system resilience should be generated from the assessment?
  - What level of detail is required?

- **System boundary**: a complex engineered system consists of a technological system, human, and organization. System boundaries in resilience assessment can be specified in various dimensions:
  - *Boundaries between technological system and human*: whether or not to include human into the system
  - *Boundaries between human-technological system and organization*: whether or not to include organization into the system
  - *Time horizon*: the time horizon is restricted to the timespan during which the technology, human, and organization can be surveyed.
  - *Geographical area*: if the technological system is stationary, its location is set to be the area of interest; otherwise, the mobility region of the technological system is considered.

The inclusion of human and organization into the system may create flexibility in operating the technological system and adapting management to provide more options for resilience improvement. Thus, it is recommended to perform resilience assessment on a system comprised of technical, human, and organizational components or sub-systems. When defining system boundaries, we should consider the answers to the three questions listed in the **Goal of the assessment**.

Based on the defined goal and system boundary, a preliminary assessment of the need for resilience assessment is conducted. This step classifies the system based on an assessment matrix shown in Fig. 2. This matrix has two dimensions:

- **Cause-effect traceability**: the traceability of causality primarily depends on the system's complexity, determined by:
  - The number of components and their level of coupling
  - Emergent and nonlinear interaction among components
  - The number of direct and indirect feedback loops
- **Manageability**: is dependent on:
  - Whether the functioning mechanism is known
  - Whether a simple system description can be provided

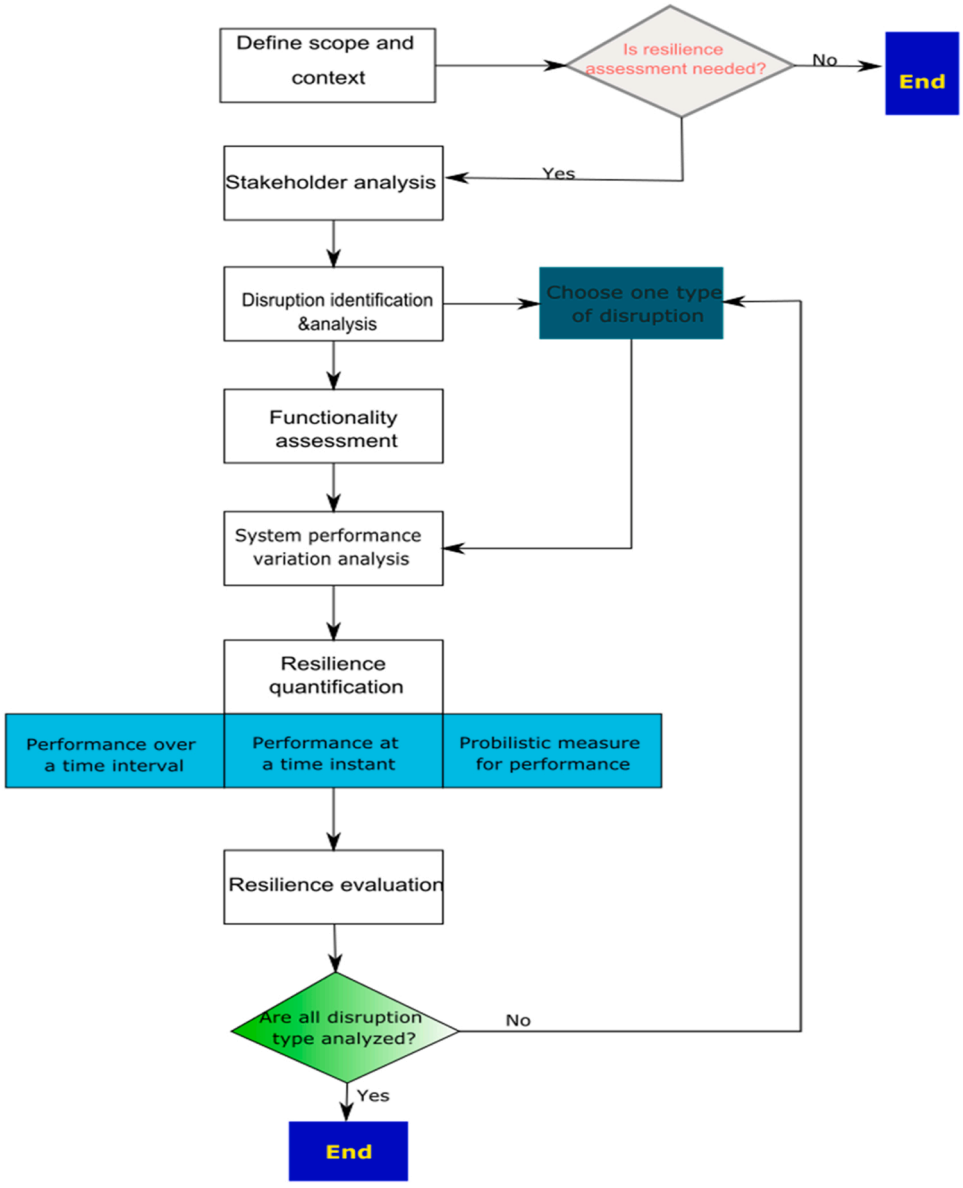


**Fig. 2.** The proposed framework for quantitative resilience assessment.

o Whether a system operates independently or interdependently

The analysis shown in Fig. 3 is qualitative, which means it needs expert judgments to determine the Cause-effect traceability and Manageability. Resiliency assessment is recommended if the system is classified as a socio-technical system. We shall conduct reliability or risk assessment for other categories to evaluate safety. However, this does not indicate that resilience assessment cannot be undertaken for these systems but is unnecessary.

### 4.2. Stakeholder analysis

The scope and context analysis answers the question "resilience of what". To further define "what", stakeholder analysis would help to identify the primary values associated with the specified system and thus provide the basis for the disruption and functionality analysis. The primary stakeholders' values determine the system's functionality they care for and the related performance indicators.

Stakeholder analysis can be conducted by various methods, including the power versus interest grid, the participation planning matrix, and social network analysis (Koromila et al., 2022). Below are the general steps for social network analysis.

1) Analyzing relevant regulations, policies, and standards;
2) Identifying stakeholders;
3) Defining interactions between stakeholders;
4) Elicitation of experts' judgments on the weightings of interactions; and
5) Performing network analysis to identify the most important stakeholder(s).

For instance, the port authority can be the most important stakeholder in the safety management of LNG transportation at a port. Port authority can determine the crucial functionality of the LNG transportation system and define performance indicators. They may also define resilience of what "to what" (i.e., the disruption types).

### 4.3. Disruption identification and analysis

Similar to hazard identification in risk assessment, determining

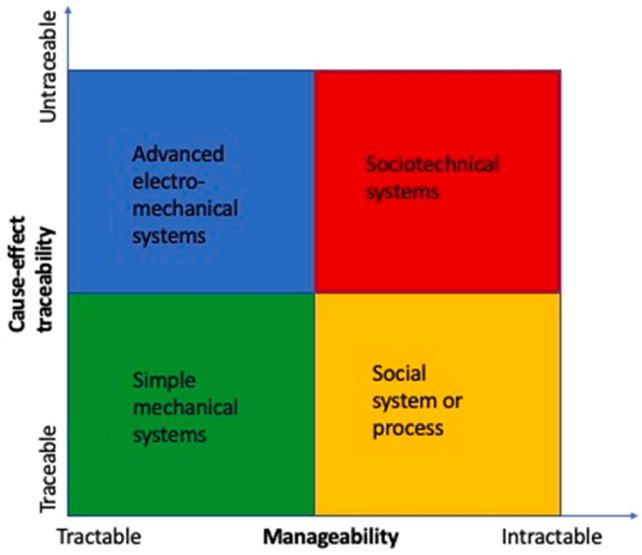


**Fig. 3.** System classification.

possible disruption events is crucial in resilience assessment. Different disruption events with various disruption intensities will result in other impacts on the performance of process systems. In chemical process systems, various disruptions have caused significant human casualties, asset loss, and environmental damage (Pawar et al., 2022). Identifying and classifying potential disruption and quantifying the intensity of disruptions is a cornerstone step. The analysis process (Fig. 4) of disruption events consists of four major steps:

1) Data collection. The primary purposes of this step are to analyze possible natural disasters based on the geographical location of the system and to collect information on disruption events that have occurred in the same type of process system;
2) Disruption identification and classification. This step can determine and classify the potential disruption based on relevant information, literature, expert knowledge, etc.
3) System structure analysis. This step aims to identify the critical equipment in the system and its redundancy and provide a basis for the subsequent analysis of the impact of disruptive events.
4) Disruption impact analysis. This step aims to analyze the impact of each piece of equipment caused by different disruptions. For the same disruption events, different equipment can be affected differently. Similarly, for the same equipment, different disruptions can affect it differently.

Take chemical process systems as an example, the disruptions can be divided into four primary categories based on published works of peer researchers, including natural events (Ricci et al., 2021; Misuri and Cozzani, 2021), cyber-attacks (Moreno et al., 2018; Ji et al., 2021; Hu et al., 2021), deliberate sabotages (George and Renjith, 2021; Moreno et al., 2018), and terrorism (Villa et al., 2017; Song et al., 2018; Reniers and Audenaert, 2014). When practitioners decide to employ the proposed method, they can determine the category of disruptions based on the system's characteristics, details, environment, etc. For example, the potential natural events should be identified by the position and environment of the system or plant. Those four main categories have their specific elements. For example, natural events comprise geophysical factors (e.g., earthquakes, landslides, volcanoes, etc.), meteorological factors (e.g., storms and lighting), hydrological factors (e.g., flooding), and climatological factors (e.g., wildfire) (Ricci et al., 2021). The general disruption events are shown in Fig. 5. Once disruptions are identified, the system structure analysis and impact analysis of disruptions should be conducted accordingly. In this paper, resilience quantification is limited to those disruption events where their impact measurement is possible.

### 4.4. Functionality assessment

It is necessary to assess the functionality of complex engineered systems to specify functional requirements. Complex engineered systems generally have several basic functions to maintain normal operation. Besides identifying basic functions, functionality assessment determines the relationship between functions and physical components. It is worth noting that basic functions are defined according to the interest of the prime stakeholder. Different stakeholders require a system to perform diverse functions. Since a complex engineered system is divided into multiple sub-systems, functionality analysis is carried out at both the system and sub-system levels.

Beginning with the task statement, the system objective is obtained to satisfy task requirements. All functions that the system needs to perform are listed, and then they are mapped to specific components. Finally, a system architecture is established from the perspective of functionality implementation. The relationship between functions, components, functions, and components is understood. Necessary functions and components are found, while unnecessary components are not requested during functionality assessment.

System functionality changes are measured in many ways, such as reliability, availability, cost, and efficiency. The functionality of a complex engineered system is described by reliability (Mottahedi et al., 2021a,b). System reliability describes the capability of maintaining desired performance under working conditions. It precisely reflects the actual performance of a complex engineered system. Besides reliability, system recovery efficiency and risk factors are closely related to system resilience. Availability refers to the system's capability to perform required functions in specific environments over time (Cai et al., 2018). It not only depends on the inherent property of the system, like structure configuration and failure rate, but also is determined by maintenance efficiency and resource. The definition of availability conforms to the essence of system resilience, so it is used to measure performance-based engineered systems. When functionality change cannot be quantified directly, monetary cost is employed to calculate functionality loss for service provision (Moslehi and Reddy, 2018). A penalty cost that describes the damage of disruptive events to the system is assigned to the corresponding loss. Low imposed cost means the system presents good resilience under disruptions. Prognostics and health management efficiency imply the degree of system restoration (Youn et al., 2011). It describes when and how the system recovers, related to the restorative capacity of system resilience. A resilient engineered system can recover to a sub-optimal state through restoration activities. Prognostics and health management efficiency is thus regarded as an effective metric for system evaluation.

The goal of a complex engineered system is to perform the desired functionality in the event of disruptions. All kinds of tasks are required to complete so that the system is equipped with multiple functions. Functions are divided into two types, including primary functions and sub-functions. Primary functions are identified according to the overall objective of the system, which is decided by the task statement. The prime stakeholder specifies the requirements of tasks to boost their profits. Several sub-functions that are supported by components compose a primary function. Successful implementation of a sub-function cannot be separated from the normal operation of indispensable components. Generally speaking, primary functions are implemented at the system level, while sub-functions are performed at the sub-system level.

It is necessary to understand the connection between primary functions and sub-functions during functionality assessment. Primary functions are composed of multiple sub-functions starting from the system objective. After that, indispensable components related to the corresponding sub-functions should be identified. In this way, the

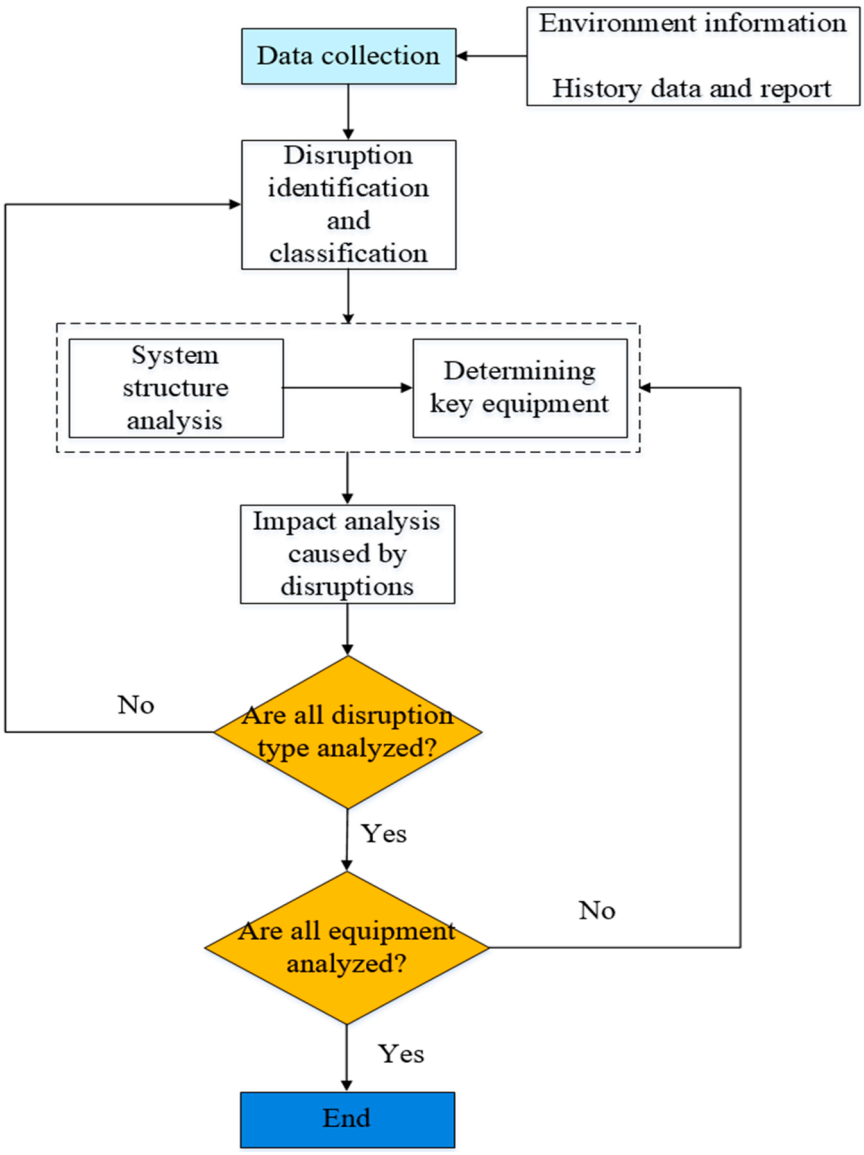


**Fig. 4.** The procedure of disruption events analysis.

functionality of the system can be measured according to the data about component behaviors. System functionality is quantified using appropriate metrics under specific conditions. Functionality assessment for a complex engineered system is carried out by following five steps.

*Step 1: Determine the overall objective of the system.*

A complex engineered system operates according to the system objective. The overall objective of the system is set to satisfy task requirements. In particular, the overall objective is supposed to reflect the interest of the prime stakeholder. There are all kinds of stakeholders for a complex engineered system. Different stakeholders have diverse effects on the determination of system objectives. The prime stakeholder is prioritized when stakeholders have conflicting requirements for system functionality. Only by determining the overall objective can basic functions be identified.

*Step 2: Identify the system functions needed for this objective.*

The overall objective is achieved through implementing system functionality. Functionality refers to the capability of the system to interact with the environment. Material, energy, and information are used to deal with a series of activities and then transformed into the desired output. Generally speaking, the system performs more than one function for the purpose of objective achievement. Functionality implementation is related to the configuration of the system structure. The more intricate the system structure, the more functions the system has.

*Step 3: Identify sub-functions of the primary function.*

Primary functions and sub-functions compose the basic functions of a complex engineered system. Primary functions performed by the whole system are closely related to the system objective. Several sub-functions are integrated into one primary function. Subsystems are responsible for performing different sub-functions, which support the implementation of primary functions. After identifying basic functions, the relationship between primary functions and sub-functions is figured out. Which sub-functions make up a primary function is understood in this step.

*Step 4: Identify the association of system components with these sub-functions.*

System components operate with the goal of functionality implementation. A sub-function is provided by one or more components, which are affected easily by disruptions. All kinds of disruptions make components degrade performance and even fail. Whether sub-functions are performed depends entirely on the behavior of system components. The observed data is used to reflect component performance and evaluate the implantation of sub-functions. Typical data includes the

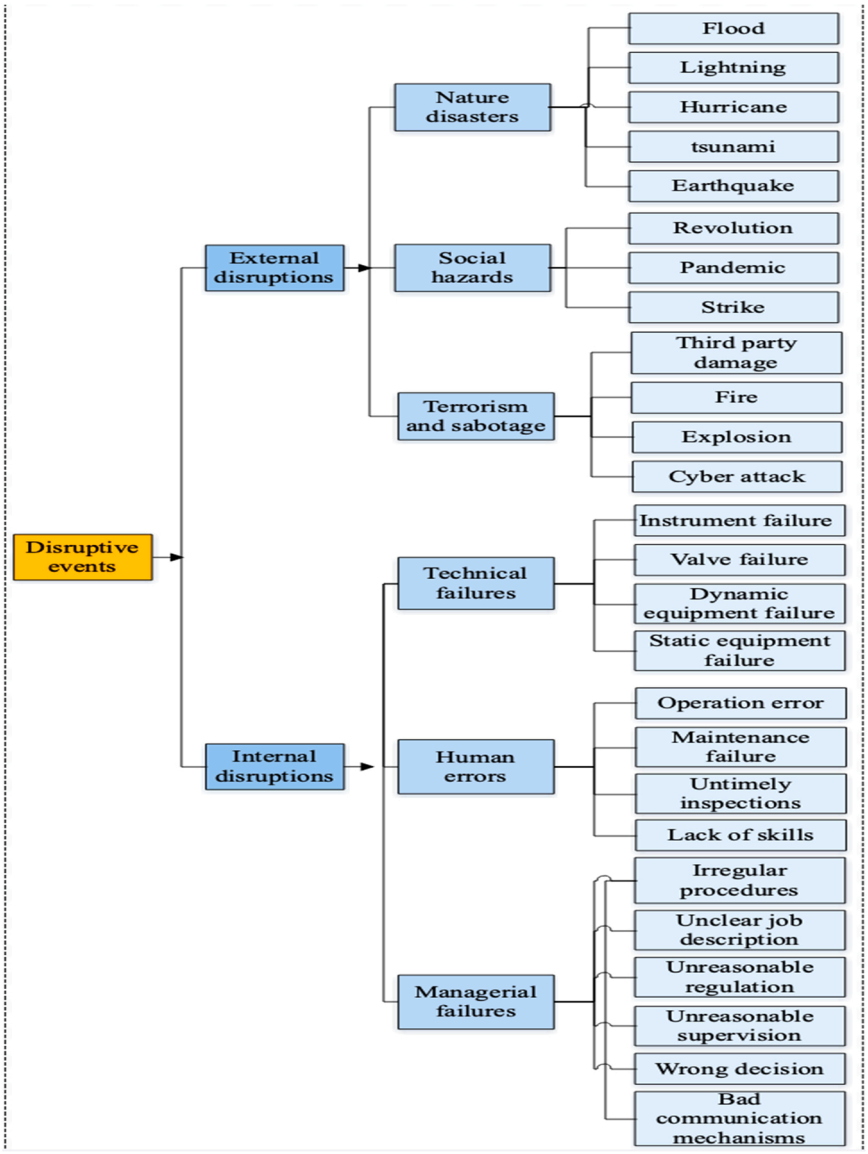


**Fig. 5.** The general disruption events.

reliability and operation time of system components.

*Step 5: Measure the functionality of the complex engineered system.*

The functionality of the complex engineered system should be quantified to facilitate the analysis of performance variation. Appropriate metrics are proposed to describe the implementation of primary functions and sub-functions. They reflect the actual performance of the system under external and internal disruptions. Examples of functionality metrics include reliability, availability, cost, and efficiency. After understanding the relationship between functions and components, it is easy to calculate these metrics based on the observed data.

Take a braking system of an aircraft as an example. The braking system is responsible for decelerating and stopping the moving aircraft during landing. It also plays a role in anti-skid protection when the aircraft coasts down the runway. Following the functionality assessment procedure, the overall objective, essential functions, and the associated components are found. A functional tree that identifies functional requirements is employed to describe the braking system, as shown in Fig. 6. Considering the interest of prime stakeholders, braking is the overall objective of the system. Three primary functions are implemented to satisfy task requirements: deceleration, parking, and anti-skid protection. The corresponding sub-functions (i.e., the basic operations of the primary function o provide the system service) and their components are determined. The overall objective, prime functions, sub-functions, and components are organized in a hierarchical structure. The highest level shows the system objective, and the lowest level expresses system components. Primary functions and sub-functions are placed at the second and third levels.

Then the efficiency of the brake system is used to measure system functionality. The braking system starts when a pilot depresses the pedal. The system will not stop working until the overall objective is achieved. The functionality metric is defined as the efficiency of the whole braking process. The system with high efficiency has outstanding performance under disruptions.

### 4.5. System resilience quantification metrics

Since many studies have been performed to develop resilience quantification metrics, this section does not aim to propose a new method but to provide a brief summary with our insights. Cheng et al. (2022) have conducted a comprehensive review of system resilience assessments.

They have identified four types of resilience metrics, classified based

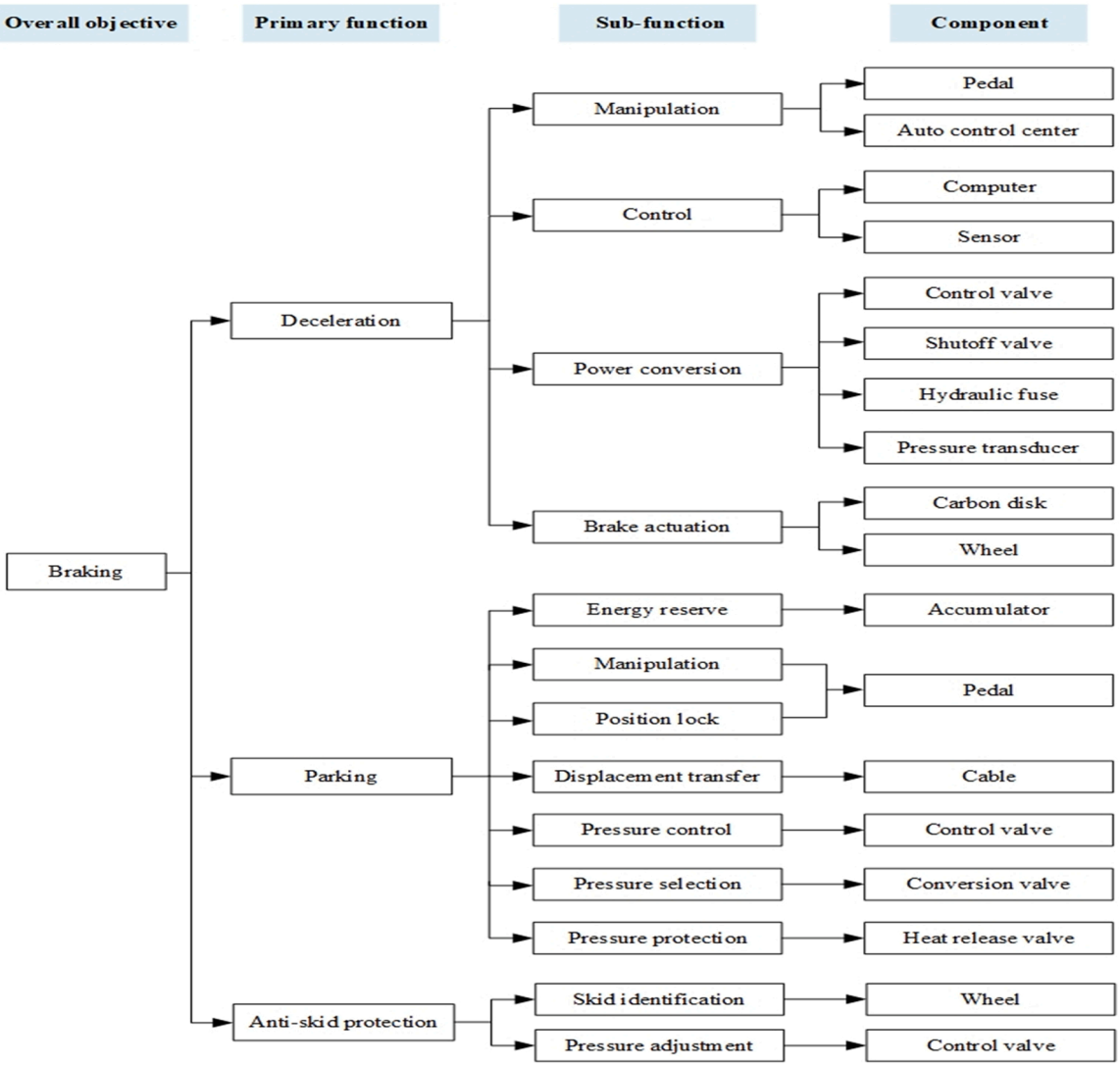


**Fig. 6.** An example of a functional tree.

on the length of disruption and recovery period:

1) Metrics based on performance over a time period
   a. The ratio between actual and desired performance during the period
   b. The ratio of performance loss and desired performance during the period
2) Metrics based on performance at a time instant
   a. Normalized performance at a time instant
   b. The ratio of the recovered and degraded performance
3) Probabilistic metrics
   a. The probability that performance is recovered to a specific level within a period
   b. The conditional probability that performance is recovered to a specific level within a period
4) Multiple indicator metrics
   a. The sum of reliability and recoverability indicators
   b. Other indicators

Recent years have seen the development of quantitative resilience assessment methods for process systems (e.g., Jain et al., 2018; Tong et al., 2020; Sun et al., 2022). These methods are primarily developed using the types 1, 3, and 4 metrics. Attaining the system performance response curve to a particular disruption is essential in resilience quantification. However, this task is challenging due to lack of data, knowledge, and experience, which leads to various levels of uncertainty. A potential solution is to utilize objective data (e.g., incident report, operational data), subjective data (e.g., expert elicitation data), and simulation data (e.g., data generated by process simulator). Zinetullina et al. (2021) provide an example of such application.

Uncertainty treatment is another challenge in resilience analysis. Pate-Cornell (1996) proposes a six-level framework for treating uncertainties in risk analysis. We believe this approach is still applicable in handling epistemic and aleatory uncertainties in resilience assessment. The choice of the levels may lead to different degrees of sophistication in the assessment, which depends on the need for decision-making, management rules, etc. Fig. 7 proposes a four-level framework for treating uncertainties in resilience assessment. It is worth noting that the present framework is developed based on Pate-Cornell's (1996) approach for handling uncertainties with adaptation to resilience assessment.

Level 1 simply involves the identification of possible disruptions and the various responses that a system may have to these disruptions. The question is "Whether a system can handle a disruption?", which is an expert judgment call and can be conducted by expert elicitation. Level 2 analyzes the worst-case scenarios in which a system's absorption capacity is exceeded. In these cases, system restoration must be conducted. Level 3 depends on the best estimate, which can be represented by a central value. Level 4 relies on a probabilistic approach for resilience

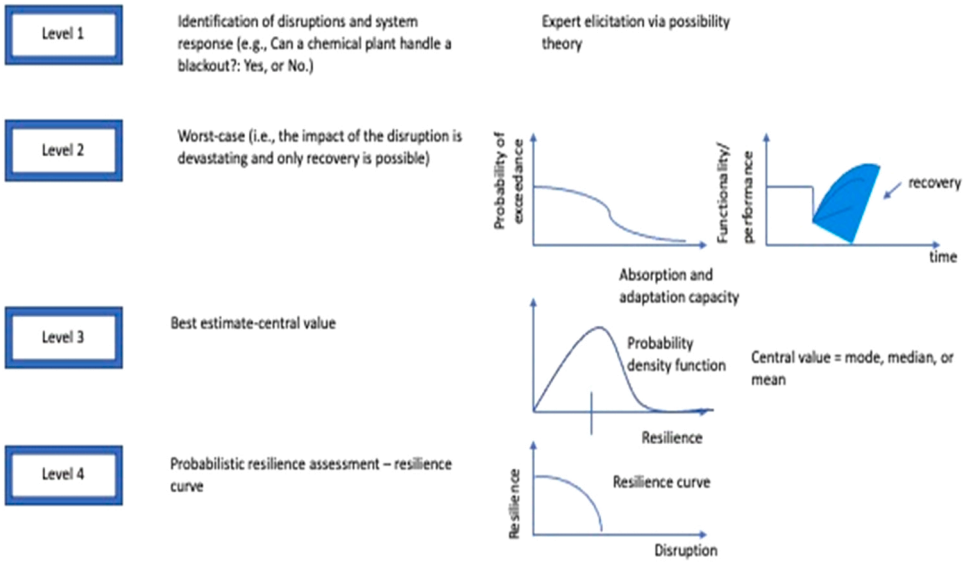


**Fig. 7.** The proposed framework for treating uncertainties in resilience assessment.

assessment. Resilience is not represented by a single estimate in probability but by a distribution subject to the intensity of a disruption. The idea is to aggregate both epistemic and aleatory uncertainties into one resilience curve.

## 5. Conclusion

Safety is an abstract concept. It needs a carrier to make it practical. Resilience is one of such carriers. In this paper, we have first attempted to pull apart some concepts related to resilience and then proposed a triplet that quantitively defines resilience. Based on this definition, a generic framework for quantitative resilience assessment is proposed. In light of the steps of the framework, the questions of the need for resilience assessment, disruption types, the association between functionality and performance, resilience metrics, and uncertainty treatment are discussed. Like risk, with the proposed definition and assessment approach, resilience is a relative metric and should always be considered in the context of decision theory. Thus, we shall investigate how to reach optimum resilience (i.e., balancing productivity, safety, and sustainability) via design and operation. Projects are planned to implement the proposed assessment approach to various complex engineered systems to verify and validate its applicability for real-world scenarios. It is worth noting that this paper does not consider anticipation as one aspect of resilience in its assessment model. Quantification of resilience may not cover all aspects but those that are identifiable. Obtaining the performance profile is essential in the present resilience quantification model. Thus, the proposed method can only quantify the system resilience to the disruptions whose impacts on system performance can be measurable.

## Declaration of Competing Interest

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