Resilience assessment framework based on criticality and resilience properties

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Abstract

Resilience evaluation in modern infrastructures, particularly in critical energy systems, is increasingly important due to rising complexity and interconnectivity. This study builds on recent advances in resilience capacities and properties, using criticality analysis and functional decomposition to characterize offshore wind farms. A preliminary assessment based on modularity and redundancy is conducted. Results indicate that a single aggregated resilience index may obscure trade-offs, as distinct configurations can yield similar values. Future work will integrate high-fidelity simulation data to refine property parameters. The present assessment constitutes a first step toward more robust resilience quantification.

Keywords: resilience; criticality; modularity; redundancy; offshore wind

Introduction

The proposed methodology assesses quantitatively the resilience of infrastructures by systematically considering system parameters in a hierarchical manner. It is structured into three fundamental steps: (1) hierarchical functional decomposition, (2) extraction of resilience properties and capacities at the top layer, and (3) detailed parametrization through high-fidelity modeling.

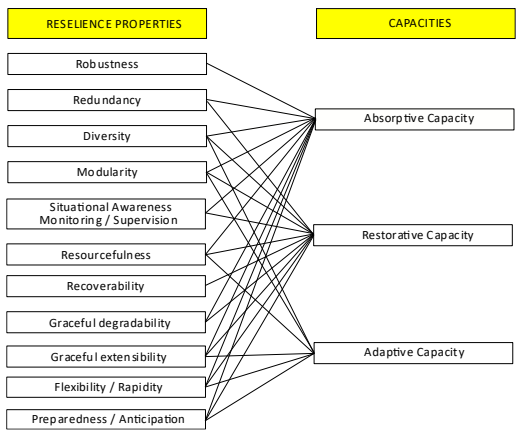


Figure 1. Resilience properties and corresponding capacities, based on (Mentges et al., 2023).

Step (1) involves breaking down the infrastructure into progressively smaller, functionally distinct subsystems. Established approaches, like those discussed by (Ouyang, 2014) and (Rinaldi, Peerenboom, & Kelly, 2001), can be applied here. Typically, the decomposition follows a top-down procedure: starting from the overall mission or function (e.g., energy provision), the system is divided into major subsystems (e.g., generation, transmission, distribution), and further refined into specific processes or assets. This representation highlights functional

dependencies, critical nodes, redundancies, and potential pathways for failure propagation. An example for an offshore wind farm (OWF) is illustrated in Figure 2.

Step (2) builds on the extracted top-layer functions and focuses on the associated resilience properties and capacities, as illustrated in Figure 1. For each property, the corresponding parameter RP_{prop} is identified, with *prop* denoting the set of properties shown in Figure 1 (e.g., redundancy, modularity). After normalization, these parameters are aggregated to derive the resilience capacities RC_{cap}, where *cap* refers to the set {*absorptive*, *restorative*, *adaptive*}. Each capacity is associated with a subset of properties $cprop_{cap}$, as indicated in Figure 1. For example, the property set of the resilience capacity *adaptive* is $cprop_{adaptive} = \{RP_{diversity}, RP_{modularity}, RP_{flexibility_rapidity}, RP_{preparedness_anticipation}, RP_{resourcefulness}, RP_{graceful_extensibility}\}$. The combination is based on weighted normalization (Petit, 2013):

$$RC_{cap} = \frac{\sum_{i \in cprop_{cap}} (w_i \cdot RC_{cap,i})}{\sum_{i \in cprop_{cap}} (w_i)} \quad (1),$$

where w_i represents the weight of the property i in the set $cprop_{cap}$, while $RC_{cap,i}$ denotes the value of the resilience capacity for property i.

In Step (3), all properties are parameterized on the basis of high-fidelity modeling and simulation of the individual subsystems. Such modeling yields, for example, component failure rates and reliabilities, potential failure paths, and other performance-relevant parameters.

Modularity and redundancy

When aiming at meaningful analysis, the estimation of the resilience properties is not trivial. For illustration, this work focuses on the properties modularity and redundancy.

Modularity refers to the extent to which a system can be decomposed into independent modules that perform distinct functions without interfering with one another (Newman, 2006). The modularity index, which represents functional independence obtained through functional decomposition (U.S. DoD, 2001), is defined as the number of edges connected to a vertex within a functional block graph at the same level of decomposition, as exemplarily illustrated in Figure 2. This study is limited to energy flow channels. As an example, consider the sub-function “Energy provision” of an OWF, which corresponds to the turbine level. Here, modularity is determined, among others, by the number of internal strings to which the turbines are connected, and which separate the turbines in individual groups. For a system with s equal strings, the modularity M_f of this sub-function f is given by s.

In the context of infrastructures, redundancy is understood as the existence of additional elements beyond those strictly necessary for system operation. Its primary role is to sustain functionality despite failure of individual components (Zio, 2016). Several approaches exist to quantify redundancy at the system level. In reliability theory, the redundancy R_{ssys} of a sub-system *ssys* results from (Birolini, 2017):

$$R_{ssys} = 1 - \prod_{i \in comp}(1 - RL_i) \quad (2),$$

where RL_i denotes the reliability of component *i* within the set of components *comp* of the sub-system.

For many infrastructure systems, the Failure Mode, Effects, and Criticality Analysis (FMECA) method, based on MIL-STD-1629A (U.S. DoD, 1980), has proven effective (Ge et al., 2025). The outcome of a CA is typically expressed in terms of a criticality index *CI*, which facilitates the prioritization of system elements. For a sub-system *ssys*, the criticality index can be estimated as:

$$CI_{ssys} = \sum_{i \, \epsilon \, comp}(\lambda_i \cdot \alpha_i \cdot \beta_i) \quad (3),$$

where CI_{ssys} denotes the *CI* of the sub-system *ssys*, λ_i is the failure rate of component *i* within the set of components *comp* of the sub-system, α_i means the conditional probability that the failure mode occurs given component failure and β_i is the probability that the failure effect results in sub-system failure. For normalization, unit interval ranking has been chosen, which proves to be robust to adding and or removing of low-impact items. Thus, the normalized criticality index $\overline{CI_{ssys}}$ results from:

$$\overline{CI_{ssys}} = \frac{CI_{ssys}}{\max(CI_{sys})} \quad (4),$$

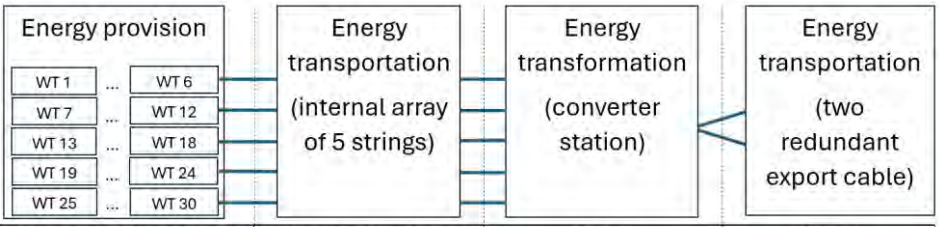
where CI_{sys} is the set of all critical indexes of the system *sys.* This value is then employed as property weight *w* for the properties in Equation (1).

Results

Following the CA in the context of functional decomposition, as it is shown in Figure 2, the least critical element of Offshore Wind Farm (OWF) is Wind Turbine (WT) which is achieved via redundancy. Criticality of each WT is estimated as ca. 3.3 %. The most critical elements are converter station and export cable, both assumed as 100 % of criticality. It is assumed that all four function blocks in Figure 2 are critical to system functionality.

Modularity index understood as functional independence suggests that export cable is the most independent element of OWF with only 1 connection. The most interconnected element is internal array of OWF with 10 sub-system dependencies for all 5 strings.

The most redundant elements are Wind Turbines (WTs) as components responsible for energy provision. The least redundant elements are energy converter station and export cable.



Criticality	(3.3 % * 30) = 100 %	(20 % * 5) = 100 %	100 %	100 %
Modularity	5	10	6	2
Redundancy	0	0	0	1

Figure 2. Functional decomposition of OWF with selected indicators and interconnections based on energy flow.

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