Proc. of the European Safety and Reliability Conference (ESREL 2026)
Edited by José C. Matos, Paulo B. Lourenço, Michael Beer, Daniel Oliveira, Edoardo Patelli, Hélder S. Sousa, Rui A. Silva and Monica Santamaria
 Published by Research Publishing, Singapore.
doi: 10.3850/ESREL2026061419_esrel26-p26574-cd

Toward a Decision-Oriented Ontology of Resilience for Complex Engineered Systems

Graeme W. Troxell

Blue Green Decisions Lab, Department of Systems Engineering, Colorado State University. Fort Collins, CO, USA E-mail: g.troxell@colostate.edu

Vincent P. Paglioni

Risk, Reliability, & Resiliency Characterization (R3C) Lab, Department of Systems Engineering, Colorado State University. Fort Collins, CO, USA. E-mail: vincent.paglioni@colostate.edu

Resilience is routinely invoked to justify infrastructure investments and emergency-management strategies, yet it remains difficult to operationalize as an interpretable measurand for decision support in interdependent lifeline systems exposed to compounding hazards. A recurring source of confusion is the divide between engineered and ecological resilience. We argue that, in decision settings, this divide is often sustained by a category mistake: regimes and equilibria are used primarily as structured descriptions of acceptable operation rather than as ontologically thick system states. Building on ResiliOnt, we present a decision-oriented ontology sketch that extends the core resilience pattern with a decision-context layer, a regime-and-trajectory layer, and an assessment-and-mapping layer. Regime descriptions are modeled as *Information Content Entities*, which allows engineered resilience to be represented as the special case in which the acceptable regime set is singleton, while ecological-style resilience permits multiple acceptable regime descriptions and admissible transitions among them. We provide a compact competency-question traceability table, a minimal formal fragment, and a worked micro-scenario for Colorado Front Range lifelines. The example includes an explicit regime-description template, regime-membership rule, regime-shift criterion, resilience metric specification and value, evidence and provenance records, uncertainty annotation, and a miniature mapping to Bayesian and dynamic Bayesian network variables.
The result is a more inspectable and reusable ontology pattern for resilience-informed decision support that clarifies measurand semantics, supports interpretability of metric outputs, and enables transparent interfaces to probabilistic causal models without embedding probabilistic semantics into the ontology itself.

Keywords: Resilience ontology, decision-oriented resilience, Information Content Entities, resilience metrics, probabilistic decision support, critical infrastructure.

1. Introduction

Resilience has become a central objective in safety, reliability, and risk management for critical infrastructures, yet the term continues to support incompatible meanings and metrics that are difficult to compare across systems and hazards. The difficulty is acute for interdependent lifeline systems exposed to rapidly evolving threats, such as wildfires in the Colorado Front Range, where cascading disruptions, partial restoration, and improvised operating modes are common. Canonical engineering formulations often represent resilience through functionality loss and recovery, with emphasis on time-to-recovery and related performance profiles. Ecological formulations, by contrast, emphasize persistence, reorganization, and the possibility of transitions among alternative regimes.

Much of the tension between these formulations, we argue, is sustained by a representational mistake. In decision settings, regimes and equilibria primarily function as structured descriptions of acceptable operation rather than as ontologically thick states. For this reason, we model regime descriptions as *Information Content Entities* (ICEs): representational artifacts that specify relevant performance variables, tolerances, time scales, and contextual conditions. Engineered resilience becomes the special case in which the set of acceptable regime descriptions is singleton, whereas ecological-style resilience permits multiple acceptable regime descriptions and transitions among them.

Building on the ResiliOnt core ontology, we present a concise decision-oriented ontology sketch that (i) adds a minimal decision context, (ii) treats resilience explicitly as a measurand with metric semantics, provenance, and uncertainty annotations, and (iii) supports a principled interface to Bayesian networks (BNs) and dynamic Bayesian networks (DBNs) through typed node and edge mapping specifications.

1.1. *Related work*

Quantitative resilience in engineered systems is commonly operationalized through service-performance trajectories under disturbance, often summarized by measures that combine depth and duration of performance loss, recovery time, and resource constraints. The community resilience framework of Bruneau et al. remains a canonical reference point for such quantification, and subsequent surveys have documented the breadth of resilience definitions and measures across engineering domains (Bruneau et al. (2003); Hosseini et al. (2016); Yodo and Wang (2016)). In power and lifeline contexts, resilience metrics have increasingly been tailored to operational considerations such as restoration dynamics, service continuity, and system reconfiguration (Panteli et al. (2017); Sweetapple et al. (2018); Curt and Tacnet (2018); Paglioni et al. (2026)).

A parallel tradition distinguishes engineered resilience from ecological resilience. Holling's formulation contrasted return-time concepts with the capacity to absorb disturbance without shifting regimes, thereby motivating multi-regime descriptions and regime-shift analysis (Holling (1973)). Work on alternative equilibria and regime shifts provided further conceptual support for this view (Scheffer et al. (1993); Neubert and Caswell (1997); Pimm (1984); Gunderson and Holling (2002)). Yet these concepts are often imported into infrastructure resilience without a precise representational account of what constitutes a regime, how regime membership is determined, or what evidential standard justifies a regime-shift claim.

Ontological work on resilience has begun to formalize key concepts using foundational commitments and conceptual modeling languages. Barcelos et al. proposed ResiliOnt, an ontology that characterizes resilience through objects at risk, threats, vulnerabilities, capabilities, and loss-of-value (Barcelos et al. (2025)). The present contribution is complementary. It preserves the ResiliOnt core structure while extending it with a decision-oriented assessment layer and a regime-and-trajectory layer, thereby supporting explicit measurand semantics and a transparent interface to probabilistic causal models increasingly used for interdependent infrastructure analysis (Bakhtiari et al. (2025); Cai et al. (2021); Sun et al. (2024)).

2. Background and problem framing

2.1. *Resilience as a measurand for safety and reliability decision support*

In safety, reliability, and risk engineering, resilience is invoked to guide decisions about prevention, preparedness, response, recovery, and adaptation when disruptions cannot be eliminated. For operational use, however, resilience must be treated explicitly as a measurand. A resilience assessment should specify the relevant service, the performance variables and acceptability thresholds, the time horizon, the disturbance class, the evidential basis of the estimate, and the uncertainty attached to the result. When these elements remain implicit, resilience values can be difficult to interpret and difficult to compare across scenarios.

2.2. *Engineered and ecological-style resilience as representational commitments*

The familiar distinction between engineered and ecological resilience is often presented as a theoretical disagreement. For infrastructure decision support, however, the more important issue is representational: how analysts specify acceptable operation, identify departures, justify regime-shift claims, and connect those claims to intervention choices using available evidence. In many infrastructure settings, what counts as acceptable is not fixed by physical dynamics alone. It is defined through regulation, service obligations, stakeholder priorities, and operational doctrine.

Emergency operating configurations may therefore count as acceptable even when they depart substantially from nominal conditions.

This suggests a reframing. The engineered–ecological contrast is often best understood as a difference in representational commitments about acceptable operation. Engineered resilience corresponds to a singleton acceptable regime description. Ecological-style resilience permits a set of acceptable regime descriptions together with admissible transitions among them. The advantage of this reframing is not merely philosophical. It clarifies what must be represented if resilience claims are to support actual decisions.

2.3. *Interdependent lifelines and probabilistic reasoning under uncertainty*

Wildfires in the Colorado Front Range illustrate the importance of interdependent lifelines and cascading disruptions. Power, communications, water, and transportation systems are linked through physical dependencies, shared hazard exposure, and organizational constraints. Disruptions propagate through these couplings, and restoration actions can introduce additional tradeoffs and timing constraints. In such settings, probabilistic causal modeling is a natural tool for reasoning under uncertainty. The interpretability of BNs and DBNs, however, depends on the clarity of the variables represented and on the justification of the dependency structure. This suggests a role for ontology: to provide explicit semantics for variables, evidence claims, dependency types, and assessment outputs.

3. Method and design principles

3.1. *Competency questions as scope control*

We adopt a competency-question-driven approach in which competency questions function as acceptance tests for the ontology. The goal is not to provide an exhaustive extension, but rather to identify a minimal set of representational commitments sufficient for decision-oriented resilience assessment and for its interface to probabilistic causal modeling. Table 1 lists a representative subset of competency questions and the principal ontology elements required to answer them.

3.2. *Foundation: ResiliOnt as the core resilience pattern*

We build on the ResiliOnt core ontology, which frames resilience using a risk-oriented structure involving *ObjectAtRisk*, *ThreatEvent*, *Vulnerability*, *Capability*, and *LossEvent*/*Loss-of-Value* (Barcelos et al. (2025)). This core pattern provides a disciplined basis for resilience claims by tying them to threat exploitation of vulnerabilities and to the enabling or disabling role of capabilities.

3.3. *Design principles*

The extension is guided by three design principles.

P1. Regime descriptions are modeled as Information Content Entities. A regime description is a structured description of acceptable operation parameterized by performance variables, tolerances, time scales, and contextual conditions. This supports both engineered and ecological-style resilience without requiring equilibrium realism.

P2. System properties, realized processes, and assessment artifacts are kept distinct. Capabilities and vulnerabilities are system properties. Disturbances, responses, and recoveries are realized processes. Assessments, regime claims, metric specifications, and metric values are information artifacts that summarize and justify claims relative to evidence.

P3. Resilience metrics require explicit measurand semantics. Metric specifications define inputs, computation rules, interpretation notes, evidence links, and uncertainty annotations. Metric values are intelligible only in relation to those specifications.

4. Decision-oriented ontology sketch

4.1. *Decision context and performance semantics*

Decision-oriented assessment requires explicit representations of what is valued, how performance is measured, and what counts as acceptable service. We therefore introduce a minimal *DecisionContext* that specifies stakeholders and con-

CQ	Question	Principal ontology elements
A1	What is the bearer of resilience: component, subsystem, or system-of-systems?	*ObjectAtRisk*, *SystemScopeSpecification*, composition relation
B1	Which services, performance variables, units, tolerances, and time scales define the assessment target?	*DecisionContext*, *PerformanceVariableSpecification*, *AcceptabilityThreshold*, *BaselineSpecification*
C1	What constitutes a regime description for this assessment?	*RegimeDescription*, *OperatingConditionSpecification*, *TimeScaleSpecification*
C2	Is acceptable operation represented by a singleton regime or by a set of admissible regimes?	*RegimeSetDescription*, *RegimeDescription*
C3	What counts as a regime shift, and what evidence justifies asserting one?	*RegimeShiftAssertion*, *RegimeShiftCriterion*, *EvidenceRecord*, *ProvenanceRecord*
G1	What explains the difference between two resilience values?	*ResilienceMetricSpecification*, *ResilienceMetricValue*, *TrajectoryRecord*, *DecisionRelevanceExplanation*
G4	How is uncertainty in the metric represented?	*UncertaintyAnnotation*, uncertainty type, credibility or distribution information
H1	Which ontology entities become BN or DBN nodes?	*NodeMappingSpecification*, *StateVariableSpecification*
H2	Which dependency types justify causal edges?	*EdgeTypeSpecification*, physical, cyber/information, organizational, shared-exposure dependencies
J2	How can resilience be represented as a measurand while accommodating multi-regime ecological-style resilience?	*RegimeDescription* as ICE, *ResilienceAssessment*, *EvidenceRecord*, *AcceptabilityCriterion*

Layer	Role and principal artifacts
ResiliOnt core	Threat-dependent resilience pattern: *ObjectAtRisk*, *ThreatEvent*, *Vulnerability*, *Capability*, *LossEvent*.
Decision context	What is valued and how service is assessed: *DecisionContext*, *PerformanceVariableSpecification*, *AcceptabilityThreshold*, *BaselineSpecification*.
Regimes and assessment	Acceptable operation, trajectories, and outputs: *RegimeDescription*, *RegimeSetDescription*, *TrajectoryRecord*, *RegimeShiftAssertion*, *ResilienceAssessment*, *ResilienceMetricSpecification*, *ResilienceMetricValue*, *EvidenceRecord*, *UncertaintyAnnotation*.
BN/DBN mapping	Mapping to probabilistic variables and edges: *NodeMappingSpecification*, *EdgeTypeSpecification*.

straints, the service under assessment, the associated performance-variable specifications (including units, sampling assumptions, and aggregation rules), the acceptability thresholds that define tolerable deviation across relevant time scales, and the baseline specification against which claims of degradation, recovery, or improvement are evaluated.

4.2. *Regime descriptions, trajectory records, and regime-shift assertions*

The central reconciliation move is implemented through a small family of information artifacts. A *RegimeDescription* specifies at minimum (i) the service or services under assessment, (ii) the relevant performance variables, (iii) the admissible values or thresholds for those variables, (iv) the temporal window over which membership is determined, and (v) the contextual conditions under which the description applies. A *RegimeSetDescription* collects the admissible regime descriptions for a given decision context. A *TrajectoryRecord* stores the time-indexed observations or estimates used to assess performance over time.

A *RegimeShiftAssertion* records a claim that a trajectory has crossed from one regime description to another. To reduce interpretive looseness, such an assertion should not be made merely because one observation crosses a threshold. It should be linked to an explicit *RegimeShiftCriterion*, an *EvidenceRecord*, and a *ProvenanceRecord*. Under this representation, engineered resilience corresponds to the special case in which the acceptable regime set is singleton, whereas ecological-style resilience permits multiple acceptable regime descriptions and admissible transitions among them.

4.3. *A minimal formal fragment*

Figure 1 provides a compact pseudo-Turtle fragment that instantiates the principal additions. The fragment is intentionally minimal. Its purpose is not to present a complete OWL module, but to make the sketch auditable by showing the main classes and relations required by the decision-oriented extension.

4.4. *Resilience assessment, metric semantics, and uncertainty*

To treat resilience as a measurand, we represent assessments and metric outputs as information artifacts linked to explicit definitions and evidence. A *ResilienceAssessment* characterizes an object at risk under a specified decision context and threat profile. The associated *ResilienceMetricSpecification* defines the inputs to the metric, including the trajectory records, thresholds, and time horizon, together with the computation rule and interpretation notes. A *ResilienceMetricValue* records a

```
:DecisionContext rdf:type owl:Class .
:RegimeDescription rdf:type owl:Class ; rdfs:subClassOf iao:InformationContentEntity .
:RegimeSetDescription rdf:type owl:Class ; rdfs:subClassOf iao:InformationContentEntity .
:TrajectoryRecord rdf:type owl:Class ; rdfs:subClassOf iao:InformationContentEntity .
:RegimeShiftAssertion rdf:type owl:Class ; rdfs:subClassOf iao:InformationContentEntity .
:ResilienceAssessment rdf:type owl:Class ; rdfs:subClassOf iao:InformationContentEntity .
:ResilienceMetricSpecification rdf:type owl:Class ; rdfs:subClassOf
iao:InformationContentEntity .
:ResilienceMetricValue rdf:type owl:Class ; rdfs:subClassOf iao:InformationContentEntity .
:EvidenceRecord rdf:type owl:Class ; rdfs:subClassOf iao:InformationContentEntity .
:ProvenanceRecord rdf:type owl:Class ; rdfs:subClassOf iao:InformationContentEntity .
:UncertaintyAnnotation rdf:type owl:Class ; rdfs:subClassOf iao:InformationContentEntity .
:NodeMappingSpecification rdf:type owl:Class ; rdfs:subClassOf iao:InformationContentEntity
.
:EdgeTypeSpecification rdf:type owl:Class ; rdfs:subClassOf iao:InformationContentEntity .

:hasPerformanceVariableSpec rdfs:domain :DecisionContext ; rdfs:range
:PerformanceVariableSpecification .
:hasAcceptabilityThreshold rdfs:domain :RegimeDescription .
:usesTrajectoryRecord rdfs:domain :ResilienceAssessment ; rdfs:range :TrajectoryRecord .
:specifiedBy rdfs:domain :ResilienceMetricValue ; rdfs:range :ResilienceMetricSpecification
.
:supportedByEvidence rdfs:domain :RegimeShiftAssertion ; rdfs:range :EvidenceRecord .
:hasProvenance rdfs:domain :RegimeShiftAssertion ; rdfs:range :ProvenanceRecord .
:hasUncertaintyAnnotation rdfs:domain :ResilienceMetricValue ; rdfs:range
:UncertaintyAnnotation .
:mapsOntologyStateToNode rdfs:domain :NodeMappingSpecification .
:justifiesEdgeType rdfs:domain :EdgeTypeSpecification .
```

Fig. 1. Minimal formal fragment for the decision-oriented extension.

computed output linked back to its specification.

This arrangement supports interpretability claims of the following kind: two resilience values differ because the underlying trajectories differ in their durations within acceptable performance bands, their depths of degradation, or their transitions among acceptable regimes. *EvidenceRecord*s and *ProvenanceRecord*s document the data sources and justification structure supporting the assessment. *UncertaintyAnnotation*s capture the relevant uncertainty type, credibility information, and, where appropriate, distributional or interval content.

4.5. *Interface to Bayesian and dynamic Bayesian networks*

The interface between the ontology and probabilistic causal models is represented through explicit mapping artifacts rather than by embedding Bayesian semantics directly in the ontology. A *NodeMappingSpecification* defines how ontology entities and states, such as vulnerability status, capability availability, or regime membership, become BN or DBN variables. An *EdgeTypeSpecification* defines the dependency categories that justify causal edges, including physical dependencies, cyber or information dependencies, organizational dependencies, and shared exposure.

Panarchy and adaptive-cycle concepts remain outside the representational scope of the present sketch. They are relevant future extensions for multi-scale regime dynamics, but they are not implemented here. The present paper instead concentrates on the minimal semantics needed for decision-oriented resilience assessment and for transparent BN/DBN mappings.

5. Illustrative micro-scenario: Front Range wildfire and lifeline interdependence

We consider a stylized Front Range wildfire scenario involving power, communications, and water infrastructure. The service focus is emergency water delivery for suppression and public safety, represented by hydrant pressure and flow at designated critical nodes together with the availability of emergency communications supporting incident command. The decision context includes utilities, emergency management, and municipalities as principal stakeholders, with a 72-hour response horizon for the present assessment.

5.1. *Instantiating regime descriptions*

Table 3 instantiates two regime descriptions for water delivery. Regime A captures nominal operation. Regime B captures an islanded but still

Field	Regime A: nominal operation	Regime B: islanded emergency operation
Service	Emergency water delivery	Emergency water delivery
Performance variables	Hydrant pressure; hydrant flow; communications availability	Hydrant pressure; hydrant flow; communications availability
Acceptability thresholds	Pressure $\geq$ 65 psi; flow $\geq$ 1500 gpm; emergency communications available	Pressure 45–64 psi; flow $\geq$ 1000 gpm; backup communications available
Time window for membership	Conditions must hold over a 15-minute aggregation window	Conditions must hold over a 15-minute aggregation window
Contextual conditions	Grid-powered pumping available	Backup generation available; fuel logistics support no more than 36 h continuous operation
Membership rule	Regime A holds if all thresholds are met in the aggregation window	Regime B holds if all thresholds are met and cumulative residence in B does not exceed 36 h

acceptable emergency mode. The ecological-style interpretation treats both as acceptable. The engineered interpretation treats only Regime A as acceptable.

A *RegimeShiftAssertion* from A to B is made only when the target conditions hold for two consecutive 15-minute windows and are supported by at least two evidence sources, one direct measurement source and one operational corroboration source. In the present scenario, that evidentiary basis may consist of SCADA pressure measurements together with a generator dispatch log or an operator event record.

5.2. *Trajectory snippet and metric computation*

Consider the synthetic 72-hour service trajectory shown in Table 4. The trajectory is deliberately simple and is included only to demonstrate how the ontology pattern can be executed. States A and B are acceptable regimes; state U denotes unacceptable operation.

Time interval (h)	Assigned state
0–8	Regime A
8–20	Regime B
20–26	U
26–54	Regime B
54–72	Regime A

Let the *ResilienceMetricSpecification* assign service scores $s(t) = 1.0$ for Regime A, $s(t) = 0.7$ for Regime B, and $s(t) = 0$ for U over a 72-hour horizon. The metric is then defined as the normalized area under the acceptable-service trajectory:

$$RM_{72} = \frac{1}{72}\int_0^{72} s(t)\,dt. \tag{1}$$

For the trajectory in Table 4, the corresponding *ResilienceMetricValue* is

$$RM_{72} = \frac{8(1.0) + 12(0.7) + 6(0)}{72} + \frac{28(0.7) + 18(1.0)}{72} = 0.75. \tag{2}$$

The interpretation is explicit: the score is lower than 1.0 because 40 hours were spent in a reduced but acceptable regime and 6 hours in unacceptable operation. The metric therefore supports a traceable explanation of why this trajectory differs from one that remained entirely in Regime A or one that experienced a longer unacceptable interval.

5.3. *Evidence, provenance, and uncertainty*

In the ontology sketch, the foregoing metric value is not free-floating. It is linked to an *EvidenceRecord* that may include SCADA pressure time series, pump-station alarm logs, and generator dispatch records. A *ProvenanceRecord* documents source identity, timestamp synchronization assumptions, preprocessing decisions, and the rule used to aggregate observations into 15-minute windows. An *UncertaintyAnnotation* records, for example, that the transition time between A and B is uncertain within one aggregation window because SCADA and dispatch logs are not perfectly synchronized. This is epistemic uncertainty about the assessment record rather than aleatory variability in the physical process itself.

5.4. *Miniature BN/DBN mapping demonstration*

Table 5 shows a compact mapping from ontology states to DBN variables. The purpose is not to propose a full probabilistic model, but to demonstrate the kind of typed traceability the ontology supports.

Ontology state or artifact	DBN variable	Edge justification type	Illustrative observation or update
Wildfire exposure state	$WildfireExposure_t$	Shared exposure	Fire perimeter and weather update
Feeder service status	$FeederStatus_t$	Physical dependency from wildfire exposure	Utility outage status
Backup generation availability	$BackupGeneration_t$	Organizational and physical dependency	Dispatch record, fuel-status report
Pump-station power status	$PumpStationPower_t$	Physical dependency from feeder and generation states	Pump alarm log
Emergency communications availability	$EmergencyComms_t$	Cyber/information and organizational dependency	Radio network status log
Water-service regime membership	$WaterServiceRegime_t$	Derived from service variables and decision-context thresholds	SCADA pressure and flow observations

This mapping clarifies how evidence enters the probabilistic model. SCADA measurements update the inferred water-service regime through the thresholds specified in the regime descriptions, while dispatch and outage records update capability and dependency states. The ontology does not replace the DBN; it makes the semantics of nodes, edges, observations, and assessment outputs explicit and reviewable.

6. Conclusion

Resilience is increasingly invoked as a decision objective in safety, reliability, and risk management for interdependent lifeline infrastructures, yet persistent plurality in definitions and metrics undermines comparability and interpretability across systems and hazards. This paper proposed a decision-oriented ontology sketch that reconciles engineered and ecological-style resilience for practical purposes by treating regime descriptions as Information Content Entities: structured descriptions of acceptable operation parameterized by performance variables, tolerances, time scales, and contextual conditions.

The contribution in this paper is intentionally modest but explicit. It provides a competency-question-grounded extension of the ResiliOnt core, a minimal formal fragment, and a worked example that shows how regime descriptions, trajectory records, assessment artifacts, evidence, uncertainty annotations, and BN/DBN mappings fit together in a decision-oriented account of resilience. On this representation, engineered resilience is the special case in which the acceptable regime set is singleton, whereas ecological-style resilience permits multiple acceptable regime descriptions and admissible transitions among them.

Future work should formalize the pattern in a full ontology implementation, connect it to richer multi-scale regime dynamics, and evaluate the resulting structures in applied lifeline scenarios.

References

Bakhtiari, S., M. R. Najafi, K. Goda, and H. Peerhossaini (2025, May). A dynamic Bayesian network approach to characterize multi-hazard risks and resilience in interconnected critical infrastructures. *Reliability Engineering & System Safety 257*, 110815.

Barcelos, P. P., R. F. Calhau, Oliveira, T. Prince Sales, F. Gailly, G. Poels, and G. Guizzardi (2025). Ontological Foundations of Resilience. In W. Maass, H. Han, H. Yasar, and N. Multari (Eds.), *Conceptual Modeling*, Volume 15238, pp. 396–416. Cham: Springer Nature Switzerland. Series Title: Lecture Notes in Computer Science.

Bruneau, M., S. E. Chang, R. T. Eguchi, G. C. Lee, T. D. O'Rourke, A. M. Reinhorn, M. Shinozuka, K. Tierney, W. A. Wallace, and D. Von Winterfeldt (2003, November). A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities. *Earthquake Spectra 19*(4), 733–752.

Cai, B., Y. Zhang, H. Wang, Y. Liu, R. Ji, C. Gao, X. Kong, and J. Liu (2021, May). Resilience evaluation methodology of engineering systems with dynamic-Bayesian-network-based degradation and maintenance. *Reliability Engineering & System Safety 209*, 107464.

Curt, C. and J. Tacnet (2018, November). Resilience of Critical Infrastructures: Review and Analysis of Current Approaches. *Risk Analysis 38*(11), 2441–2458.

Gunderson, L. H. and C. S. Holling (Eds.) (2002). *Panarchy: Understanding Transformations in Human and Natural Systems*. Washington, DC: Island Press.

Holling, C. S. (1973, November). Resilience and Stability of Ecological Systems. *Annual Review of Ecology and Systematics 4*(1), 1–23.

Hosseini, S., K. Barker, and J. E. Ramirez-Marquez (2016, January). A review of definitions and measures of system resilience. *Reliability Engineering & System Safety 145*, 47–61.

Neubert, M. G. and H. Caswell (1997, April). Alternatives to resilience for measuring the responses of ecological systems to perturbations. *Ecology 78*(3), 653–665.

Paglioni, V. P., G. Troxell, A. Brown, S. Conrad, and M. Arabi (2026). Developing a quantitative resiliency approach.

Panteli, M., P. Mancarella, D. N. Trakas, E. Kyriakides, and N. D. Hatziargyriou (2017, November). Metrics and Quantification of Operational and Infrastructure Resilience in Power Systems. *IEEE Transactions on Power Systems 32*(6), 4732–4742.

Pimm, S. L. (1984, January). The complexity and stability of ecosystems. *Nature 307*(5949), 321–326.

Scheffer, M., S. Hosper, M.-L. Meijer, B. Moss, and E. Jeppesen (1993, August). Alternative equilibria in shallow lakes. *Trends in Ecology & Evolution 8*(8), 275–279.

Sun, J., K. Bathgate, and Z. Zhang (2024, June). Bayesian network-based resilience assessment of interdependent infrastructure systems under optimal resource allocation strategies. *Resilient Cities and Structures 3*(2), 46–56.

Sweetapple, C., M. Astaraie-Imani, and D. Butler (2018, December). Design and operation of urban wastewater systems considering reliability, risk and resilience. *Water Research 147*, 1–12.

Yodo, N. and P. Wang (2016, November). Engineering Resilience Quantification and System Design Implications: A Literature Survey. *Journal of Mechanical Design 138*(11), 111408.