MODELS FOR MANAGING THE RESILIENCE AND CONTINUITY OF PUBLIC FUNCTIONS IN THE CONTEXT OF DISASTERS AND CRISES

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Abstract

This article examines models for managing the resilience and continuity of public functions in the context of disasters and crises. The focus is placed on identifying critical interdependencies among essential public services and the possibilities for their maintenance under extreme conditions. Contemporary concepts of integrated management, based on proactive planning and adaptive response, are presented. International best practices and standards related to the resilience of infrastructural and social systems are analyzed. Mechanisms for institutional coordination and interaction with civil society are discussed. The study also proposes mathematical approaches for risk assessment and for evaluating the effectiveness of continuity measures. The results contribute to the development of policies and strategies aimed at enhancing societal resilience against future threats.

Keywords: *Resilience; Continuity; Public Functions; Disasters; Crises; Risk Management; Critical Infrastructure.*

1. INTRODUCTION

Under global challenges such as climate change, pandemics, technological accidents, and hybrid threats, the question of the resilience and vulnerability of essential societal functions (ESFs) has become particularly salient. These functions include healthcare, water supply, energy, telecommunications, logistics, and other systems whose disruption results in significant social and economic consequences.

The concept of resilience extends beyond physical protection and encompasses the ability of systems to absorb shocks, adapt, and recover into a new functional reality [1], [2].

Conversely, vulnerability is determined by internal weaknesses, the lack of alternative mechanisms, and dependencies on external systems that facilitate the propagation of impacts during disasters and crises [2].

This study analyzes the fundamental aspects of resilience and vulnerability of ESFs through a review of the scientific literature and good practices in order to present tools for assessing and enhancing systemic resilience.

2. THEORETICAL FRAMEWORK AND DEFINITIONS

2.1. Definitions of Resilience

In the context of public functions, resilience is defined as the ability of a system or network to anticipate, respond, absorb, adapt, and recover after a disruptive event while maintaining its critical functionality [2], [3], [4].

Contemporary understanding includes three key components [1], [5]:

– absorption of shocks (robustness and buffering capacity);
– adaptation and transformation (adaptability and flexibility);

- recovery and continuity of operations.

According to Linkov et al. (2014) [1], resilience can be measured by the indicator shown in Equation (1):

$$R = \frac{Qmin}{Q0} + \frac{Trec}{Tmax} \quad (1)$$

where:

- Q_0 is the initial performance level;
- Q_{min} – the minimum level after the shock;
- T_{rec} – the recovery time;
- T_{max} – the admissible recovery threshold.

The closer the result is to 1, the more resilient the system [1].

2.2. Definitions of Vulnerability

Vulnerability is the degree to which a system, infrastructure, or social group is susceptible to adverse effects of hazards due to internal weaknesses, resource shortages, or a lack of adaptive capacity [6], [7].

The IPCC defines vulnerability as a function of three basic components:

- exposure – the likelihood the system will be affected by a specific event;
- sensitivity – the degree to which it reacts to impacts;
- adaptive capacity – Its ability to cope and recover.

A quantitative representation is provided in Equation (2) [8]:

$$V = \frac{E.S}{AC} \quad (2)$$

where:

- V – denotes vulnerability;
- E – exposure;
- S – sensitivity;
- AC – adaptive capacity.

Lower adaptive capacity implies higher vulnerability.

Social vulnerability is also shaped by unequal access to services, infrastructure, and information. Cutter et al. (2003) emphasize that poverty, age, disability, language barriers, and marginalization increase risk for particular groups [9].

UNDP (2023) recommends that vulnerability be viewed not as a static condition but as a dynamic process that changes over time and with the external environment [7].

2.3. Essential Societal Functions and Critical Infrastructure

Essential societal functions (ESFs) are those services and systems that sustain the basic functioning of society – healthcare, security, electricity, water supply, transport, telecommunications, waste management, etc. [10].

These functions are closely linked to critical infrastructure (CI) – assets, networks, and facilities whose disruption or destruction would have serious consequences for society, the economy, or national security [11], [12].

The relationship between ESFs and CI is systemic – disruption of one function often produces cascading effects on others. For example: power outages affect water supply, telecommunications, and healthcare; transport breakdowns hinder emergency aid and the delivery of food and medicines; failures in information systems hamper crisis management and public communication. The European Union defines the protection of ESFs as a priority within the Union Civil Protection Mechanism [13].

A model for assessing the vulnerability of essential functions includes the indicators summarized in Equation (3) [10]:

$$E.S.F_{risc} = f(PI, DE, RI) \tag{3}$$

where:

- *PI* – is potential impact;
- *DE* – dependency on other elements;
- *RI* – the redundancy index.

Lower RIcorresponds to higher risk of functional collapse during a crisis.

3. Mechanisms of Resilience and Vulnerability in Crisis Situations

Understanding how ESFs withstand or fail during disasters and crises is key to building effective resilience strategies. Resilience and vulnerability are not opposites but interrelated characteristics that determine system response to destructive events.

3.1. Components of Resilience

UNDRR (2020) identifies four principal components of resilience [14]:

- adaptive capacity – flexible governance, updating of plans and technologies;
- absorptive capacity – the ability to withstand impacts without interruption of function;
- recovery capacity – rapid return to normal or improved performance;
- transformative capacity – changing the system to be better prepared for future events [1], [15].

An exemplary functional resilience model is represented in Equation (4):

$$R_f = \alpha A_f + \beta B_f + \gamma C_f + \delta T_f \tag{4}$$

where:

- R_f – is the resilience of function *f*;
- A_f – adaptability;
- B_f – absorptive capacity;
- C_f – recovery capacity;
- T_f – transformative capacity;
- α, β, γ, δ – are weights reflecting the importance of each component.

3.2. Factors of Vulnerability

Vulnerability reflects the susceptibility of a system to harm and is determined by three key factor groups [7], [9]:

- exposure (e.g., a hospital located in a floodplain);
- sensitivity (e.g., aging assets, poor maintenance);
- lack of capacity (absence of reserves, plans, and personnel).

A functional vulnerability model is expressed in Equation (5):

$$V_f = +S\frac{E_f.S_f}{C_f} \quad (5)$$

where:

- V_f – is the vulnerability of function f;
- E_f – exposure;
- S_f – sensitivity;
- C_f – response capacity.

The lower C_f is, the higher the vulnerability.

4. RISK IDENTIFICATION AND MODELS FOR ASSESSING RESILIENCE

Resilience of ESFs cannot be managed without the systematic identification of risks and the application of quantitative and qualitative assessment models. Risk assessment involves identifying threats (e.g., earthquakes, cyberattacks), estimating their probability, and determining potential consequences. According to ISO 31000 and UNISDR (2017) [16], the formal expression for risk is:

$$R = P\ .\ I \quad (6)$$

where:

- R is risk;
- P – the probability of occurrence;
- I – its impact on public functions [16], [17].

In the context of interdependent systems, extended models are used, as indicated in Equation (7):

$$R_s = \sum_{i=1}^{n} P_i.I_i + \sum_{j=1}^{m} D_i.V_i \quad (7)$$

where:

- D_j is the degree of interdependence among functions;
- V_j – the vulnerability of connected nodes.

4.2. Methods for Assessing Resilience

The most widely used approaches include:

Scorecard Models. Used by UNDRR and the World Bank – capacities are scored (e.g., 1 to 5) for institutional readiness, infrastructural robustness, recovery and adaptation capacity. Example: *Disaster Resilience Scorecard for Cities* [14].

Network-based Models. Interconnected-system models simulate failures and the propagation of impacts through network analysis [18], [19]. Networks consist of nodes (e.g., hospitals, power plants) and edges (dependencies). The effect of a failed node on the rest of the network is then evaluated.

4.3. Indicators of Resilience and Vulnerability

Following Cutter et al. (2010), resilience can be assessed using indicators such as access to reserves, recovery time, public awareness and behavior, and degree of inter-institutional integration [9].

An aggregated resilience index is represented in Equation (8):

$$IR = \frac{(C_1 + C_2 + \dots\dots\dots C_n)}{n} \quad (8)$$

where C_i are criterion scores, commonly scaled from 0 to 1.

5. Institutional Role and Cross-sector Coordination

Managing the resilience of ESFs requires coordinated interaction among institutions, sectors, and levels of governance. Because threats often simultaneously affect multiple subsystems (energy, transport, healthcare), isolated approaches are ineffective. An integrated, multi-pronged response is needed.

5.1. Inter-institutional Coordination

UNDRR (2020) highlights the following for effective coordination [14]: clear institutional responsibilities; real-time data sharing; regular joint exercises; joint disaster action plans; and resource sharing (staff, equipment, communications). In crises, every minute is critical; lack of inter-agency synchronization increases community vulnerability [20], [21].

5.2. Multi-level Governance

Crisis governance operates at several levels: national (strategic planning, resource provision), regional (coordination among municipalities), and local (operational management and public communication). An effective model is the Whole-of-Society Approach (WHO/UNDP), defined as: "State, market, civil society and individuals working in synergy to strengthen resilience" [7], [20].

5.3. Cross-sector Dependence and Coordination

ESFs do not operate in isolation. For example: an electricity outage → communications failure → hospital service collapse → increased threat to life. Sectors requiring the highest degree of coordination include:

Table 1. Sectors and Their Critical Dependence

Sector	Critical Dependence
Energy	Transport, healthcare, telecommunications
Water supply	Health, hygiene, fire safety
Healthcare	Energy, transport, IT
Transport	Energy, logistics

On this basis, cross-sector coordination emerges as a key factor of resilience [7], [22].

6. Innovative Tools and Approaches for Strengthening Resilience

Contemporary ESF challenges call for approaches that go beyond traditional preparedness plans. New technologies, digital tools, and concepts such as digital twins and simulation-based decision models play an increasingly important role in building system-level resilience.

6.1. Scenario Modelling and Simulations

Scenario modelling supports strategic planning through the analysis of hypothetical yet plausible events, including chain reactions during failures, analysis of network choke points, simulation of recovery processes, and forecasting social/logistical consequences [22], [23]. Applications such as EvacuAid and agent-based modelling are used to forecast evacuation behavior, traffic disruption, hospital-system collapse, and other aspects of vulnerability [24], [25].

6.2. Digital Twins

A digital twin is a virtual model of real infrastructure that enables real-time monitoring, scenario simulation, risk and impact assessment, and adaptive strategies. Example: a digital model of the power grid can forecast storm-related failures and propose optimal rerouting of power flows [26].

6.3. GIS and Spatial Analysis

Geographic information systems (GIS) support the localization of vulnerable areas, mapping of system dependencies, modelling of evacuation routes and safe zones, and spatial impact assessment. Tools such as ArcGIS, QGIS, and HEC-RAS are successfully used by civil protection services [20], [21].

6.4. Mathematical Models and Metrics

Resilience can be quantified using several core indicators:
Resilience Index (RI) – see Equation (9):

$$RI = \frac{C_r + A + R}{3} \tag{9}$$

where:
- C_r – is shock-absorption capacity (robustness);
- A – adaptability;
- R – recoverability.

RI ranges from 0 (no resilience) to 1 (maximum resilience).
Interdependent Vulnerability Index (IVI) – see Equation (10):

$$IVI = \sum_{i=1}^{n} (V_i . D_i) \tag{10}$$

where:
- V_i – is the vulnerability of subsystem i;
- D_i – its degree of dependency on other subsystems.

7. Case Studies and Lessons from Real Events

Analysis of real disasters and crises reveals how ESF resilience and vulnerability manifest amid complex, dynamic, and often interlinked threats, offering lessons about institutional coordination, system adaptability, and strategic planning.

7.1. The Earthquake and Nuclear Crisis in Fukushima, Japan (2011)

On 11 March 2011, a magnitude 9.0 earthquake followed by a tsunami caused extensive infrastructure damage and a nuclear accident at the Fukushima Daiichi plant. The event demonstrated cascading dynamics and highlighted: the lack of backup cooling systems; disrupted inter-institutional communication; the need for mass evacuation; and long-term social and environmental impacts [20], [21], [27].

7.2. Western Europe Floods (2021)

Torrential rainfall in July 2021 caused severe flooding in Germany, Belgium, and the Netherlands, resulting in hundreds of fatalities. Communications breakdowns, power outages, and transport system failures revealed insufficient integration of early warnings with local protection structures. According to the European Commission (2022), this incomplete integration was among the main causes of the scale of damage [28].

7.3. Texas Power Grid Failure (2021)

In February 2021, a cold wave triggered a collapse in Texas's power system. Despite technological development, the lack of interconnection with other state grids and insufficient reserves led to mass outages affecting over 4 million people, disruptions in water supply and heating, and increased mortality due to hypothermia and accidents [22].

7.4. The COVID 19 Pandemic and Critical Public Services

COVID 19 placed severe pressure on: the health sector (overloaded hospitals, shortages of staff and equipment); the education sector (shift to online learning); and the economy/social protection (mass unemployment, vulnerable groups). UNDP (2021) notes that pandemic-induced stress exposed systemic vulnerabilities across sectors, underscoring the need for digital resilience and social equity [7].

Quantitative Example: Modelling Impact Propagation in Interdependent Systems

Scenario. In a city of 500,000 inhabitants, a natural disaster (severe flooding) triggers a failure in the power system (E). We evaluate consequences for other interdependent systems: W (water supply), H (healthcare), T (transport), C (communications).

Step 1: **Dependence Coefficients (α)** (based on literature – Liao et al., 2023; Pescaroli & Alexander, 2016 [25], [27]).

Table 2. Dependence Coefficients (α)

From → To	α
E → W	0,9
E → H	0,8
E → T	0,7
E → C	0,95
W → H	0,6
C → H	0,7
C → T	0,5

Step 2: Propagation Formula

For each system S_i, total impact is defined by Equation (11):

$$I(S_i) = \sum_j \alpha_{j\to i} . I(S_j) \tag{11}$$

where:

- $\alpha j \to i$ is the dependence coefficient from system S_j to S_i;
- $I(S_j)$ the impact in S_j.

Step 3: Initial Outage in Power (E = 1,0)

Table 3. Initial Power Outage and Propagated Impacts

System	Calculation	Result
E	–	1,00
W	0,9 × 1,00	0,90
C	0,95 × 1,00	0,95
T	0,7 × 1,00 + 0,5 × 0,95	0,7 + 0,475 = 1,175 → limited to 1,0
H	0,8 × 1,00 + 0,6 × 0,90 + 0,7 × 0,95	0,8 + 0,54 + 0,665 = 2,005 → limited to 1,0

Conclusion. The primary power outage yields total failure (I=1,0) of all other critical public functions within one to two iterations – evidence of high systemic vulnerability and the need for fault tolerance and backup systems.

8. Good Practices and Recommendations

Ensuring ESF resilience under contemporary disasters and crises requires a systematic approach combining institutional coordination, engineering robustness, social engagement, and information support. Based on current research, practices, and policies, the following are recommended:

8.1. Multisector Integrated Planning

- develop shared strategic resilience frameworks across critical infrastructure sectors – energy, healthcare, transport, communications [7], [12];
- introduce unified national and regional continuity plans aligned with risk and vulnerability analyses [10].

8.2. Use of Digital Twins and Simulation Models

- implement digital twins as virtual replicas of infrastructure for impact simulation and preparation for cascading-risk scenarios [26];
- develop scenario simulations that include parameters for the propagation of effects across interdependent systems [29].

8.3. Strengthening Community Adaptive Capacity

- promote community-based initiatives for improving preparedness and adaptability;
- conduct regular public training and drills (mass evacuation, infrastructure failure, hybrid threats).

8.4. Reinforcing Key Infrastructure Elements

- apply redundancy, diversity, and modularity principles in the design and maintenance of critical systems [30];
- invest in autonomous and backup sources for energy, communications, and logistics, especially in healthcare and water supply.

8.5. Enhanced Inter-institutional Coordination

- establish interoperable communication platforms among state authorities, municipalities, and infrastructure operators [28];
- appoint resilience coordinators within major entities, with clearly defined roles during emergencies.

8.6. Quantitative Assessment of Systemic Vulnerability

- use resilience indices and interdependence matrices to identify critical nodes and links in infrastructure networks [31];
- apply formal models such as Equation (12):

$$R_i = P_i . I_i + \sum_{j=1}^{n} \alpha_{ji} . R_j \quad (12)$$

where:
- R_i is risk to system i;
- P_i – the probability of a primary failure;
- I_i – impact intensity;
- α_{ji} – inter-system dependencies.

The foregoing shows that achieving a resilient system requires not just technical modernization but a transformation of risk governance culture – prioritizing interdependencies, flexibility, and the human factor.

Conclusion

The resilience and vulnerability of essential societal functions are interlinked characteristics that determine the ability of societies to cope with contemporary disasters, crises, and accidents. Resilience does not simply mean a return to normal; it also entails the capacity to adapt, transform, and innovate in response to destructive impacts.

Key findings include: systemic vulnerability is amplified by interdependence among critical infrastructures and social systems, especially where reserve capacity and flexibility are lacking; effective risk management requires an integrated approach combining institutional policy, engineering solutions, and behavioral mechanisms at both macro and micro levels; proactive strategic planning, digital-twin scenarios, and quantitative assessments enable the identification of critical weak points and optimization of responses; best practices show that inter-institutional coordination, community engagement, and modern ICT solutions are crucial to building a resilient environment.

In this context, resilience should be viewed not only as a strategic goal but as a continuous process of learning and adaptation in which all stakeholders – from central government to civil society – play a critical role.

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