eXtreme
strategie e soluzioni per la resilienza delle infrastrutture critiche

Extreme Events and Critical Infrastructures: Strategies for Resilience

Call for proposals for development plans on strategic issues, designed as a joint effort between associations within the Emilia-Romagna Smart Specialisation Strategy

INTER CLUST-ER CALL FOR PROPOSALS

Rev_1 – February 2026

CLUST-ER BUILD EDILIZIA E COSTRUZIONI
CLUST-ER INNOVATE INNOVAZIONE NEI SERVIZI
CLUST-ER TOURISM TURISMO E TERRITORIO
CLUST-ER URBAN ECONOMIA URBANA

Summary

In recent years, we have seen how exceptional climatic phenomena, once rare, have become the new normal. Floods, landslides, interruptions in essential services: every crisis reminds us how fragile our infrastructures are and how fundamental the work is of those who, every day, commit themselves to making them safer, more resilient, and more sustainable.

As highlighted in the context of the *"Framework Agreement between the Region and the University of Bologna to jointly address climate change,"* Professor Giovanni Molari, Rector of the University of Bologna, states that resilience can no longer be seen as merely a matter of technologies or procedures: "The rapid evolution of the climate crisis and the vulnerability of our territories to natural risks require new strategies and new responses."[1]

It is a collective vision, a responsibility shared among institutions, businesses, the scientific community, and citizens. It is the ability to learn from events, to integrate knowledge and skills, to innovate, and to collaborate beyond the boundaries of individual sectors.

The AIIC (Italian Association of Experts in Critical Infrastructures), in the report *"Resilience of Critical Infrastructures and Climate Change,"*[2] also emphasizes that "the resilience of critical infrastructures cannot be entrusted to a single approach or isolated technological solution. The complexity and increasing frequency of extreme events require an integrated vision, in which thorough knowledge of networks and the ability to assess vulnerabilities and priorities through advanced and easily readable tools become essential elements for planning and risk management."

[1] https://www.regione.emilia-romagna.it/notizie/2025/marzo/difesa-del-territorio-per-unemilia-romagna-piu-sicura-e-resiliente-accordo-quadro-tra-regione-e-universita-di-bologna-per-affrontare-insieme-il-cambiamento-climatico

[2] Resilienza delle infrastrutture critiche e cambiamenti climatici. Stefanini, A., Bari, S., Bertocchi, G., Bologna, S., Carrozzi, L. Cipriani, G., Dursi, E., Franchina, L., Fumagalli, A.A., & Traballesi, A. (2024).

Overview

The management of critical infrastructures during extreme events represents a strategic challenge for regional safety, economic stability, and the protection of daily life.

In recent years, the Emilia-Romagna Region has recorded a significant increase in extreme climatic events. The 2023 floods in Romagna and the 2024 floods in the Parma/Reggio Emilia areas exposed the vulnerability of critical infrastructures to hydrogeological hazards such as landslides, sudden floods, and urban inundation, with notable impacts on territorial accessibility and on the continuity of emergency services.

These phenomena, once considered rare, are becoming the new normal, posing increasingly complex challenges in the management of regional infrastructures. Among these, the protection of critical infrastructures is a priority: their compromise may generate cascading effects and weaken the resilience of the socio-economic system.

The unpredictability of extreme events requires an integrated approach based on preventive risk analysis, emergency planning, coordination among public and private entities, and advanced technologies for monitoring and response, an approach that places resilience and environmental sustainability at its core, together with deep knowledge of the infrastructures that currently exist.

It is essential to strengthen the capacity to monitor past, current, and future instabilities, as well as the behavior of watercourses and their evolution in emergency scenarios, with particular attention to landslides, floods, and inundations. Another fundamental aspect is the need to keep essential services active, prevent the abandonment of territory, strengthen the resilience of digital infrastructures, and support local economies.

Resilience becomes a strategic objective: designing safe and flexible infrastructures capable of resisting and rapidly restoring their functionality in case of crisis. The central objective of the integrated development strategy of the four regional Clust-ERs (BUILD, INNOVATE, TOURISM, URBAN) is to develop innovative solutions to ensure safety, operational continuity, and integration of emerging technologies within critical infrastructures.

The Extreme project's strategies and solutions for the resilience of critical infrastructures, funded by the Emilia-Romagna Region as an inter-cluster project, aims to develop innovative solutions to increase the resilience of infrastructures in the region, with a focus on logistics and mobility. The goal is to reduce physical and digital risks, guarantee operational continuity, and facilitate integration with emerging technologies.

The Emergency Management System context

Emergency management represents the foundation on which the resilience of a territory is built. Understanding the institutional, regulatory, and operational context of the civil protection system is essential to effectively address the challenges posed by extreme events. In this context, it is crucial to analyze the structure and functioning of the emergency management system in Emilia-Romagna, highlighting the role of the different institutions involved, the methods of coordination, and the main criticalities characterizing the response to crises, in order to identify effective strategies for protecting critical infrastructures and ensuring community safety.

At national level, and consequently at the regional and local levels, the body most involved in emergency intervention and securing sites affected by natural crises or extreme events is the Civil Protection.

Civil Protection in Italy is governed by Legislative Decree 2 January 2018, no. 1, which reorganized the previous regulatory framework by unifying: principles, objectives, organizational structure, and the distribution of competences among the various institutional levels.

Civil Protection is a public function exercised by a complex system of subjects, national, regional and local, that work together to ensure the safeguarding of human life, the integrity of property, settlements, and the environment through coordinated activities of forecasting, prevention, mitigation, preparedness, emergency management, and overcoming emergency situations.

The regulation provides a clear distinction among:

- forecasting, which includes scientific activities to identify risk sources and assess their intensity and probability;
- alerting, the process through which authorities establish alert levels and activation measures based on scenarios provided by functional centers;
- planning, preventive and programmatic, which identifies operational models, support functions, decision chains, and available resources;

- emergency management, the set of measures adopted before, during, and after a calamitous event.

The distribution of responsibilities in emergencies is defined by Article 7 of the Code, which classifies events into three types:

- Type A events, manageable by municipalities or their associations using ordinary powers and resources available in the territory;
- Type B events, characterized by supra-municipal dimensions and requiring coordinated intervention by the Region;
- Type C events, of such intensity or extent that they require extraordinary national intervention, with the direct activation of the State and the Prime Minister, who may issue ordinances derogating from existing regulations.

The structure of operational bodies includes the Fire Brigade, Police Forces, the Italian Red Cross, the National Health Service, the Armed Forces (within their competence), and organized volunteer groups. These entities act within a framework of institutional cooperation and are coordinated, depending on the case, by the Mayor, the Prefect, the Region, or the National Department.

Regional Civil Protection framework in Emilia-Romagna

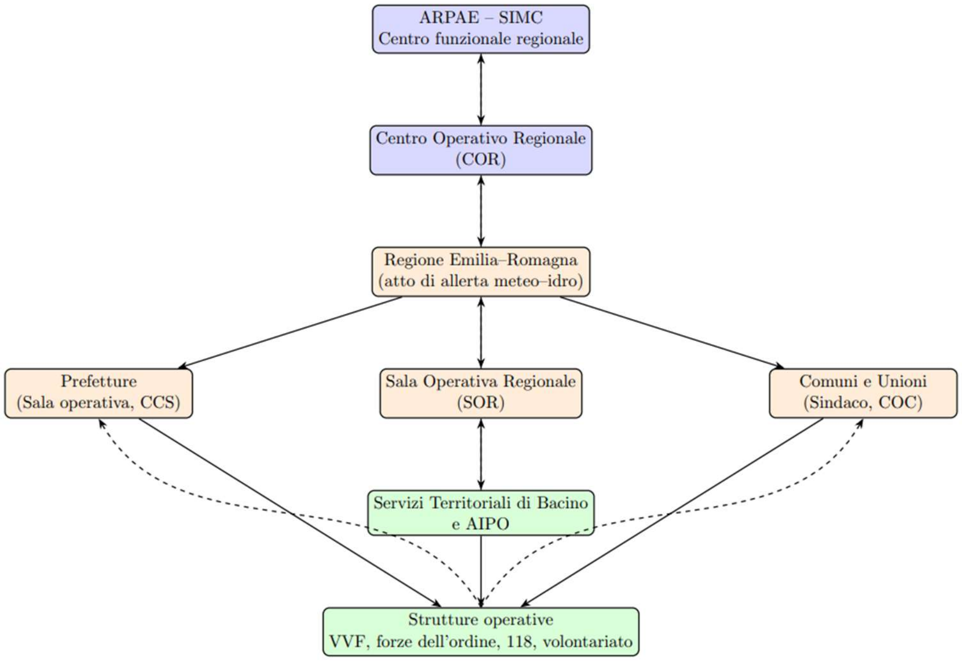
The civil protection system of Emilia-Romagna is regulated by Regional Law 7 February 2005, no. 1, which identifies territorial safety as a priority objective of public action and defines an organizational model based on integration among different levels of government, Region, Provinces, Municipalities, Unions of Municipalities, Mountain Communities, and associated forms, to which regional technical structures and organized volunteer groups are added. The system is composed of all the institutions that contribute, each according to their own responsibilities, to safeguarding people, the environment, and the settlement and production heritage.

Activities include the development of risk knowledge, emergency planning, operator training, public information, alerting activities, rescue operations, and overcoming the emergency. The Region must not only ensure the ability to analyze and predict risks but also to prepare operational, organizational, and logistical tools that enable rapid mobilization of resources and structures, ensuring continuity and effectiveness of civil protection activities.

The Region holds functions of guidance, coordination, and programming and must ensure unified emergency management across its territory, coordinating local authorities and working closely with the competent state administrations.

Its operational structure consists of the Regional Agency for Territorial Safety and Civil Protection, endowed with technical-administrative autonomy, responsible for implementing the activities provided for by law, including resource management and the regional mobile emergency unit. The operational articulation includes the Regional Operational Center (COR), responsible for technical coordination, and the Regional Emergency Operational Committee (COREM), responsible for strategic coordination in the most complex situations. The network includes the Basin Territorial Services (STB), responsible for hydraulic surveillance, watercourse monitoring, and urgent safety interventions, in structured collaboration with ARPAE, recognized as the regional technical-scientific body.

The Regional Law assigns fundamental tasks to the provinces and municipalities. The provinces are responsible for data collection, provincial emergency planning, road management and initial technical measures in the area. The municipalities remain the local civil protection authorities, responsible for municipal planning, informing citizens and activating rescue and assistance services, confirming the mayor's power and duty to direct civil protection interventions in their territory.



The regional system is therefore highly integrated, with forecasting, alerting, planning and management of operations governed by the Region through a network of specialised structures in constant contact with Prefectures, Provinces, Municipalities, Unions of Municipalities and voluntary organisations. This institutional structure, based on solid regulations consistent with the national framework, provides the basis for understanding the specific regional operational chain, which is analysed in the following chapter.

The cooperation with the Regional Directorate of the Fire brigade

In this context, moreover, the Regional Civil Protection System, especially with regard to the prevention and management of wildfire and hydrogeological risks, makes use of the cooperation of the Regional Directorate of the Fire Brigade of Emilia-Romagna, with the primary objective of strengthening civil protection operational activities and making interventions more effective, expanding operational capacity in emergency contexts.

The agreement translates into a reinforcement of coordination between their respective Operations Rooms, through the strengthening of connections and radio communications, the integrated management of emergency calls, and the presence of the Fire Brigade within the Regional Operations Room, the Rescue Coordination Centers, and the Integrated

Provincial Operations Rooms, activated in the event of weather alerts or avalanches of particular severity.

The collaboration also extends to training activities, joint exercises simulating emergency scenarios, and the sharing of data, maps, images, and video material in order to improve territorial knowledge and support surveillance activities.

The cooperation model is thus conceived as a tool for enhancing operational readiness and ensuring a unified response to complex emergency situations, combining technical expertise, territorial presence, and coordinated operational capacity.

Weaknesses in the emergency management system

The joint analysis of emergency management systems highlights an institutional and regulatory framework that is overall robust, characterized by a clear division of competences, a good level of technical specialization, and increasing integration among levels of government. However, a detailed examination of the alert and activation chain reveals some structural weaknesses that affect its full effectiveness, especially in the initial phases of emergency events.

A first critical area concerns the heterogeneity of operational capacity at the local level. Although the Civil Protection Code and Regional Legislation assign the Mayor a central role, the availability of trained technical personnel, digital tools, and updated emergency plans varies significantly among municipalities, particularly smaller ones. This heterogeneity results in differences in the ability to promptly receive alerts and to feed information flows toward higher levels, creating “weak zones” within the civil protection chain.

Another key weakness concerns the complexity of the information system, which shows overlapping information flows from different sources and communication systems. These systems are used to transmit data and enable faster information exchange, but the fragmentation can lead to documentary inconsistencies, informational misalignment, and difficulties in reconstructing the sequence of events, especially during the initial, more chaotic phases of an emergency.

An additional significant criticality involves the integration of actors and sectoral competencies. The presence of multiple competent bodies (Regions, Prefectures, Provinces, Municipalities, ARPAE, STB, AIPO, Reclamation Consortia, network managers) requires continuous coordination governed by a clear legal framework. Difficulties may emerge, however, when the severity or rapid evolution of an event necessitates an immediate increase in coordination level, something that is burdensome during emergencies and is not always fully codified in shared operational tools. Furthermore, the management of infrastructural risk is still partly separated from the alert chain.

In summary, the regional civil protection chain of Emilia-Romagna is a technically advanced and well-structured system, but its effectiveness depends heavily on the coherence of communications, the capacity of local authorities to carry out their assigned roles, and operational integration among involved actors that may show weaknesses especially in the initial and most intense phases of emergency events.

Objectives and operational strategies

The methodological reconstruction of emergency management makes it possible to draw useful evaluations both analytically and operationally. Indeed, it becomes clear that the passage from technical knowledge to political decision-making and field action represents the core of the system and must be supported through an integrated multilevel structure.

The presence of structures such as ARPAE, the Agency for Territorial Security and Civil Protection, the Basin Territorial Services, and the Regional Operations Room provides an important basis for tackling complex events. However, it is essential that these structures be able to interact through common platforms populated with data useful for preventive evaluation and made available to political decision-makers. Response capacity depends on the quality of human resources and on the integration of information systems, but also on the clarity and quality of the information provided.

In particular, it is crucial to manage emergencies while considering the structural strategic importance of infrastructures and the various services linked to them, especially those essential to the operation of safety services and the socio-economic system. The goal is to guarantee continuity and prevent cascading effects in other sectors.

In anticipation of and during extreme events, protecting these infrastructures - considered, in all respects, critical infrastructures - requires an integrated and proactive approach, focusing on:

- Ensuring continuity of essential services (energy, water, transport, ICT, health, finance) even in crisis scenarios.
- Reducing structural and operational vulnerabilities, preventing cascading effects between interdependent sectors.
- Promoting resilience as the capacity to absorb impact, adapt, and rapidly restore functionality.
- Fostering multidisciplinary cooperation among public bodies, private actors, and scientific communities.

To achieve these objectives, the VC Intercluster intends to focus on three main macro-objectives, leveraging the expertise of members of the four Clust-ERs to assess the state of the art and develop solutions usable at local and territorial scales, while working on the interaction between these emerging solutions and existing or developing services. The goal is also to clearly define what will be needed to achieve these objectives and to open dialogue with identified stakeholders, such as Civil Protection, public authorities, private operators managing critical infrastructures, and citizens.

The three macro-objectives are:

1. Strengthening response capacity through pre-crisis intervention
2. Ensuring safety and operational continuity during emergencies
3. Managing infrastructures sustainably and resiliently

OB 1 — Strategy for the First Objective (Pre-Crisis Monitoring)

The first objective focuses on using sensor systems and monitoring tools integrated into existing platforms with user-friendly interfaces. Combined with data analysis systems and predictive risk modeling, these tools can issue early warnings of extreme scenarios, support surveillance efforts, and provide advance identification of alternative access routes in case of interruptions to emergency and logistical services.

OB 2 — Strategy for the Second Objective (Communication During Emergencies)

Communication during emergencies does not directly protect critical infrastructures but enables effective emergency support and operational continuity. The goal is to develop solutions, only available on the market individually, that can integrate into existing networks and maintain essential communication services even during crises or localized malfunctions, facilitating timely intervention and reducing the risk of isolation.

OB 3 — Strategy for the Third Objective (Resilient Infrastructures)

This objective focuses on strengthening infrastructures, both critical buildings and major transport routes linking populated and productive areas, by understanding their vulnerabilities and increasing their resilience to extreme events. The use of Geographic Information Systems (GIS), integrating environmental and infrastructural information, can help public decision-makers and private operators define strategies to mitigate risks.

Pre-crisis monitoring analyses and simulations

Territorial surveillance is a fundamental practice for strengthening territorial resilience and enabling a faster and more targeted response to events that are imminent or underway and expected to worsen.

At the regional level, numerous environmental monitoring systems already exist, including:

- hydrometric and pluviometric networks
- environmental and sewer sensors
- satellite observation (e.g., Copernicus)
- Geographic Information Systems (GIS)

Although these represent valuable information resources, they exhibit structural criticalities:

- absence of a single platform for integrated analysis and visualization
- limited use of predictive analyses and simulations
- data often used a posteriori, reducing the effectiveness of pre-crisis response

Overall, territorial surveillance remains fragmented and mostly reactive, making it necessary to evolve toward a predictive, interoperable, continuous model integrated with logistical planning and emergency management.

Existing Solutions in Monitoring Systems, Potentialities and Critical Issues

As previously mentioned, there already exists a series of consolidated solutions for environmental monitoring. These solutions respond to many problems, but they also show that the pre-crisis phase is still only partially covered, because the integration between environmental, infrastructural and satellite data is rare and difficult, and because interoperability between environmental monitoring data and emergency operations is limited.

In this context, the existing solutions for the management of extreme events can be grouped into three main categories:

1. Early Warning Systems
2. GIS platforms for emergency management
3. Urban and territorial Digital Twins

Early Warning Systems (EWS)

Early Warning Systems represent the most consolidated approach. They are based on real-time monitoring of environmental variables and on alert thresholds. They are widely used by meteorological and hydrological services and by Civil Protection structures, with examples in Italy and in cities such as Amsterdam, Rotterdam and Hamburg.

Their main limitations are:

- sector-specific approaches
- scarce integration with infrastructural data
- limited ability to support operational decisions and scenario simulations

GIS Platforms for Emergency Management

GIS platforms are used mainly during or after emergency events, in order to visualize maps, risk layers and operational information. They are used by Civil Protection structures and by local administrations, for example in cities such as Barcelona and Paris.

Their limitations include:

- limited use in the pre-crisis phase
- mainly passive use of data
- limited use of predictive analyses

Urban and Territorial Digital Twins

Digital Twins represent an emerging approach, based on dynamic digital representations of territories and infrastructures, fed by real data and simulation models. They have been developed in cities such as Singapore, Helsinki, Rotterdam, London, and more recently Bologna, with applications for planning, climate adaptation and infrastructure management.

Their limits include:

- technological complexity
- implementation and maintenance costs
- limited operational use in immediate pre-crisis phases

Integrated System Solutions operating in synergy with Emergency Analysis Systems

The existing solutions presented in the previous chapter are the result of important studies and experiments. They must be enhanced and used as a starting point for the development of even more integrated solutions, capable of providing ready-to-use responses for public and private actors responsible for monitoring, evaluating and responding to emergency events that could compromise essential activities for the functioning of the regional socio-economic system.

The solutions that will need to be developed and tested must aim at:

- leveraging the strengths of existing tools
- integrating them into systems that are user-friendly and easy to approach
- being sufficiently economical to use
- providing adequate responses to user needs, enabling quick and precise reactions to emergency risks

In this context, the availability of platforms that combine environmental data, infrastructural data and operational data allows anticipating critical scenarios and supporting informed decisions.

It is precisely in this direction that the PRE-EMERGE project is located. It is presented as a concrete example of a predictive environmental monitoring system, designed to integrate advanced technologies and provide operational support in the pre-crisis phase.

The following chapter illustrates its characteristics and potential, showing how it can contribute to structuring a more resilient system for infrastructures and territories.

The PRE-EMERGE Tool, an example of a Predictive Environmental Monitoring System

PRE-EMERGE (Prevention and Processing of Geo-environmental Emergencies) is a project in the implementation phase by the Big Data Group [3]. It is conceived as a pre-crisis environmental monitoring tool, capable of integrating data from territorial sensors, satellite observations and environmental models, and able, through advanced analysis techniques, to anticipate the impacts of extreme events on critical infrastructures.

It is designed to strengthen response capacity to physical risks before the emergency occurs. The system arises from the need to overcome a predominantly reactive approach to risk management, offering operational information in the phase when decisions can still reduce the impact on infrastructure and on emergency logistics.

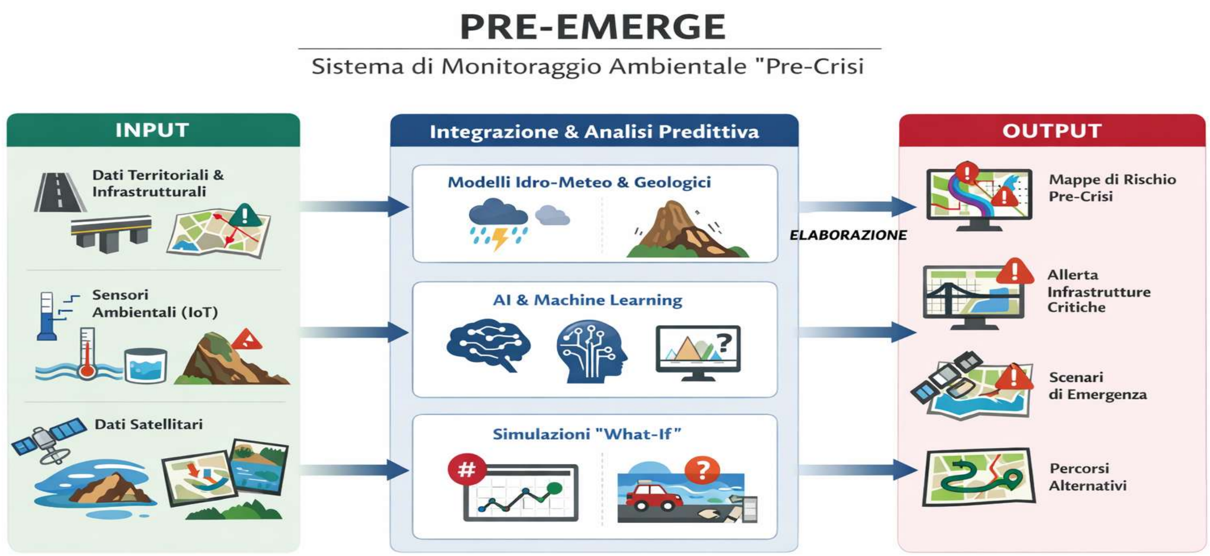
PRE-EMERGE combines:

- data from territorial sensors
- satellite observations
- territorial databases

[3] Urban Intelligence and Healthcare Research Lab, Department of Engineering "Enzo Ferrari" of Modena

- environmental simulation models
- predictive analysis techniques and artificial intelligence algorithms

The objective is not only to observe the current state of the territory, but also to anticipate its evolution, identifying in advance the criticalities that could compromise the functioning of the infrastructural network, such as the flooding of road segments, the instability of slopes, interruptions of strategic connections or the isolation of key areas.



From an operational point of view, the tool is designed as a connection element between environmental monitoring, simulation and planning, with a clear focus on emergency logistics. The information produced supports Civil Protection, the Fire Brigade, rescue services and infrastructure managers in preparing activities, for example through the advance definition of alternative routes and the evaluation of the accessibility of urban and extra-urban areas in critical conditions. The tool can be used throughout the entire emergency cycle, although its greatest added value is found in the pre-crisis phase.

From a technological perspective, it is based on a multi-source data integration architecture that combines territorial and infrastructural data, environmental sensor measurements and satellite information. These data are harmonized in space and time and made available within a GIS environment, which serves as the basis for further analyses. On this foundation, simulation models, for example hydro-meteorological and geological models, operate together with predictive analysis techniques and artificial intelligence algorithms to identify anomalous patterns, estimate risk evolution and support probabilistic assessments.

A key element of the tool is its robustness with respect to sensor reliability issues. Possible missing data, malfunctions or degraded sensor readings are mitigated through integration with satellite data, spatially nearby information and model-based results, ensuring continuity of monitoring even in critical conditions.

The results of the analysis are translated into operator-ready outputs, for example:

- dynamic pre-crisis risk maps
- automatic identification of critical infrastructures and road segments
- scenario simulations to evaluate the impact of environmental threshold exceedances on territorial accessibility

These outputs are accompanied by operational indications, such as:

- proposed alternative routes
- identification of logistical nodes at risk
- estimation of intervention time windows

Information is accessible through an interactive GIS platform and dashboards for technical users and can be integrated with existing regional systems. The datasets generated can also be reused in the post-event phase and for structural planning, contributing to a long-term vision of territorial resilience.

This evolution of predictive environmental monitoring systems highlights the importance of integrating advanced technological data with information collected directly from the territory. To obtain a truly complete and timely risk picture, it is essential to also enhance the contributions of citizens and local administrations.

In this perspective, the next chapter presents CITTADIN-AI, a tool that uses reports and communications from the community and institutions, integrating them with technical data to support more reactive and widespread emergency management.

CITTADIN-AI, more capillary monitoring born from the community

CITTADIN-AI is a tool, still in the process of implementation by the Big Data Group, that operates in that time band between the absence of crisis and the true crisis, that is, when everything still functions correctly but the symptoms of what could become an emergency begin to appear. Its objective is to valorize the communications of citizens, administrations and Civil Protection, transforming them into structured and georeferenced information in support of operational management. In the time interval that separates ordinary disruptions from critical events, in fact, much territorial information is disseminated in unstructured texts: notices of road or bridge closures, reports of flooding or landslides, official communications on institutional websites and social media. These pieces of information, though timely, are fragmented and difficult to integrate into decision systems, also because they provide a local picture of the problem.

The integration of information from many local systems, together with the data produced by other tools such as the above-mentioned PRE-EMERGE, makes it possible to have a more complete picture of the problem and of how much it is under control or could lead to an emergency. The system, in fact, automatically gathers content from heterogeneous sources, such as official sites, public communications, institutional social channels and controlled citizen contributions, involving the population as "distributed sensors", complementary to physical and satellite data, intercepting, analyzing and transferring to PRE-EMERGE the information almost in real time. Through natural language processing techniques and language models, NLP and LLM, the system identifies the type of event, the infrastructural elements involved, and the spatial localization.

The information thus extracted, validated and integrated with PRE-EMERGE, makes it possible to provide a complete and timely information picture, anticipating infrastructural criticalities, improving awareness and supporting operational decisions, thanks to the contribution of all users. For example, a report of flooding of a secondary road might not be signaled by sensors, but by inhabitants and emergency operators on site.

The outputs are made available on a GIS platform and on operational dashboards, ensuring coherence and continuity. The structured information becomes an integral part of monitoring, usable in real time or for post-event analyses, contributing to building a historical memory and improving strategies of preparation and response to emergencies.

Communication for resilient ICT infrastructures

Objective OB 2, that is, the strategy aimed at keeping fundamental communication services active during emergencies, develops starting from the potential and operational needs of modern 5G cellular networks.

Their characteristics of optimization to guarantee efficiency, broadband and centralized control make possible notable performance in normal operating conditions, however they also conceal a fragile assumption, namely that the infrastructure persists, power is continuous, connectivity is stable and coordination is possible. In crisis situations, whether natural disasters, large-scale power outages or search and rescue operations, SAR, these assumptions fail simultaneously. What is interrupted first is not necessarily radio coverage or broadband, rather the very logic by which we expect network services to function. This structural fragility has been repeatedly documented in disaster response analyses by international sector organizations, such as the ITU Focus Group on disaster relief systems[4].

It is important to have a structure that places "safe" infrastructures alongside "normal" network infrastructures. Resilient infrastructures, "hard to destroy", do not seek to prevent failures. They consider failures as the norm and their objective is continuity of service, that is, the ability to sustain essential ICT and communication services, for example chat, voice messages and voice calls, in degraded, intermittent and unpredictable conditions. Research on resilient networks and protection of critical infrastructures constantly shows that systems designed for gradual degradation outperform those that are highly optimized yet very fragile in crisis situations[5].

This change of perspective motivates a layered ecosystem of approaches whose strength lies precisely in their complementarity.

Mesh as a design philosophy

Mesh networking is often presented as a technical alternative to centralized infrastructures. In practice, it is better understood as a design guideline to guarantee support for decentralization and reciprocal transmission, where every node, or some selected nodes,

[4] ITU-T Focus Group on Disaster Relief Systems, "Framework for disaster-relief systems," International Telecommunication Union, Tech. Rep., 2014

[5] J. P. G. Sterbenz et al., "Resilience and survivability in communication networks: Strategies, principles, and survey of disciplines," Computer Networks, vol. 54, no. 8, pp. 1245–1265, Jun. 2010

can take on partial responsibility for the survival of the network. Connectivity is no longer guaranteed end to end, it is instead negotiated at every hop. Empirical studies on community networks, for example Guifi.net and Freifunk, and tactical ad hoc implementations show how this redistribution of responsibilities makes possible continuous functioning even in the presence of numerous node and link failures.

In SAR contexts, where teams move independently, terrain obstructs line of sight and infrastructures can be absent or damaged, mesh connectivity makes communication possible wherever proximity allows. NATO STO reports and field trials have shown that even when performance collapses, paths break and latency increases, the network does not stop, it deforms[6]. This ability to degrade instead of failing outright is precisely what centrally optimized systems lack.

However, a mesh network by itself is not sufficient, because a classic ad hoc mesh network presupposes continuous paths and frequent updates. When partitions last minutes or hours, data routing stops. In this case, Delay Tolerant Networking, DTN, integrates mesh logic by redefining the very semantics of communication. Instead of relying on simultaneity, data are transported, stored and forwarded opportunistically. Decades of research on DTN, from early work on the Internet in space to more recent humanitarian networking experiments by the ICRC, show that accepting delay as a design parameter enables communication where real-time networking is impossible[7].

Mesh and delay tolerance together form a continuum between synchronous and asynchronous communication. This continuum is essential in environments where connectivity oscillates unpredictably and planning cannot assume either permanence or immediacy.

Low energy consumption as temporal resilience

Power outage is often the main cause of network death. Consequently, energy must be treated not as an operational parameter, rather as a structural constraint. Studies conducted by IEEE PES and reports on disaster response exercises consistently identify power loss as the principal factor limiting the longevity of communications. This was largely confirmed by recent floods that have occurred in recent years in our territory, the case of the historic center

[6] NATO Science and Technology Organization, "Communications in Degraded and Denied Operational Environments," STO Technical Report, 2019
[7] V. Cerf et al., "Delay-Tolerant Networking Architecture," IETF RFC 4838, Apr. 2007

of Faenza is emblematic, which led to the flooding of medium-voltage stations and, consequently, to the fall of proximity communications both Internet and cellular. This also followed from the ever greater localization of the coverage radius of new-generation cellular antennas, from 4G onward.

In this field, low-power network technologies, in particular those that favor ultra-low bitrates and long durations, extend the temporal horizon of communication. LPWAN technologies such as LoRa and NB-IoT, widely documented in sector white papers, for example Semtech[8] and 3GPP[9], demonstrate functioning from several days to several years with limited energy budgets. Although such systems are not capable of supporting rich multimedia content, they excel in persistence.

These characteristics make possible a different class of services, such as status beacons, alerts, localization signals and telemetry, which remain available even in the presence of broadband network outage. Field implementations by organizations such as UN OCHA and Médecins Sans Frontières have shown that minimal signaling often has an operational value that is disproportionate[10]. It is fundamental to underline that low-power approaches do not replace mesh or broadband communications, rather they constitute a durable signaling substrate.

Heterogeneity as a strategic lever

A characteristic that distinguishes a resilient network is technological heterogeneity. Multiple radios, frequency bands, protocol families and energy sources can coexist, not for the purpose of maximizing performance, but for the purpose of resisting uniform failures. Research in resilience engineering repeatedly highlights diversity as a fundamental mechanism of resilience, one that exceeds pure redundancy in complex systems.

What degrades one medium can spare another. What is blocked, obstructed or overloaded in a specific frequency band can remain fully functional in another. This logic extends beyond radio systems to architectures: peer-to-peer communication complements

[8] Semtech Corporation, "LoRaWAN® for Disaster and Emergency Communications," White Paper, 2020
[9] 3GPP, "NB-IoT; Technical Specification Group Services and System Aspects," TS 23.682
[10] United Nations Office for the Coordination of Humanitarian Affairs, "Emergency Telecommunications Cluster: Field Operations Overview," UN OCHA Report, 2018

infrastructure-assisted links, content-centric dissemination complements endpoint addressing, and devices carried by people complement static relays[11].

Mobile nodes, including people, vehicles, drones and so on, become part of the infrastructure not for reasons of design elegance but for necessity. Movement bridges separations. Encounters become routing events. Communication ceases to be purely technical and becomes socio-technical, integrated into human behavior and into logistics. This phenomenon has been documented in studies of opportunistic networking and in large-scale mobility traces analyzed by the CRAWDAD research community.

Mapping and scenario generation

From an operational point of view, the first fundamental activity to implement is the accurate census of all the physical components present in the territory that enable connectivity. These include mobile telephone antennas, radio bridges and even fiber-optic backbones that constitute the structure of broadband connectivity. This information already exists, but it is fragmented among different data owners and difficult to integrate into a strategic overview.

This mapping must not be limited to a simple collection of information. It must become a tool for technical and strategic analysis: it is necessary to understand whether a specific area depends on a single infrastructure without redundancy, or whether a network node is particularly vulnerable because it is located in an area exposed to hydrogeological risk. By integrating data from telecommunications operators, national registries and local administrations, it is possible to build a complete picture which, through the use of geographic information systems (GIS), becomes clear and immediately interpretable.

Parallel to the census, it is necessary to simulate what could happen to the communication network in the case of extreme events, in order to work on increasing its resilience. The goal is to suggest the creation of alternative paths, redundancy and backup systems capable of guaranteeing operational continuity even in difficult conditions, and of preventing the scenarios identified in simulations.

[11] L. Zhang et al., "Named Data Networking," ACM SIGCOMM Computer Communication Review, vol. 44, no. 3, pp. 66–73, Jul. 2014

What makes a network resilient is a coordinated set of strategies: mesh connectivity that redistributes responsibility, delay tolerance that redefines the time dimension, low-power persistence that extends survivability, heterogeneity that resists uniform failure, and architectural choices that prioritize decomposition over optimization.

Strategies and operational hypotheses for addressing the emergency

In synergy with and as a supplement to these approaches, it is very important to introduce new processes and technological solutions.

A first possible proposal, advanced by the member CIRI ICT, Industrial Research Center of the University of Bologna for information and communication technologies, and one that can be examined thanks to the new possibilities enabled by 5G, consists in deploying low-cost mesh technologies capable of absorbing the emergency peak through temporary solutions.

In this sense, the idea is to study a hybrid solution which, assuming that the cellular network has not completely collapsed across the entire territory, can create a bridge through mesh technology between the zones no longer covered due to loss of power supply, for example caused by floods as mentioned earlier, and the part of the network still functioning but no longer reachable.

This solution could also include the deployment in the territory of low-cost electric generators, for example gasoline generators, properly equipped with onboard cellular communication technologies capable of creating the “backbone” of the support mesh that is necessary in extreme and peak conditions.

At the same time, the creation of a network of volunteers trained to activate and operate the same mesh in the event of an emergency should be planned, similar to what already happens today, although in a different field, with defibrillators placed across the territory.

This solution is conceived primarily for the population, so that it can integrate the solutions already available for Civil Protection experts, who can use other dedicated infrastructures which, in this way, could be further strengthened with an additional and alternative communication channel.

Criteria for the classification of sensitive infrastructures

What has been introduced and discussed in the previous chapters becomes even more important the further we enter the context of priority road infrastructures and strategic buildings, since they play a particularly significant role for the regional socio-economic system.
The objective therefore becomes twofold: on the one hand, to identify and classify the most sensitive and structural elements of the territory, and on the other, to build a solid information base that makes it possible to define intervention priorities in an objective, coherent and integrated manner with existing planning.

Identification of sensitive road infrastructure

The first phase of the work concerns the survey and classification of priority road infrastructures that can be considered sensitive with respect to landslide and hydrogeological risk.
This set includes not only the main road arteries, but also bridges, viaducts and secondary connections that have a strategic function for local mobility.

The sensitivity of a road section does not depend solely on its physical exposure to danger, but also on its function.
For example, a road that connects an inhabited center to a health facility will have high priority even if the hazard index is moderate, because its interruption would cause isolation with significant repercussions for the safety of the population.

Identification of classes of sensitive buildings

Parallel to the survey of the road network, a classification of strategic buildings is necessary, that is, buildings that, due to their function or value, can be considered sensitive. These include:

- Energy production and transformation plants, fundamental for maintaining communications and the socio-economic system
- Schools and educational buildings, places with a high concentration of people and a need for orderly evacuation
- Hospitals, clinics and health-care facilities, essential for assistance during emergency events
- Strategic buildings, such as municipal buildings, operational headquarters of local police, fire brigade stations and other critical operational sites
- Archives, libraries and buildings containing documentary heritage, because they house highly perishable and often irreplaceable assets

The analysis of these buildings must not be limited to a simple enumeration.
It is necessary to consider:

- their accessibility during an emergency
- their location with respect to hazard areas
- the availability of alternative routes in case of interruptions.

Census of infrastructures with respect to the Flood Risk Management Plan (PGRA)

Once the sensitive roads, bridges and buildings have been identified, the next step consists in their census and in verifying their geographic location with respect to criticalities, beginning with those defined by the Flood Risk Management Plan, PGRA.
The PGRA hazard and risk maps constitute the official basis for evaluating hydraulic and hydrogeological risk and make it possible to associate each surveyed element with a defined risk class.

In this context, Geographic Information Systems, GIS, represent a fundamental platform not only for managing territorial data, but also for implementing multicriteria methodologies capable of integrating heterogeneous variables and providing a more solid and transparent decision-making framework.

The application of GIS to the representation of urban networks uses an analytical approach based on multicriteria evaluations.
This allows integrating physical, functional, environmental and socio-economic indicators, enabling more comprehensive analysis of networks.
This approach considers not only infrastructural configuration but also external factors that influence the network's capacity to function correctly.

This multi-criteria assessment provides an integrated view that correlates:

- the location of the infrastructure or building;
- the hazard level of the area (frequency and potential extent of events);
- the vulnerability of the element itself;
- the strategic importance of the function performed.

The result is a detailed picture of the level of exposure and operational relevance of each element which, combined with analytical and predictive assessment techniques, allows risk and priority maps to be constructed based on weights assigned to specific criteria, calibrated according to the needs of the urban context.

Hierarchical classification of infrastructures from a resilience perspective

With the set of collected data, it becomes possible to conduct a spatial analysis based on objective criteria, which makes it possible to classify the surveyed elements according to intervention priority.
The objective is to identify which infrastructures require urgent actions, which infrastructures require constant monitoring, and which ones may be subject to long-term planned interventions.

From a resilience perspective, not all infrastructures have the same weight.
Some infrastructures perform essential functions for the operation of the urban system, while others represent alternatives with less impact in the event of interruption.

Through integrated data analysis, it becomes possible to determine:

- which infrastructures constitute vital elements for the continuity of urban services
- which segments of the road network play a critical role for accessibility to strategic structures
- where interventions are necessary to increase the capacity of the system to absorb or resist extreme events

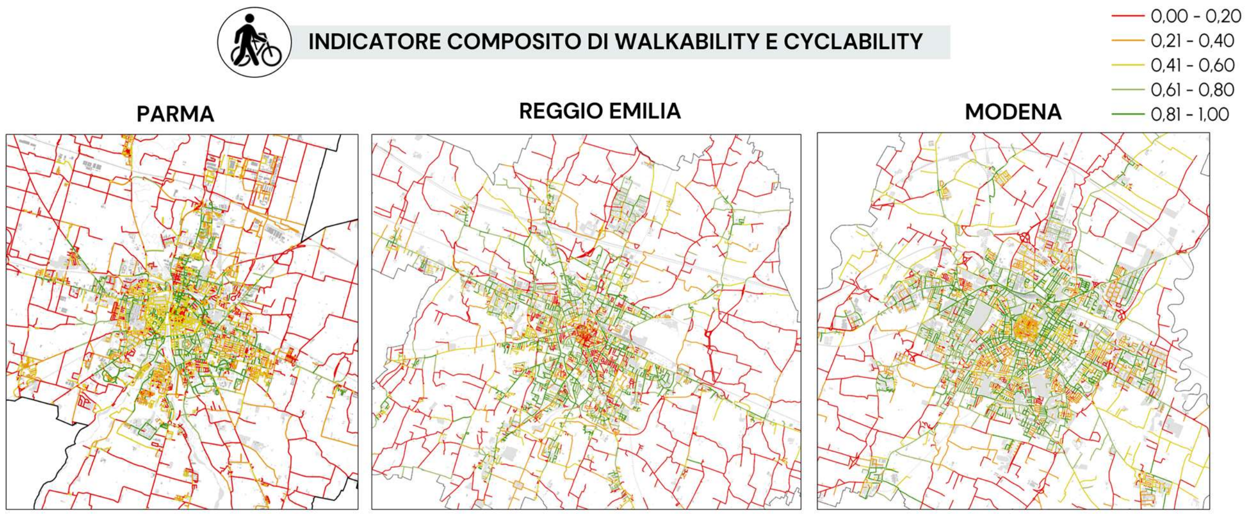
Hierarchical classification is therefore not a simple exercise in categorization.
It is a process that requires a deep understanding of the interactions between infrastructures, urban morphology and territorial risks.

The proposed methodology makes it possible to assign each network element a level of criticality based on quantitative criteria, reducing subjectivity and fostering more informed decision-making.

The resulting approach allows administrations and planners to carry out preventive choices, such as programming investments, in an efficient manner aimed at operational continuity, improving the overall resilience of the urban system through targeted, scalable interventions based on transparent criteria.

Tools for mapping and GIS analysis

Among the tools that, although developed in contexts different from emergency management, already provide operational responses and may serve as a basis for the development of a system for mapping and hierarchical classification of infrastructures, or as a methodological guide for such a system, is the mapping of pedestrian and cycling networks in the cities of Parma, Modena and Reggio Emilia.
This mapping was developed as part of recent research projects and is capable of integrating the network graph with numerous physical, functional and environmental attributes of the road network, including initial attributes useful for assessing infrastructure resilience, such as safety conditions, accessibility and roadway widths.



By extending the above GIS methodology to risk parameters linked to different kinds of extreme events, for example flooding, heat waves, structural failures and interruptions of infrastructural continuity, it becomes possible to make available, within interoperable GIS platforms, both existing studies and studies to be produced ad hoc on different territories. These platforms can offer transversal and shared information capable of supporting local decision-makers.

In such a system, it becomes possible to integrate GIS models with data not only from official databases already available, but also from data produced within the various sectors involved in research activities.

Overall Assessment

No single approach is capable of producing a resilient structure in crisis situations.

The analysis carried out highlights how the resilience of urban and territorial infrastructures cannot be entrusted to a single approach or to an isolated technological solution.
On the contrary, the growing complexity and frequency of extreme events require an integrated vision, in which in-depth knowledge of networks and the ability to assess criticalities and priorities through advanced and easy-to-read tools become essential elements for planning and for risk management.

What is most needed is the ability to systematize all the information that is already the subject of analysis and processing by one or more actors, to process this information within a broader framework and to make it available to all operators called to contribute to territorial resilience, including local and territorial planners, operational teams during emergencies and operational entities once the crisis has been resolved.

In this context, the extension of GIS methodology, enriched with multicriteria assessments, makes it possible to go beyond simple cartographic representation of networks. It offers instead a dynamic platform capable of integrating heterogeneous data, simulating crisis scenarios and supporting timely and informed decision-making.
This approach makes it possible to identify not only the physical vulnerabilities of infrastructures, but also to evaluate their strategic role within the urban system, promoting a hierarchical classification that considers both function and position with respect to specific territorial risks.

Resilience, in this perspective, is no longer just a technical characteristic.
It becomes a transversal objective involving administrations, infrastructure managers, the scientific community and citizens.
Only through collaboration and the sharing of data and expertise is it possible to build urban systems capable of absorbing impacts, adapting and rapidly restoring functionality after a crisis, moving toward more conscious and proactive management of critical infrastructures.