multi-Risk sciEnce for resilienT commUnities undeR a changiNgclimate

Codice progetto MUR: **PE00000005** – CUP LEAD PARTNER

Deliverable title: Open Knowledge-Sharing Platform

Deliverable ID: DV 6.6.4

Due date: 30/11/2025

Submission date: 30/11/2025

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1. Technical references

Project Acronym	RETURN
Project Title	multi-Risk sciEnce for resilienT commUnities undeR a changiNg climate
Project Coordinator	Domenico Calcaterra UNIVERSITA DEGLI STUDI DI NAPOLI FEDERICO II domcalca@unina.it
Project Duration	December 2022 – November 2025 (36 months)

Deliverable No.	DV 6.6.4
Dissemination level*	PU
Work Package	WP6 – Integrated technologies and solutions for holistic risk reduction
Task	T6.4 - Information and knowledge sharing for critical infrastructure protection and resilience
Lead beneficiary	ENGINEERING
Contributing beneficiary/ies	UNIROMA1

* PU = Public

PP = Restricted to other programme participants (including the Commission Services)

RE = Restricted to a group specified by the consortium (including the Commission Services)

CO = Confidential, only for members of the consortium (including the Commission Services)

Document history

Version	Date	Lead contributor	Description
0.1	15.09.2025	Francesco Serio (ENG)	First draft
0.2	30.10.2025	Giuseppe Cammarata (ENG)	Critical review and proofreading
0.3	10.03.2026	Mara Lombardi (UNIROMA1)	Edits for approval
1.0	18.03.2026	Giuseppe Cammarata (ENG) Mara Lombardi (UNIROMA1)	Final version

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3. Abstract

Deliverable D6.6.4 – Open Knowledge-Sharing Platform presents the creation of an integrated digital ecosystem for emergency management and critical infrastructure monitoring. The system combines operational and collaborative capabilities in a single architecture, capable of collecting, analyzing, and sharing real-time data from heterogeneous sources. Through reporting modules, dynamic dashboards, multi-channel notification systems, and artificial intelligence tools, it enables continuous event monitoring and strategic decision-making support. At the same time, it integrates a knowledge-sharing environment that centralizes protocols, procedures, best practices, and training materials, promoting cooperation and learning. Interoperable information flows ensure security, constant updating, and data consistency among all stakeholders. The use of AI algorithms enables automatic and contextualized analysis, improving situational awareness and the effectiveness of operational responses. Thanks to this integration, the system reduces reaction times, optimizes coordination, and strengthens resilience.

4. Introduction

The document describes the development of the Open Knowledge-Sharing Platform, an advanced digital solution designed to provide integrated support for emergency management and critical infrastructure monitoring, promoting a proactive, collaborative, and resilient approach. The system consists of two distinct and complementary platforms, designed to operate synergistically within a single interoperable ecosystem:

1. An Operational Platform (eReturn Dashboard), which constitutes the functional core of the system, supporting operational decisions and coordinated emergency management. It is designed for the real-time collection, processing, and visualization of data from heterogeneous sources and offers advanced tools for analyzing and correlating territorial and infrastructure information. Its main features include:
   - Reporting modules, which allow citizens and operators to submit observations and alerts in real time;
   - Operational dashboards, which offer dynamic and interactive visualizations of collected data;
   - Multi-channel notification system, capable of distributing personalized alerts via email, Telegram, or web platforms;
   - Integration of artificial intelligence and advanced analytics tools, to transform heterogeneous data into structured and actionable intelligence.
2. A Knowledge Sharing Platform (eHub) that represents the collaborative and educational dimension of the system. Conceived as a digital hub for cooperation, training, and knowledge dissemination among institutions, operators, and communities. Its main features include:
   - A centralized Knowledge Hub, which organizes and makes accessible protocols, operating procedures, guidelines, and best practices;
   - A multi-channel notification system, capable of distributing personalized alerts via email, Telegram, or the web platform;

The Open Knowledge-Sharing Platform represents an advanced and innovative model for managing emergencies and critical infrastructure, combining intelligent technologies, civic participation, and data analytics. Thanks to this integration, the platform supports faster, more targeted, and informed decisions, improves collaboration between institutions and citizens, and strengthens the overall resilience of the system, providing a benchmark for the modern and shared management of critical events.

5. Architecture and Main Components

The Open Knowledge-Sharing Platform's architecture is designed according to the principles of modularity, scalability, and interoperability, with the goal of ensuring robustness, adaptability, and efficient integration with external systems. The platform is configured as a distributed digital ecosystem, composed of independent and interoperable microservices that cooperate through standardized APIs, orchestrated by a central workflow management layer.

The architectural model adopts a Multi-Layer approach composed of four main levels:

1. Presentation: Provides web and mobile user interfaces for citizens, operators, and administrators. It is designed to ensure accessibility, responsiveness, and operational continuity under variable network conditions.
2. Application: Implements the business logic of functional modules (reporting, crowdsourcing, AI, dashboards, notifications, knowledge management), managing workflows, application security, and intermodule communication.
3. Data Integration: Manages data ingestion, normalization, and correlation processes from heterogeneous sources (IoT sensors, institutional databases, crowdsourced contributions, territorial datasets). This is where data fusion and semantic alignment take place using shared vocabularies and ontologies.
4. Data Storage: Ensures data persistence in structured and unstructured archives, with hybrid solutions based on document databases and relational systems, ensuring high availability and redundant backup mechanisms.

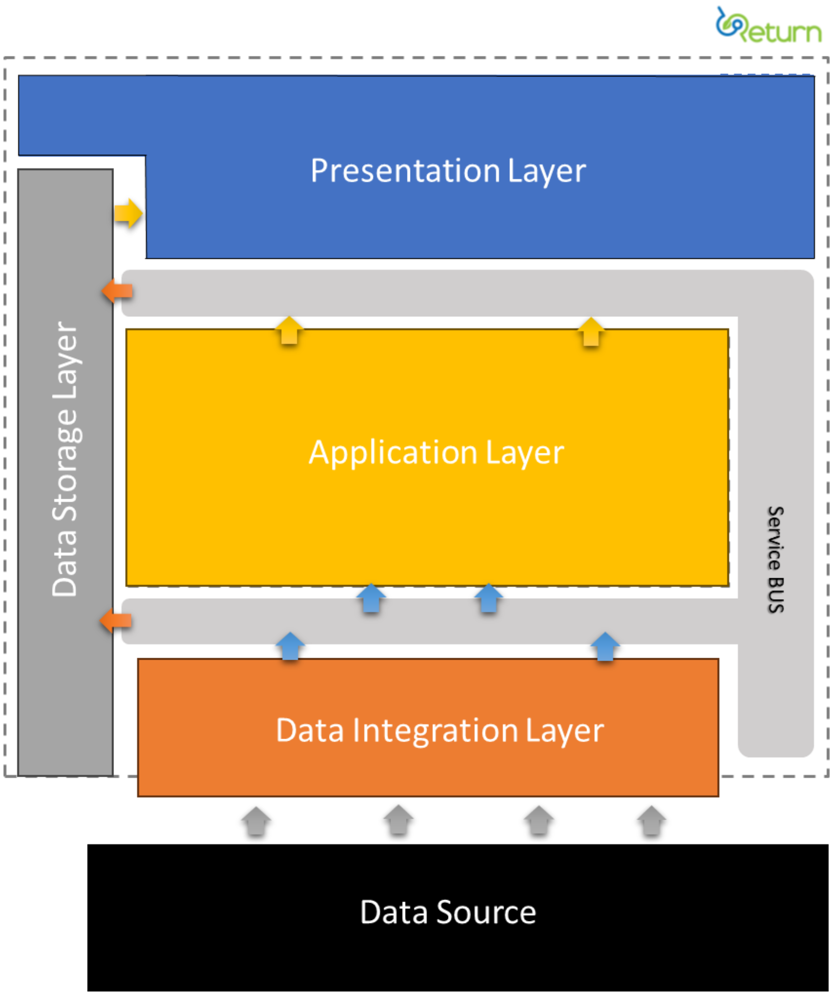

Figure 1 Architectural Model

The functional modules that make up the platform are autonomous but fully interoperable:

- Crowdsourcing manages the collection of reports from citizens and operators. It interfaces with geolocation services and AI-based validation engines.
- Analytics and Artificial Intelligence provide semantic classification, automatic correlation, and data validation services using machine learning algorithms.
- Dashboard and Analytics implement multi-level visualization interfaces and integrates with external analytical tools such as Kibana for advanced analysis.
- Knowledge Hub provides a centralized repository for knowledge management, sharing technical documentation, operating procedures, and best practices.
- Multi-Channel Notification System provides scalable and redundant communication via web, email, and Telegram channels, with routing and priority logic based on user profile and level of criticality.

The use of modular and reusable modules ensures high flexibility, expandability, and maintainability of the system, while workflow-based management enables effective coordination of decision-making processes, multi-channel communication, and the distribution of situational images. The platform thus promotes a continuous and reliable flow of information, enabling immediate collaboration among all stakeholders involved in managing emergencies and complex situations, supporting both infrastructure resilience and transparency in communication with citizens.

Data Governance and Security

The platform implements a comprehensive set of advanced security measures, designed to continuously guarantee the integrity, confidentiality, and availability of processed data.

Multi-factor authentication (MFA) mechanisms are provided to ensure secure access even in multi-user and distributed scenarios.

The system supports the use of One-Time Passwords (OTPs), ensuring compatibility with existing infrastructures and access traceability. communications between modules and between client and server are protected by end-to-end encryption, based on digital certificates and public-key algorithms that prevent interception or manipulation of information flows. All relevant transactions are recorded in centralized audit trail systems, ensuring traceability.

Personal data protection is guaranteed in accordance with the General Data Protection Regulation (GDPR) and applicable national privacy regulations, strengthening user trust and ensuring system reliability.

Special attention is also paid to the management of cookies and tracking preferences, which is developed in a transparent, configurable manner and compliant with European standards. The platform adopts a cookie management system that allows users to clearly select which types of cookies to accept (strictly necessary, functional, analytical, third-party), thus ensuring full control over the use of their browsing data. Strictly necessary cookies are limited to basic functionality and system security, while any optional cookies are activated only with explicit consent. All user choices are recorded and can be changed at any time through a dedicated interface, ensuring transparency, reversibility, and full regulatory compliance.

Thanks to this integrated, modular, and secure architecture, the solution not only ensures operational continuity and effective emergency management, but also rigorously protects user rights and privacy. In this way, the Open Knowledge-Sharing Platform consolidates itself as a reliable, resilient tool that complies with the highest ethical, technological, and regulatory standards in the digital emergency management landscape.

6. Innovation and Added Value

Overall, the Open Knowledge-Sharing Platform emerges as an interactive, distributed, and adaptive digital ecosystem capable of profoundly transforming the traditional approach to emergency and critical infrastructure management. Its main innovation lies in the system's ability to overcome the top-down communication paradigm, fostering an open and participatory operational environment in which citizens, field operators, and institutions collaborate actively. In this framework, stakeholders are no longer passive recipients of information but active contributors in building a collective, dynamic, and shared situational awareness.

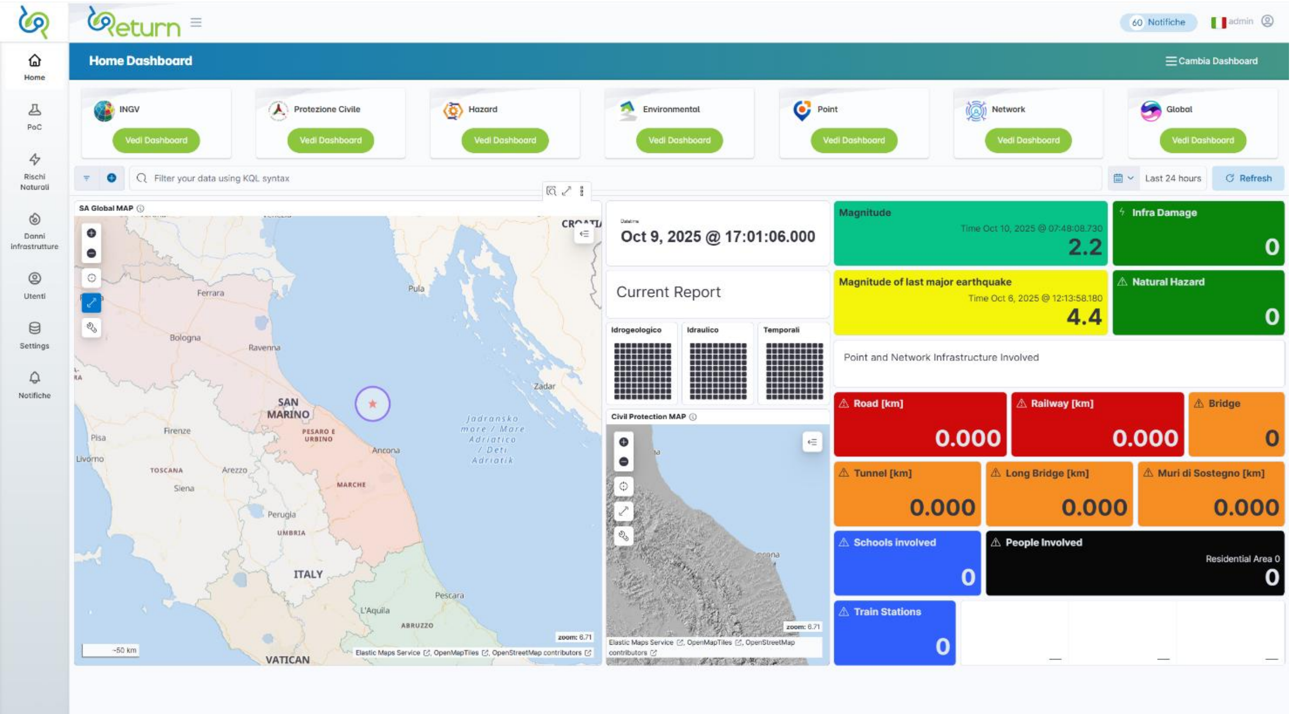

Figure 2 Home Dashboard

A particularly important aspect is the integration of advanced artificial intelligence technologies, which enable the automatic translation of natural language citizen reports into structured, validated, and immediately actionable information. This dramatically reduces manual processing times and mitigates the risk of human error, while improving data quality, reliability, and timeliness for decision makers. The platform also allows for the harmonization and standardization of communication flows between different stakeholders and organizations, facilitating multi-level coordination during critical situations and ensuring a shared situational vision even in complex and highly uncertain environments.

The platform is not limited to real-time emergency management alone but promotes continuous learning and knowledge transfer. By collecting and organizing operational experiences, creating repositories of best practices, and sharing concrete use cases, the platform fosters the development of a dynamic information base, useful for improving protocols and response strategies. This process increases organizational preparedness and strengthens resilience capacities, both at the local and systemic levels, strengthening inter-institutional cooperation and trust between public and private actors and civil communities.

The implemented system stands out for integrated innovation across technological, operational, and organizational levels. Technologically, it is based on a modular, scalable microservices architecture with standardized APIs, enhanced by advanced artificial intelligence modules that automatically and uniformly translate natural language reports, improving speed and reliability of analysis. A key added value is the civic crowdsourcing component, which transforms citizens into active players in monitoring and risk management, integrated into multi-level dashboards for personalized analytical and geospatial views. Operationally and collaboratively, the platform surpasses traditional top-down models with a participatory ecosystem that unifies data and enables bidirectional communication through multichannel notifications, reducing reaction times and enhancing inter-agency coordination even in complex scenarios. The knowledge sharing component acts as a dynamic and interoperable environment for continuously building and updating a repository of best practices, protocols, and lessons learned, fostering organizational learning and systemic resilience.

7. Expected Results and Operational Impact

The implementation of the Open Knowledge-Sharing Platform aims to have a transformative impact on the emergency and critical infrastructure management system, generating operational and information resilience as the primary outcome. Thanks to an interconnected and collaborative digital environment, the platform enables faster, more transparent, and shared management of critical events, supporting a decision-making process based on reliable and continuously updated data.

One of the most significant expected outcomes is a reduction in emergency response times: the automation of data collection and analysis processes, combined with the ability to provide a unified situational picture, allows for more timely and targeted interventions. At the same time, the platform fosters inter-agency and inter-sector coordination, ensuring interoperability and continuity of operations even in complex and time-pressured scenarios. This approach contributes to increasing situational awareness at all operational levels, providing decision-making support tools to both central authorities and local operators in the field.

In addition to immediate improvements in operational performance, the platform generates medium- to long-term systemic benefits. The integrated approach allows for more efficient optimization of available resources, reducing waste and duplication, and mitigates information redundancies by creating a single, validated flow accessible to all stakeholders. The availability of complete, accurate, and timely information significantly improves the quality of strategic decisions, allowing for more effective planning of prevention, preparedness, and response activities.

A distinctive feature is the active involvement of the civilian population, which helps transform citizens from passive observers to informed and responsible partners in risk management. This direct participation not only enriches the system's information base but also fosters the development of a widespread culture of community resilience, considered a key strategic asset for more effectively addressing future emergencies. The combination of inter-institutional collaboration, advanced technological support, and civic participation produces an operational and social impact that goes beyond the individual critical event, helping to strengthen the systemic capacity of communities and vital infrastructure to adapt and respond.

Ultimately, the expected results materialize not only in greater operational efficiency, but above all in a paradigm shift in emergency management, based on cooperation, shared knowledge and sustainable resilience.

8. Context and Motivations

Critical infrastructures form the nervous system of contemporary societies, including energy networks, transportation systems, telecommunications, water services, and healthcare facilities. Managing them in emergency situations represents a major challenge, characterized by organizational, operational, and technological complexity that requires innovative, integrated, and scalable solutions. The high level of interdependence that characterizes these infrastructures means that the failure of a single component can generate cascading effects with consequences that are difficult to predict and manage. This phenomenon is further exacerbated by the distributed nature of the networks and the multiplicity of actors involved, ranging from private operators to government agencies, crossing geographical, institutional, and jurisdictional boundaries.

In this scenario, effective emergency management cannot ignore a systemic and multidimensional vision capable of integrating heterogeneous data sources, predictive models, and decision-support tools. From this premise, the need for an integrated knowledge-sharing platform emerges, enabling the collection, organization, and correlation of information from heterogeneous systems, delivering it in a coherent and interoperable format. The goal is to standardize the processes of collecting, processing, and disseminating information, while promoting the automation of complex analyses and the ability to correlate multiple events in real time.

A key aspect of the platform is the ability to customize the presentation of information based on the role, skills, and operational responsibilities of users, improving the timeliness and accuracy of decisions. This is complemented by the importance of including the civilian population and various institutional and private stakeholders in the emergency management cycle, leveraging the contribution of crowdsourcing and promoting participatory monitoring and reporting processes.

Finally, the platform must ensure high scalability and flexibility, so as to adapt to emergency scenarios of varying scale and complexity, supporting both the response to localized events and the management of large-scale systemic crises. Thus, it emerges as a strategic tool for strengthening the resilience of critical infrastructure, improving interinstitutional coordination, and supporting decision-making processes based on reliable, up-to-date, and contextualized data.

9. Deliverable Scope

The platform under development is designed as an advanced multi-level decision-support system, aimed at coherently integrating analytical tools, dynamic visualizations, and active participation mechanisms. The adopted approach seeks to provide practical operational solutions both for field technicians, emergency coordinators, and decision-makers involved in the overall crisis management process.

The user interfaces are conceived to ensure a smooth and reliable experience even under high operational pressure. The focus on User Experience guarantees consistency and ease of interaction, while the User Interface design emphasizes visual clarity, accessibility, and a structured organization of information. As a result, content is presented in an immediately usable form, facilitating navigation and reducing potential errors in data interpretation processes.

The system is oriented toward translating complex information into clear, contextualized, and actionable insights, through interactive dashboards that support situational analysis and accelerate decision-making. Interfaces and information architecture are designed to automatically highlight the most relevant elements for each professional profile, thereby improving the quality and timeliness of operational decisions. The definition and implementation of specific KPIs for different types of critical infrastructures will provide relevant, up-to-date metrics useful for monitoring the evolution of situations and supporting corrective actions.

Additionally, the platform will include functionalities for the automatic generation of concise reports, ensuring data accuracy, communication clarity, and maximum usability, thus enabling the rapid sharing of information among all involved actors.

Another key dimension of the development is represented by the civic crowdsourcing module, which promotes active citizen participation in emergency management. This component enables the collection, validation, and integration of field reports, establishing a bidirectional flow that strengthens collaboration between institutions and the public. Citizen reports help enrich the available information framework and are returned in the form of timely and personalized alerts, enhancing public awareness and response capacity.

Through the integration of these functionalities, the platform takes shape as an advanced technological environment capable of leveraging available data, supporting multi-level decision-making processes, and encouraging the direct involvement of both institutional actors and the general population.

10. Functional Requirements

The platform's functional requirements describe the operational capabilities needed to ensure comprehensive support for emergency management activities and collaboration between citizens and authorities. The reporting system is the heart of the platform and allows citizens to submit new reports via a web interface, through clear and structured forms. Each contribution can include detailed information about the event, geographic coordinates detected automatically or entered manually via integration with Google Maps APIs, as well as multimedia attachments such as georeferenced photographs and text descriptions. To facilitate and speed up the submission process, an artificial intelligence model has been integrated that supports the automatic generation of intelligent descriptions, improving the quality and consistency of the data collected. All reports are accompanied by an automatic timestamp and a status that tracks their entire lifecycle, from registration to validation to closure.

Another functional element is the multi-channel notification system, designed to ensure timely and targeted communications. Users can receive automatic alerts via email, in-app notifications on the web portal, and Telegram messages, configuring the frequency and type of updates. This mechanism ensures the immediate dissemination of critical information, including changes in report status and alert messages validated by the competent authorities.

For authorities and operators, the platform provides an operational dashboard that allows them to monitor all active reports in real time. Filtering tools by geographic area, event type, and severity level allow for the efficient management of large volumes of data, while automatic and manual validation features ensure the reliability of the information collected. The ability to correlate reports, especially in the case of events involving adjacent areas, is essential for building an accurate situational picture. Complementing these features are analysis and reporting tools that generate statistics and visualizations useful for decision-making.

Finally, user and permission management is a central aspect of the platform. The system provides secure registration and authentication procedures, along with a role-based access control model that allows for differentiation of the features available to citizens, operators, and administrators. In this way, the platform not only ensures effective and secure use, but also promotes structured and scalable collaboration among all stakeholders involved in the emergency management process.

11. Non-Functional Requirements

The platform's non-functional requirements are divided into three key areas:

Performance and Scalability: the system must guarantee high and consistent performance even under heavy load. Specifically, response times must not exceed three seconds for standard operations and eight seconds for complex analyses based on artificial intelligence algorithms. The platform must simultaneously support more than 1,000 active users and be able to process more than 500 reports per hour without performance degradation. Furthermore, availability for critical operations must remain above 99.5%, thus ensuring operational continuity even in emergency scenarios.

Security. In terms of security, the architecture includes a mandatory two-factor authentication (2FA) system, applied to both the main platform and the Knowledge Hub, based on RFC 6238-compliant One-Time Password (OTP) security standards. The generated codes are six-digit, with configurable time validity, and based on the HMAC-SHA1 algorithm to ensure cryptographic robustness. At the enterprise level, advanced role-based access control (RBAC) features are provided with granular permissions, secure session management using JWT tokens with automatic refresh and configurable timeouts, and API protection through rate limiting mechanisms, authentication tokens, and input sanitization.

Privacy. Regarding privacy, the platform adopts a privacy-by-design and privacy-by-default approach, ensuring transparent consent management and data minimization. Automatic retention and purging policies are implemented to reduce data retention beyond necessary times, along with audit logging systems to ensure complete access traceability and automated procedures for breach detection and response. This ensures the system complies with current regulatory standards, promoting the protection of personal data and user trust.

12. Civic Crowdsourcing and Reporting System

The platform integrates an advanced crowdsourcing system for emergency management, designed to transform citizens from passive recipients of information into active and informed contributors. The conceptual framework is based on the principles of collective intelligence and distributed sensing, leveraging the widespread presence of citizens across the territory to create a network of "human sensors" that integrates and complements traditional technological systems.

This participatory model has a user-centered design and is based on simplicity, intuitiveness, and immediacy, encouraging broad and timely participation, even in conditions of high stress or criticality. The goal is not only to collect data, but to enable a two-way communication channel between the civil community and authorities, creating a shared information base that fuels overall situational awareness.

The reporting interface, accessible from both desktop and mobile devices, was developed with particular attention to user experience and maximum accessibility. The web version features a clear and straightforward form, while the mobile version, optimized for touchscreens and enhanced with native features, allows for immediate submission of reports, even in the field and in contexts with limited connectivity. Interaction is guided by structured forms with standardized fields, designed to reduce ambiguity and errors and speed up data entry. Each step of the process is accompanied by visual feedback mechanisms, which confirm the user's submission of the report and display its processing status, increasing transparency and trust.

The details captured by the reports are extensive and cover various information dimensions. Each contribution contains detailed geographic information, such as GPS coordinates acquired through automatic geolocalization, addresses, and map references. Users can specify the type of event through a combination of automatic categorization and manual selection, also indicating the severity level according to standardized scales that allow authorities to quickly prioritize events. Multimedia material, such as georeferenced photographs or short text descriptions, can be attached to enhance the report with qualitative details that are difficult to detect from numerical data alone. Each report is also accompanied by an automatic timestamp, ensuring its temporal traceability and facilitating its integration into evolutionary analysis systems.

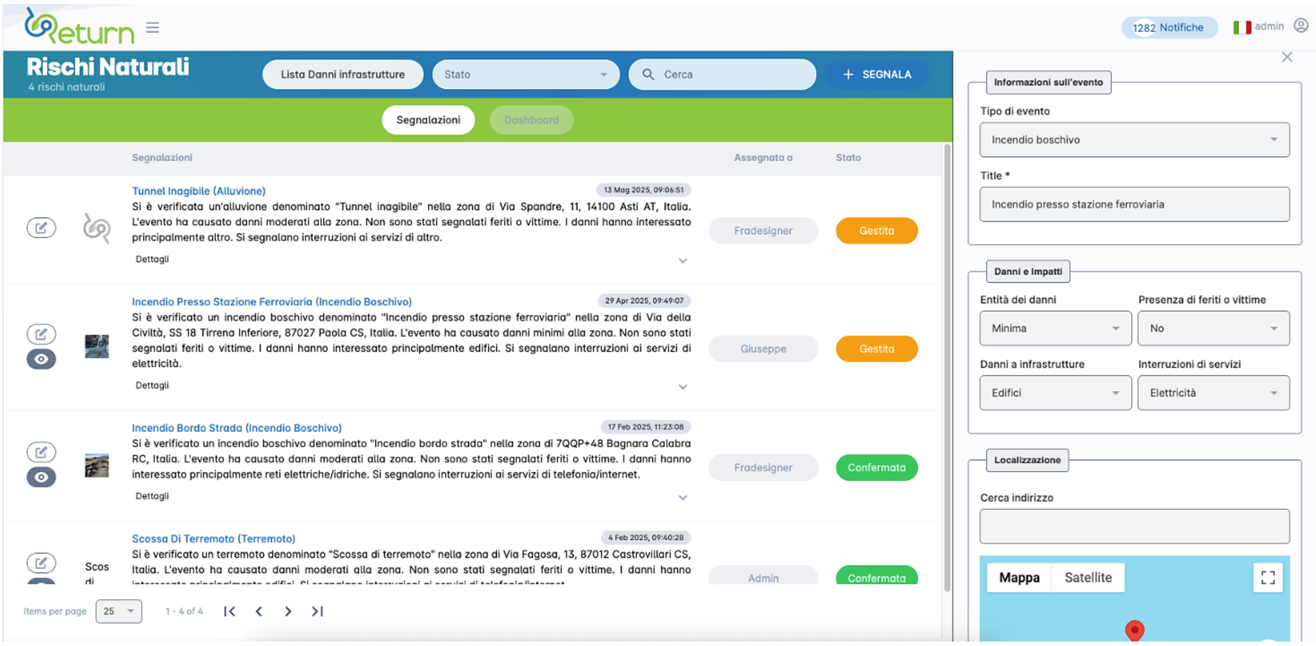

Figure 3 Reporting Interface

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A key aspect of the system is the "**automatic notification**" mechanism, which ensures timely communication and operational continuity. Whenever a report undergoes a change in status—for example, from entry to validation or handling—or a change in criticality level, the user or operator assigned to the report receives an immediate notification via email, web, or Telegram. These alerts contain all the updated details, ensuring that the parties involved are constantly informed and can react promptly, reducing response times and increasing the effectiveness of coordination.

To ensure the information collected is reliable, accurate, and usable, the platform integrates a multi-level validation process that combines artificial intelligence tools with human review mechanisms. The reliability verification algorithms, based on machine learning models trained on large sets of historical data, are able to recognize recurring patterns that indicate the credibility of reports or, conversely, the presence of anomalous and potentially suspicious behavior.

These models comprehensively evaluate multiple dimensions, including consistency with sensor data, the geographic and temporal plausibility of the event, and the participant's historical reputation, built on past behavior and the reliability of previous contributions. Anti-spam algorithms and semantic filters identify duplicate or inconsistent reports, while cross-validation systems automatically correlate contributions from similar geographical areas, increasing the overall information robustness. Reports classified as highly critical are subjected to a human moderation process, which provides an additional level of review and confirmation, activated for more complex or sensitive cases. Through these advanced anomaly detection and behavioral analysis mechanisms, the platform is able to promptly intercept and filter harmful, irrelevant, or misleading content, ensuring a high level of quality, reliability, and transparency in the information disseminated.

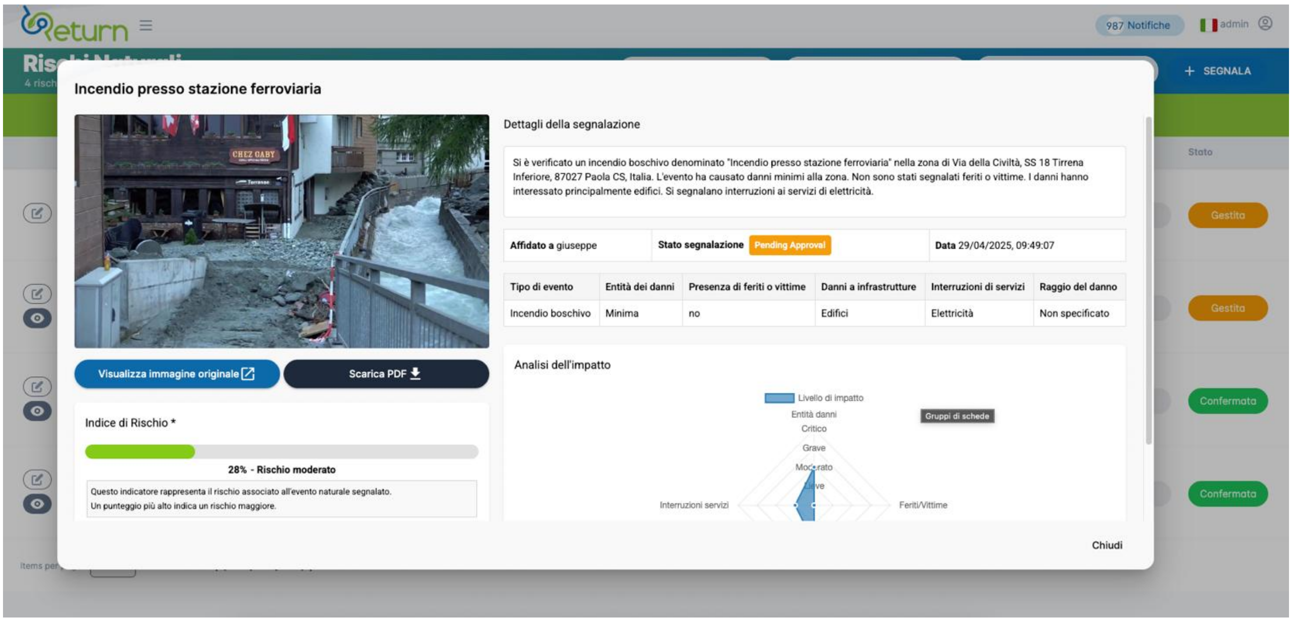

Figure 4 Report Details

In this way, the crowdsourcing interface is not just a data collection tool but becomes a structured channel for active collaboration that guarantees information accuracy, reduces response times, and helps build a shared culture of community resilience, strengthening mutual trust between citizens and institutions.

13. Artificial Intelligence System

The advanced AI-based analytics module is one of the platform's distinctive elements, introducing innovative capabilities for interpreting, correlating, and synthesizing information. It significantly reduces manual processing times and improves the quality and reliability of data available to decision makers. Integration with OpenAI APIs enables the transformation of unstructured textual information into coherent and actionable technical analyses, contributing to more timely and effective emergency management.

The system's architecture is based on a service-oriented model, designed to ensure flexibility, scalability, and resilience. It integrates a multi-model framework that uses different GPT variants depending on the complexity and criticality of the required analyses: models optimized for speed and high volume are used in standard and real-time analyses, while more advanced models are adopted in cases requiring complex and in-depth reasoning. A further configuration combines speed and accuracy for scenarios that require timely yet analytically rich responses.

The architecture was designed to be extensible, allowing for the future integration of additional models, both developed by OpenAI and proprietary, thus ensuring sustainability and scalability. Intelligent routing logic automatically selects the most appropriate model based on text complexity, event priority, and criticality level, dynamically balancing the workload between different models. This approach optimizes response times, reduces operating costs, and ensures compliance with agreed-upon SLAs.

The analysis capabilities span multiple levels. Semantic analysis enables automatic recognition of the report's intent and identification of key entities, such as locations, infrastructure, and types of damage. Sentiment evaluation determines the tone and perceived urgency, while dedicated algorithms extract relevant keywords and technical terms. A particularly innovative aspect is the system's ability to transform informal and descriptive language into standardized technical terminology, producing structured and uniform descriptions. Based on this, the module can automatically assign a risk level consistent with the analyzed content and generate immediate actionable suggestions to support decision-making. The system is also designed to process input from heterogeneous sources. Citizen reports, often written in colloquial language, are automatically corrected and translated into standardized technical information, ensuring consistency across different platforms. Formal or semi-structured reports from institutions and organizations are processed to extract key information and summarized through intelligent summarization functions, with the possibility of cross-referencing existing databases and sources. Finally, input from decision makers, such as operational notes or technical observations, is integrated into decision-making workflows, with an enrichment that facilitates the production of briefings, report management and decision documentation, also supporting traceability via audit trails.

In summary, the AI-Enhanced Analysis Module enables the transformation of a multiplicity of heterogeneous inputs into structured, contextualized and actionable knowledge, improving the timeliness of operational responses, the consistency of shared data and the overall quality of the decision-making process at all levels of emergency management.

14. Dashboard and Analytics

14.1. Platform Operational Dashboard

The Open Knowledge-Sharing Platform integrates an advanced system of operational dashboards that provides an immediate, accurate, and fully actionable visual representation of reported hazards and damages.

The dashboard architecture is designed according to a multi-level model that allows for the needs of different operational profiles, differentiating the display based on the roles and responsibilities of users. First-level operators have access to a real-time view, optimized for constant monitoring and timely event management, with rapid filtering and notification tools. Emergency coordinators, on the other hand, can rely on a management dashboard that aggregates information, identifies trends, and highlights operational priorities, thus supporting coordination and resource allocation activities. Finally, high-level decision makers access a strategic dashboard that presents summary indicators, KPIs, and metrics useful for guiding political and strategic choices.

The Open Knowledge-Sharing Platform interface integrates advanced representation tools that enrich the decision-making process through the multi-level and multi-lateral visualization of acquired and normalized data. The interactive map, updated in real time, allows for the precise geographic location of events and their contextualization in relation to other overlaying territorial data, such as infrastructure, critical networks, and environmental hazards, facilitating integrated geospatial analysis. The event timeline allows for detailed chronological reconstruction, with progressive drill-down capabilities down to individual events, enabling historical exploration and fine-grained temporal analysis.

Heatmaps highlight the areas of greatest criticality and event concentration, using metrics derived from information fusion processes, which combine heterogeneous sources to provide high-level, synthesized information. Interactive graphs and charts enable dynamic statistical analysis and the identification of emerging trends, supported by advanced data analytics techniques such as network analysis and geospatial analytics. These techniques allow for the analysis of relationships between network nodes, the evolution of critical issues, and the spatial-temporal correlations between events and infrastructure assets, providing quantitative and qualitative support for decision-making.

A dedicated alert panel manages high-priority notifications, classifying them according to configurable urgency levels to ensure a timely and scalable response based on the operational context and user roles. In this way, the platform combines operational immediacy, summary capabilities, and strategic vision, providing tools consistent with the responsibilities and needs of each player involved in managing critical situations.

Integration with advanced data analytics tools, such as Kibana, further enhances this representation, offering customizable interactive dashboards that combine geographic maps, timelines, statistical charts, and summary indicators. The modular GUI and use of interactive widgets allow users to explore data with dynamic filters, drill-down, and cross-filtering, facilitating analysis even for users with non-specialist technical skills and supporting rapid, informed decisions at every stage of emergency management.

14.2. Kibana Integration for Advanced Analytics

Integration with Kibana represents a key added value for the platform, not only for enhancing analytical capabilities but also for the quality of the user experience. Kibana offers interactive, intuitive, and highly customizable dashboards that allow users to explore data in real time through a modular graphical interface, combining geographic maps, timelines, bar charts, and summary indicators to facilitate a quick and in-depth understanding of phenomena.

In particular, Kibana's strength lies in its advanced management of maps and geospatial data: it allows for the precise visualization of events and assets on interactive maps, integrating contextual data through customizable overlays, such as infrastructure layers, critical networks, and environmental data. The maps are updated in real time and support zoom, filter, and dynamic selection capabilities, allowing both a comprehensive view and a granular analysis of phenomena in the area.

From a GUI perspective, Kibana uses interactive widgets that enable drill-down and cross-filtering, offering a seamless navigation flow between aggregated and detailed data, without the need for advanced query skills. This modularity allows for seamless transitions from a high-level strategic view to operational details, based on user roles, with configurable dashboards and custom filters. Color clarity and visual consistency significantly increase communication effectiveness, even in highly stressful operational situations.

Furthermore, Kibana supports the construction of dynamic views that combine different types of data from information fusion and advanced data analytics processes, such as network analysis and geospatial analytics, leveraging the high-level insights obtained from the aggregation, normalization, and overlay of heterogeneous data. This enables more informed and rapid decision-making, extending the platform's use to a broad spectrum of users, from citizens to technical analysts, from operators to political authorities.

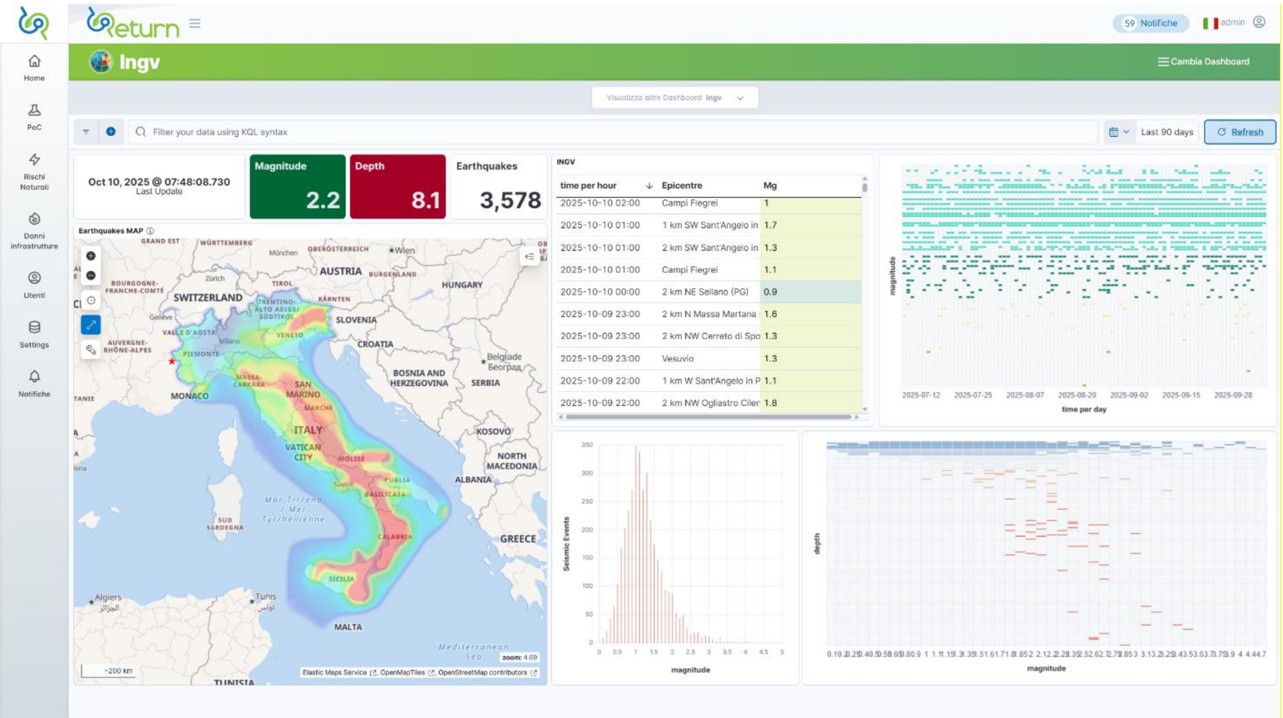

Figure 5 Advanced Analytics

The integration with Kibana not only enhances the platform's operational intelligence, but profoundly redefines how data is consumed, interpreted, and shared. Thanks to a user-centric GUI optimized for UX, Kibana makes analytics accessible not only to technical experts but also to users with diverse skills, thus fostering highly actionable decision-making. Dynamic visualization tools allow users to easily explore data in real time, combining geographic maps, timelines, graphs, and summary indicators into highly customizable dashboards.

Drill-down, cross-filtering, and interactive widgets facilitate seamless navigation between high-level strategic views and granular operational details, helping to significantly reduce search times and increase the precision of analyses in emergency situations. The ability to configure customized analytical environments for different stakeholders—from citizens and operators to policymakers—allows targeted monitoring of performance indicators, vulnerabilities, and evolving conditions, supporting rapid, informed, and informed decisions.

Furthermore, Kibana enables advanced spatial data management, integrating interactive maps updated in real time that facilitate event location, spatial data overlays, and contextual geospatial analysis. This combination of analytical power and usability translates into more effective decision support, capable of adapting to the complex needs of emergency management, ensuring transparency, collaboration, and timely action. Using

Kibana, you can create highly informative dashboards, rich in widgets that highlight trends, patterns, and other key analytical metrics for increasing detailed knowledge of infrastructure and the territory. These multifaceted dashboards allow you to visualize data from multiple dimensions, combining different types of visualizations such as geospatial maps, time graphs, heat maps, bar charts, and statistical tables, thus offering an in-depth, multidimensional understanding of the observed phenomena.

Kibana's versatility allows users to build views that adapt to different operational contexts, integrating normalized data and information fusion results with advanced analytics such as network analysis and geospatial analytics. This multilayered approach to data visualization supports the identification of complex relationships between events, assets, and territories, improving monitoring, forecasting, and decision-making capabilities in emergency management and critical infrastructure maintenance.

Furthermore, dashboard customization through interactive widgets facilitates fluid and dynamic navigation between different information levels, allowing users to focus on the most relevant parameters for roles and responsibilities, thus transforming data into actionable and strategic information for all stakeholders.

15. Knowledge Hub - Sharing Knowledge

15.1. Knowledge management and valorization

The Knowledge Hub serves as the platform's centralized repository and institutional memory, designed for the management, organization, and dissemination of knowledge. The system is not a static repository, but a dynamic knowledge-sharing environment, promoting semantic interoperability between operators, authorities, and the public.

This environment hosts a wide range of content: updated publications (news, blogs, policy documents), tools for conducting surveys and questionnaires, advanced statistical analyses, and systems for identifying emerging trends. A further added value is the document repository, which collects standardized operating procedures, technical manuals, guidelines, and training materials for various professional profiles. The archive also includes historical events and post-event analyses, allowing for the capitalization of past experiences and the promotion of continuous improvement processes.

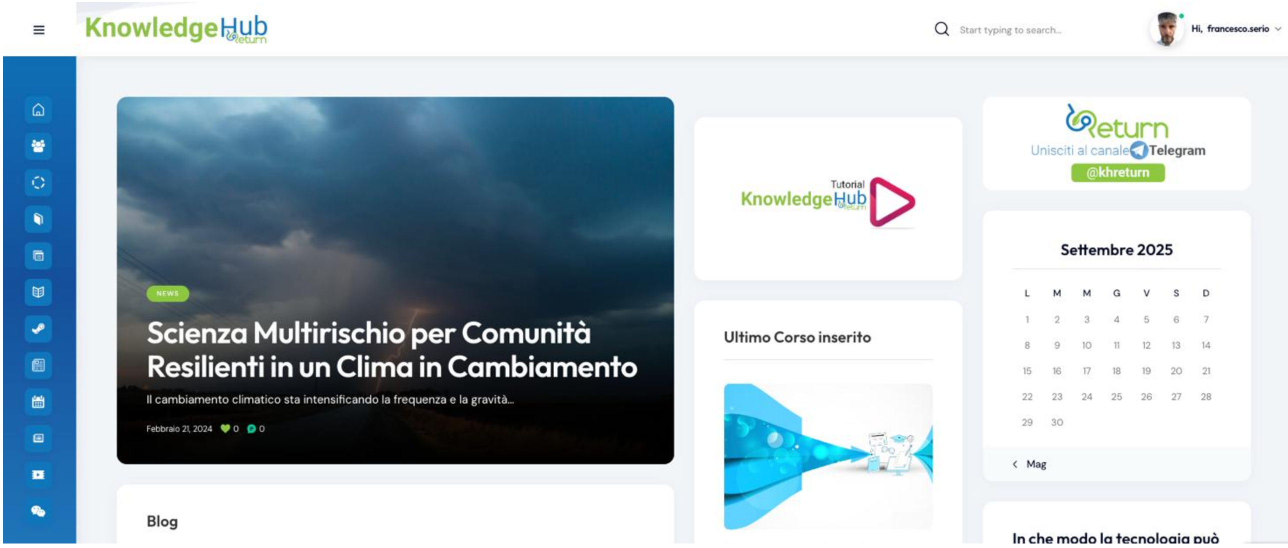

Figure 6 Knowledge Hub

The platform also integrates spaces for social and professional interaction, such as thematic forums and collaborative environments, which foster discussion among users of different backgrounds and expertise. Access to resources is enhanced by an advanced semantic search engine, capable of returning relevant and targeted results, and by collaboration tools that encourage shared knowledge building and the adoption of best practices.

Operationally, the Knowledge Hub is closely linked to a Multi-Channel Notification System that ensures rapid and effective information dissemination thanks to a flexible and redundant architecture. Notifications are sent via various means—such as web notifications, instant messaging, and email—to ensure maximum user coverage. Messages are tailored based on the recipient's role and the severity of the event, while automatic escalation mechanisms and delivery monitoring tools allow verification of actual receipt and maintenance of service even in emergency situations.

The knowledge base structure includes Standard Operating Procedures (SOPs) in the form of structured documents for emergency management, a database of best practices with a collection of case studies and effective approaches, technical documentation including technical manuals and operational specifications, training materials with content for different user roles, a regulatory framework containing regulations and compliance requirements, and historical data with an archive of past events and related lessons learned.

The knowledge management features implement an advanced search engine with full-text search, filtering and tagging, version control for managing document versions with change tracking, access control with granular permissions based on user role, collaboration tools that include commenting, review and approval workflows, and content curation through a rating system and recommendation engine.

15.2. Multi-Channel Notification System

The notification system provides scalable and customizable multi-channel communication, ensuring that critical information reaches all stakeholders through the most appropriate and effective channels.

The choice of Telegram as the primary channel responds to the need to ensure continuity of communication even in contexts of limited or degraded connectivity. The implemented notification channels include web notifications through native browser notifications with rich content, in-app notifications with an alert system integrated into the Platform interface, and dashboard alerts with dedicated panels for persistent messages.

The Telegram integration includes a dedicated bot for automated notifications, channel broadcasting for public channels with general information, and group notifications for specific operational teams. The email system integrates connections to corporate systems, bulk emailing capabilities for mass sending during emergencies, and email tracking for monitoring delivery and reading receipts.

The routing and personalization logic implements user profile-based criteria with role-based message filtering and prioritization, individually configurable preferences for preferred channels, location-based filtering for geographically relevant notifications, time-based respect for business hours and time zones, and automatic escalation logic for unread critical messages. The configuration and management system provides an admin panel for managing channel configuration, setup and credentials management, user management for managing user profiles and preferences, routing rules for configuring routing logic, and a performance dashboard for monitoring the notification system.

This integrated ecosystem ensures that critical information reaches the right stakeholders, at the right time, through the most effective channel, creating a robust and reliable communications system for emergency management.

15.3. Multiscale Territorial Laboratories

Given the platform's architectural structure and the articulation of its functional components, it is essential to emphasize how the implemented solutions find concrete application in real-world environments for testing and operational validation. The Smart Box concept fits into this framework, extending the platform's scope beyond the digital dimension, allowing its analytical and response capabilities to be tested and optimized directly on the ground. It serves as a local laboratory for observation, data collection, and performance assessment of complex infrastructure systems. It thus becomes a ready-to-use knowledge module.

This component allows for the effectiveness of analytical and predictive models to be verified through direct application in scenarios characterized by a high degree of interdependence between natural phenomena and critical infrastructure. The Smart Box concept translates into a network of multi-scale natural laboratories distributed along strategic corridors, such as Alpine highways or rail and road networks in the Mediterranean region. These are areas characterized by the simultaneous presence of natural hazards, geological complexity, and a high concentration of infrastructure. These territories represent ideal contexts for analyzing the interactions between the environment and transport systems, allowing us to delve deeper into the dynamics of interdependence and identify possible knock-on effects.

From a functional point of view, the framework operates as a real Smartbox, divided into two main components fully integrated into the overall platform:

• *The Catalogue*, which provides a comprehensive and structured inventory of the data and products collected by the various Spokes, including territorial datasets, analytical outputs, and supporting documentation. It ensures traceability and centralized access to information, promoting content sharing and interoperability.

• *The Explorer*, which represents the interactive interface that allows users to explore, visualize, and query the spatial data and maps available in the system, offering advanced navigation, geospatial analysis, and scenario comparison *tools.*

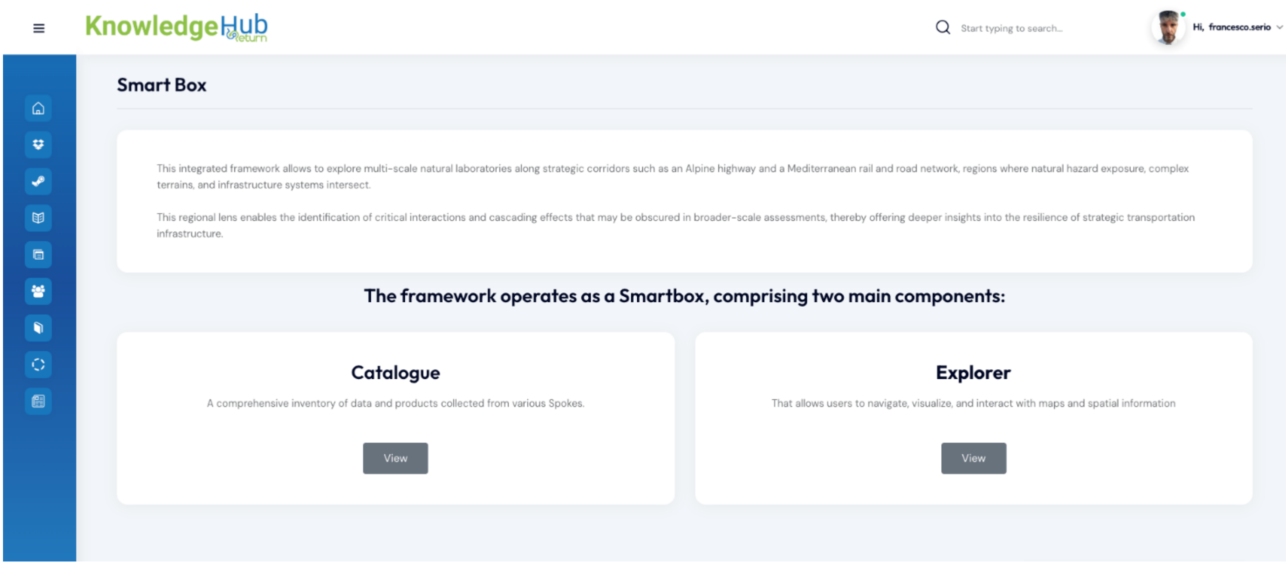

Figure 7 Smart Box Components

The integration of these two components ensures a direct connection between the information and operational dimensions, enabling the transformation of data collected in the field into dynamic and immediately usable knowledge. The Smart Boxes, fed by constant and empirically validated information flows, contribute to strengthening the Knowledge Hub and continuously improving risk assessment and emergency response models.

Through this approach, the platform extends its analytical and intervention capabilities beyond the digital domain, anchoring itself in the territory as a living system of observation and learning. This increases situational awareness, improves multi-level preparedness, and strengthens the overall resilience of strategic transport infrastructures.

16. Integrated emergency management and operational coordination

The platform is designed to manage a broad spectrum of emergency events, from natural disasters such as earthquakes, floods, and extreme weather events to technological incidents such as service outages, infrastructure failures, or cyberattacks.

Activation procedures are standardized yet configurable to adapt to specific operational contexts and regulatory requirements. Alert levels follow a graduated scale that correlates the severity of the event with the most appropriate response actions, facilitating escalation procedures and resource mobilization. The system supports both automatic activations based on predefined thresholds and manual activation by authorized personnel.

Managing critical information for the population is a central element of the platform, which provides a comprehensive system for disseminating life-saving information during emergencies. Assembly and meeting points are georeferenced and accompanied by detailed information on their location, the characteristics of available services, reception capacity, and accessibility for vulnerable groups. Evacuation routes are optimized by considering traffic flows and potential obstacles, ensuring safe and rapid evacuation operations.

Coordination between stakeholders is supported by standardized information exchange protocols, ensuring interoperability between different entities while respecting security and privacy requirements. The command-and-control system facilitates cooperation between stakeholders, promoting a shared understanding of the situation and collaborative decision-making tools. The traceability of decisions and actions taken during emergencies ensures the availability of a complete log, useful for post-event analysis, lessons learned, and compliance with regulatory requirements. The system maintains a chronological record of decisions made, actions implemented, and results achieved, ensuring operational transparency and accountability.

17. Implementation

17.1. Technologies Used

The platform's implementation is based on a set of modern, scalable, and high-performance technologies, chosen to ensure long-term robustness and ease of maintenance. The server uses Node.js as the application engine, leveraging Express.js as a framework for developing APIs and programming interfaces, in a microservices architecture that ensures modularity, functional isolation, and the possibility of future expansion. This approach allows individual services to be distributed and scaled independently, improving efficiency and component lifecycle management.

The user interface is developed with Angular, a platform that enables the creation of adaptive and modern web applications, equipped with advanced features typical of progressive web apps (PWAs). The component structure promotes code reuse, modularity, and simplified maintenance, ensuring seamless and tailored user experiences.

For data management, the platform uses MongoDB as a document database for scalable and flexible storage, Redis for temporary storage, caching, and session management, and Elasticsearch for advanced text search and powerful analytics capabilities. The communication protocols adopted include REST for accessing web services, WebSocket for real-time two-way interactions, and MQTT for integration with IoT devices, ensuring a reliable and high-performance data flow between sensors, backend, and frontend.

This technological combination enables an agile, resilient system capable of integrating and orchestrating heterogeneous data from multiple sources, supporting the complex processing and advanced visualization typical of the critical situations monitored by the platform.

17.2. Development Methodology

The platform's development follows an agile and iterative methodology, which prioritizes flexibility, collaboration, and continuous adaptation to evolving requirements. This approach ensures constant convergence between the implemented features and the actual needs of users and stakeholders involved. The work is organized into short cycles, called iterations or sprints, during which the project team develops, integrates, and tests a set of clearly defined features. Each cycle concludes with a joint review, during which the results achieved are presented and feedback is gathered to guide decisions for subsequent phases. This reduces the risks associated with misinterpreted requirements or features that are inconsistent with the intended use cases.

Particular attention is paid to software quality. Verification activities include testing at various levels: unit checks on individual modules, integration tests to verify the correct functioning of the entire system, end-user validation through demonstration sessions, and performance testing under realistic operating conditions. This is complemented by the systematic use of separate development, testing, and production environments, which allows for experimentation with new features without compromising the stability of the operating system.

The development process is supported by collaborative management tools that enable activity traceability, progress monitoring, and structured requirements and defect management. Each change is peer-reviewed to ensure consistency with project standards and code quality. Furthermore, new versions are released incrementally and continuously, ensuring a constant flow of improvements without service interruptions.

Finally, the adopted methodology promotes strong involvement of external stakeholders. Through periodic workshops, co-design sessions, and field validation activities, end users directly contribute to the platform's evolution. This ensures that the developed solution is not only technically sound, but also fully compliant with the operational expectations and specific needs of the various contexts of use.

18.4. Integration with Existing Systems

We perform a comprehensive mapping of integration points with existing systems and external services to ensure interoperability, traceability, and architectural consistency. This includes detailed documentation of the data formats used, such as JSON and XML, and the communication protocols employed, including HTTP/HTTPS, SOAP, and REST, accompanied by technical specifications on flows, dependencies, and information exchange methods.

For security and compliance, we define access, encryption, and credential management policies in line with current regulations and international best practices. Authentication and authorization mechanisms are based on established standards such as OAuth 2.0, with the possible use of OpenID Connect in identity management workflows to strengthen access protection and traceability. In more complex contexts, characterized by federated environments or cross-domain Single Sign-On (SSO) systems, the SAML (Security Assertion Markup Language) protocol is implemented, enabling secure integration between distinct domains.

To simplify integration between heterogeneous ecosystems, middleware or API gateways are adopted to act as an intelligent bridge between legacy systems and new application architectures. These components allow you to centralize traffic control, apply uniform security policies, manage authentication, throttling, and caching mechanisms, and monitor service performance in real time, thus ensuring a stable, secure, and optimized information flow. In scenarios where it is not possible or convenient to intervene directly on the systems, integration can occur via API wrappers, which introduce a modern, standardized interface without modifying the logic or structure of the underlying system.

The progressive adoption of open API standards and shared protocols promotes interoperability, scalability, and regulatory compliance, in line with key international standards such as GDPR, ISO/IEC 27001, and the OpenAPI guidelines. During the transition phase, backward compatibility and operational coexistence between new and legacy systems are ensured, while also ensuring long-term sustainability and reusability of solutions in future contexts.

18. Validation and Testing

The progressive adoption of open API standards and shared protocols promotes interoperability, scalability, and regulatory compliance, in line with key international standards such as GDPR, ISO/IEC 27001, and the OpenAPI guidelines. During the transition phase, backward compatibility and operational coexistence between new and legacy systems are ensured, while also ensuring long-term sustainability and reusability of solutions in future contexts.

The testing process developed through several phases:

- The first phase, in which technical tests verified the correctness of the system's functionality and stability, with particular attention to integration modules and critical components.
- Operational tests were conducted in simulated scenarios that reproduced realistic emergency conditions, allowing us to observe the platform's behavior in complex, data-intensive situations.
- Validation with end users provided direct feedback on the effectiveness of the interfaces and the overall quality of the user experience. Thanks to the adoption of structured and repeatable procedures, the validation process not only ensured the system's reliability but also laid the foundation for its scalability and the possibility of reusing the methodologies in future contexts.
- Pilot testing was conducted on carefully selected case studies to represent different types of emergencies and to involve key institutional and community stakeholders. The test environments were configured to faithfully replicate the operating conditions, while maintaining the control parameters necessary for accurate performance measurement. Through the pilot programs, stakeholders had the opportunity to directly experience the platform, contributing observations and suggestions that proved crucial to its refinement. This approach not only validated the features already developed but also verified the practical applicability of the solutions and gathered useful insights to guide future developments. Furthermore, the results obtained from the pilots demonstrated the system's ability to adapt to different operational contexts, strengthening its transferability at the European level.

The overall testing results confirmed the platform's compliance with established requirements, highlighting adequate response times, good concurrent user management capabilities, and high system availability. Usability tests revealed an overall positive level of user satisfaction, while also identifying some room for improvement in the interfaces and interaction methods. The systematic analysis of stakeholder feedback provided valuable insights for optimizing internal processes and introducing new features, thus supporting a path of continuous improvement.

In conclusion, the entire validation and testing process not only certified the platform's technical robustness but also played a key role in strengthening its operational relevance, its ability to scale in complex scenarios, and its transferability to different national and European contexts. The experience gained thus represents a methodological asset that can be capitalized on and replicated in future projects.

19. Deployment and Operations

The platform's deployment was planned according to a phased strategy, designed to minimize operational disruptions and facilitate gradual user adoption. The transition to the system was accompanied by meticulous data migration procedures, ensuring information integrity and consistency through validation checks, comprehensive backups, and recovery plans capable of ensuring operational continuity even in the event of critical issues.

A key element of the deployment phase was user training. Training activities were differentiated based on the roles and responsibilities of the various stakeholder groups, including hands-on sessions, targeted support materials, and learning paths tailored to actual operational needs. User manuals, demonstration videos, and interactive workshops were developed to ensure not only technical knowledge of the platform but also informed and integrated use into daily processes.

Post-release management is supported by a clear organizational model, which assigns specific responsibilities for technical maintenance, user support, and strategic oversight. Operating procedures standardize incident management, continuous monitoring activities, and change processes, ensuring that platform evolution occurs in a controlled and documented manner. Maintenance plans include periodic updates, security patches, and the gradual implementation of new features, defined based on user feedback and priorities identified by stakeholders.

Another key aspect is the sustainability plan, which addresses both the economic and technological dimensions. From a financial perspective, the model defines diversified sources of funding and cost optimization strategies to ensure long-term service continuity. From a technological perspective, the development roadmap takes into account emerging innovations and industry trends, ensuring the platform can evolve in line with market developments and new operational needs.

Finally, scalability was conceived as a structural requirement, enabling the platform to adapt to growth and expansion scenarios. This means the system can support a growing number of users, increasingly large data volumes, and diverse application contexts, while maintaining reliability, performance, and security. In this way, deployment represents not just the initial activation, but the start of a sustainable operational cycle capable of ensuring value over time.

20. Impacts and benefits

The adoption of the platform has had significant impacts both on the operational level of the organizations involved and on the social and community level. The integration of digitalized processes, real-time information sharing, and the use of common standards have led to a substantial change in emergency management, with tangible impacts in terms of efficiency, safety, and collective trust.

From an operational perspective, the system drastically reduces response times thanks to more streamlined information flows, the immediate availability of critical data, and the automation of procedures that previously required manual and often redundant interventions. Decisions are made more quickly, supported by a clear and shared vision of the situation, which fosters effective coordination between agencies, local authorities, and emergency response services. The standardization of communication protocols reduces misunderstandings and delays, creating a common language that streamlines collaboration between diverse stakeholders.

A further benefit comes from reducing duplication of information. Aggregating data from multiple sources into a single, reliable platform eliminates inconsistencies, contradictions, and parallel collections of information, strengthening the reliability of analyses and decisions. This ensures that each stakeholder operates on the basis of unified knowledge, increasing the coherence of actions and the overall effectiveness of responses.

The positive impacts not only affect institutional operators but also directly impact the population. Citizens have timely access to clear and verified information, which helps them orient their behavior in crisis situations, reducing panic and increasing personal safety. Reliable and continuous communication helps strengthen trust in institutions, improve the perception of their own protection, and foster collective resilience. At the same time, active citizen participation through bottom-up reporting and crowdsourcing mechanisms strengthens a sense of civic responsibility and makes the community an integral part of the emergency management system, transforming citizens from mere recipients to actual collaborators in the response process.

Finally, impacts are systematically measured through specific indicators. Technical parameters such as system availability, response speed, data accuracy and reliability, and the level of use of various features are considered. These are complemented by social and organizational indicators, which allow us to assess the level of user adoption, the effectiveness of coordination efforts, and community involvement in the various phases of emergency management. These measurements serve not only as a monitoring function, but also form the basis for continuous system improvement and progressive adaptation to the needs of local communities and individuals.

In short, the platform does not simply introduce technological innovations; it generates a multiplier effect that enhances the operational capacity of institutions, increases the resilience of communities, and strengthens the bond of trust between citizens and the civil protection system.

21. Development of tailored communication strategies for sharing results

Set up tailored communication strategies aimed at increasing the interested parties' awareness of the risks they are exposed to. Risk communication is also addressed to stakeholders and at every level of coordination Analysis of standard methods and IT Services for information and knowledge sharing, related to events involving CIs, with the actors responsible for emergency management (e.g. maintenance personnel, firefighters, civil protection).

21.1. Multi-risk perception assessment to increase interested parties' awareness

In contemporary risk management, the concept of multi-risk refers to the coexistence, within the same territory and time frame, of multiple natural and/or anthropogenic hazards that may interact in cumulative, cascading, or synergistic ways (UNDRR, 2021). Multi-risk scenarios may involve simultaneous events (e.g., flooding in an area already weakened by an earthquake), causal sequences (e.g., rainfall-induced landslides), or systemic overlaps of different threats affecting the same communities (e.g., hydraulic, health, and infrastructural risks in complex urban environments).

From a risk perception perspective, multi-risk contexts introduce additional cognitive complexity. Individuals do not assess hazards in isolation; rather, they compare, prioritize, downplay, or amplify them depending on their experience, available information, and social context. The perception of one risk may therefore be intensified or attenuated by the presence of other risks perceived as more urgent, familiar, or severe (Renn et al., 2011).

These dynamics have important implications for questionnaire design. Surveys focusing on a single hazard may produce partial or distorted results, as they fail to reflect how citizens mentally frame real-world threats. Including questions that explicitly address multiple risks (e.g., hydraulic, seismic, health, technological) enables a more realistic and multidimensional understanding of cognitive, emotional, and behavioral responses (Komendantova et al., 2014).

Moreover, multi-risk perception may generate cognitive interference or conflict, for instance, varying levels of trust in institutions depending on the hazard addressed, or saturation of attention when multiple warning messages compete. Designing survey instruments that differentiate sections by hazard type, use separate scales for emotional and probabilistic assessments, and explore perceived interactions and priorities can therefore enhance validity.

Operationally, explicitly acknowledging the multi-risk nature of a territory strengthens the validity of perception studies and provides strategic insights for integrated risk management, communication planning, and the development of realistic civil protection scenarios.

21.2. Risk perception assessment to improve relationships of trusts between institutions responsible and citizens

Systematic and context-specific knowledge of citizens' risk perception represents a strategic lever for improving interactions between the population and institutions responsible for prevention, early warning, and emergency response. Beyond capturing individual opinions, it enables understanding of the social and relational dynamics that shape institutional trust, preparedness, and adaptive capacity.

Empirical research shows that risk perception directly influences compliance with civil protection measures. When risks are perceived as significant but manageable, individuals are more likely to adopt proactive and responsible behaviors. Conversely, distorted or fatalistic perceptions may lead to denial, inaction, or maladaptive responses (Paton, 2008; Bubeck et al., 2012). These findings call for communication strategies that move beyond one-way, paternalistic approaches toward more dialogical and participatory models.

Effective risk management depends on trust between institutions and citizens, grounded in transparency, consistency, and responsiveness. Trust is not built solely through the transmission of technical information; it requires careful consideration of informational needs, expectations, and the cognitive and emotional vulnerabilities of exposed populations (Terpstra, 2011). Collecting and analyzing local perceptions enables the tailoring of communication content and channels, reducing misalignment and enhancing the effectiveness of prevention and early warning policies (Burningham et al., 2008).

Here we propose the results of a pilot case to survey multi-risk perception of citizens of Rome. Responses are crucial to inform responsible institutions to set up tailored communication strategies aimed at increasing the interested parties' awareness of the risks they are exposed to. Risk communication is also addressed to stakeholders and at every level of coordination

The questions we can answer through the questionnaire are the following:

- Which hazards are perceived as most concerning by citizens?
- How is public risk perception shaped by perceived levels of individual knowledge and institutional expertise?
- To what extent does prior personal experience influence levels of concern? These questions help identify potential gaps between perceived and objective risk, particularly in relation to the spatial distribution of the samples.
- What is the level of trust in the authorities responsible for risk management in the two countries? How does this relate to perceptions of individual and institutional preparedness?
- Do socio-demographic variables (e.g., age, education) reveal systematic patterns in risk perception or trust?

21.3. Regulatory Framework

The relevance of subjective risk perception is reflected in international, European, and national regulatory frameworks. The Sendai Framework for Disaster Risk Reduction 2015–2030 promotes a comprehensive understanding of risk "in all its dimensions," including cognitive, social, cultural, and institutional factors, and encourages participatory approaches and assessment of public awareness.

At the European level, Directive 2007/60/EC on the assessment and management of flood risks states that flood risk management should consider social, environmental, economic, and cultural aspects. Article 9 further requires public participation in the preparation and review of Flood Risk Management Plans, implying the need to assess public awareness and perception through transparent and inclusive methodologies.

Nationally, the Italian Civil Protection Code (Legislative Decree 1/2018) identifies among its core functions the promotion of civil protection knowledge and culture among affected populations (Art. 2). Preventive information and risk communication are therefore recognized as fundamental components of the system and necessarily rely on understanding how risk is perceived by citizens. The National Risk Information and Communication Plan further emphasize listening to local communities and encourages the use of surveys and questionnaires to improve communication strategies.

Finally, as risk perception surveys involve direct data collection from individuals, they must comply with data protection regulations. Regulation (EU) 2016/679 (GDPR) requires that personal data be processed lawfully, fairly, transparently, and in accordance with principles of data minimization and purpose limitation (Arts. 5–6). Although not specific to risk perception research, GDPR provides the essential ethical and methodological framework for conducting such studies. Anonymous or pseudonymized data collection is crucial to ensure informed participation, protect privacy, and reduce response bias.

21.4. Methods

21.4.1 Survey design

The questionnaire administered was designed building on previous studies on perception of multiple risks (Mondino et al., 2020a,b; Di Baldassarre et al, 2021) and concerned the following nine phenomena: epidemics, floods, droughts, wildfires, earthquakes, war, economic crisis, terrorist attacks and climate change. The survey focused on five aspects: potential impact of each phenomenon, the perceived probability of occurrence of the phenomenon, level of confidence in competent authorities, perceived level of safety in relation to the phenomenon and knowledge of the phenomenon. The questions proposed in the questionnaire are shown in Table 1. In addition to those questions, respondents were also asked to provide socio-demographic information such as age, gender, type of employment and zip code to investigate the relationship between responses and both demographic characteristics and the exposure of respondents' residency to each threat.

The proposed questions had either predefined response options corresponding to "yes" or "no", or a number on a Likert scale (from 1 to 5 i.e. from "not at all" to "very much"), one of the most used psychometric tools in research on educational and social sciences (Joshi et al., 2015). For all questions, the participants were given the opportunity to express neutrality position through "don't know" answer option, provided to prevent respondents from feeling obligated to answer on topics either outside their knowledge or sensitive.

Participants were informed that participation was voluntary and anonymous and agreed to participate in this study by completing and submitting the survey. The survey was conducted only among adults, i.e. over 18 years.

Each respondent was only able to answer the questionnaire once, and no questions were required to answer.

Variable	Question	Answers available
Experience	1. Have any of these phenomena ever happened to you (in Rome or elsewhere)?	"Yes", "No" or "Don't know"
Potential impacts on the respondent	2. In case the following phenomena happen, how much damage can they cause to you and your home?	On a scale from 1 "Not at all", to 5 "Many," or "Don't know".
Authorities' level of preparedness	3. How prepared are the responsible authorities to deal with the following phenomena?	On a scale from 1 "Not at all", to 5 "Very much," or "Don't know".
Respondent's level of preparedness	4. In case they happen to you, how prepared are you to deal with them?	On a scale from 1 "Not at all", to 5 "Very much," or "Don't know".
Level of knowledge of the phenomenon of the respondent	5. How well do you know these phenomena?	On a scale from 1 "Not at all", to 5 "Very much," or "Don't know".
Level of safety felt by the respondent	6. Do you feel safe living in Rome (or where you live)?	On a scale from 1 "Not at all", to 5 "Very much," or "Don't know".

Perceived probability of occurence	7. Can any of these events happen in Rome (or where you live)?	On a scale from 1, "Very unlikely" to 5, "Very likely," or "Don't know"
Respondent's knowledge level of the interventions	8. Do you know if there are any interventions or facilities in Rome to reduce flood damage?	“Yes”, “No” or “Don't know”

Table 1 Questions proposed in the survey, corresponding variable and possible answers available.

21.4.2 Study area and sample analyzed

The study focused on the metropolitan area of Rome, Italy, whereby 297 citizens were interviewed in any of the 15 municipalities in which the city is subdivided, with uneven spatial distribution. The survey administration campaign was conducted during May 2023. The administration of the questionnaires to the citizens took place through the method of "snowball sampling", i.e. one of the most widespread methods aimed at collecting data used in qualitative research (Naderifar et al., 2017) whereby networking and referral features are central. According to this method, researchers begin to disperse the questionnaire usually to a small number of initial contacts, which meet the research criteria and are invited to become research participants. Then, they are asked to recommend other contacts that meet the search criteria, which in turn recommend other potential participants and so on. From the initial social network, the sampling momentum develops, capturing a growing chain of participants. Sampling usually ends when the target sample size or saturation point is reached (Parker et al., 2019). In this research the respondents must have been 18 years old and should reside in Rome, respondents that did not meet these prerequisites were excluded from the analysis. The sample collected has is composed of 63% male respondents and 37% females with age ranging from 18 to more than 60.

The data analysis was carried out using either the Wilcoxon or the Kruskal Wallis tests. Through these statistical tests it was possible to compare the responses of subsets of the main sample and to verify whether there was a significant difference in the risk perception of the two subsets compared.

21.4.3 Results

Results shown that some municipalities provide answers on the Likert scale significantly different from the average depending on the phenomenon. For instance, the perceived level of damage due to floods reaches its peak in Municipality XV, where diverse flooding events occurred in recent years as for instance in June 2021. This area also includes the Milvian Bridge, where the Tiber Riverbanks are at their lowest elevation. As a result, this location is typically the first point of overtopping, increasing the likelihood of flooding in Rome. Municipality VI has a higher level of perceived damage in case of drought, climate change and economic crises. Interestingly, the Municipality XI show the highest level of trust in the authorities for almost all threats.

The area of respondents’ residency suggests playing a significant role especially when it comes to flood and wildfires risks. Comparing the mode of responses for each municipality reveals that the responses generally present similar values on the Likert scale. However, variations do exist in the perceived level of damage due to a potential flood. In most municipalities, this perception is rated at 3. Notably, in municipalities V and VIII, the perceived damage is at its lowest, with a rating of 2. Conversely, municipalities VI and IX report a higher perceived damage level, with a rating of 4. The highest perceived damage is observed in municipality X, with a rating of 5. The rationale behind these results may be attributed to the varying flood risks across different municipalities (Ridolfi et al., 2025). In municipality X, the high flood risk, particularly near the Tiber River mouth, has led to frequent flooding in nearby settlements. Similarly, municipalities VI and IX have experienced multiple recent floods, largely due to issues with the secondary hydraulic network. Conversely, municipalities V and VIII exhibit the lowest flood risk, if any, matching lower perceived damage levels.

Comparing the responses concerning potential wildfire damage reveals the highest concern in Municipalities I and II, where the historical city center is located. In these areas, wildfires would have catastrophic consequences due to the high population density. Similarly, Municipalities III, XII, and XV also show high levels of concern, as these areas encompass a significant percentage of woodland and green spaces, including the expansive Roman countryside.

Regarding the phenomena of economic crisis, climate change, and epidemics, particularly the COVID-19 pandemic that has significantly impacted recent years (Mondino et al., 2020a), respondents generally report a high level of personal knowledge about these issues. However, their perceived level of safety remains low. This discrepancy is likely due to the direct and recent experiences with the COVID-19 pandemic, which has heightened awareness but also contributed to feelings of vulnerability. Similarly, concerns about climate change and the economic crisis are driven by their relevance and the perception of these issues as immediate, everyday risks. This comparison may thus reveal an underlying sense of distrust in authorities' ability to manage emergencies effectively, Figure 1.

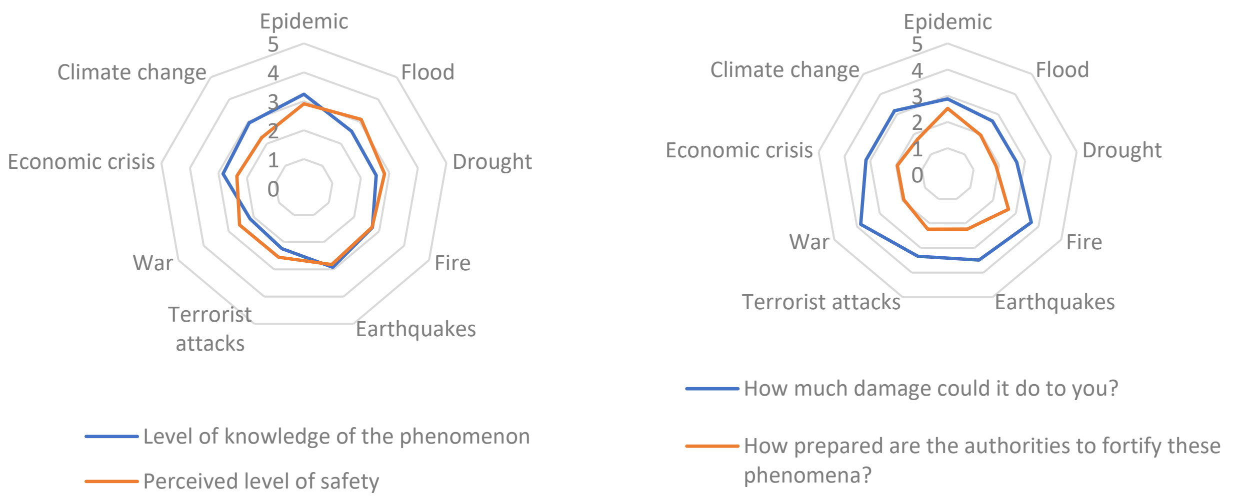

Figure 1 Level of knowledge of the phenomena and perceived level of safety (left panel) and possible damage and level of trust in the authorities (right panel) for the phenomena

Numerous studies on risk perception highlight the significant influence on risk perception related to gender. Empirical evidence consistently shows that gender is a crucial variable, with women generally assessing risks more severely than men and expressing higher concern (Vermigli et al., 2011; Slovic, 2000).

However, while quantitative analyses confirm this gender difference, qualitative analyses suggest it also stems from other factors, such as the type of risk, different meanings attributed to it, and power relations between men and women (Vermigli et al., 2011; Bronfman and Cifuentes, 2003).

Our findings align with this perspective, revealing statistically significant differences between the risk estimations of women and men.

Specifically, significant differences were observed in responses related to trust in competent authorities (for floods, droughts, and fires), knowledge of phenomena (for epidemics, floods, droughts, and fires), and the perceived degree of safety (for floods, earthquakes, and climate change). Conversely, there were no significant gender differences in the perception of damage for all phenomena; trust in authorities for epidemics, earthquakes, and climate change; knowledge of earthquakes and climate change; and the perceived degree of safety for drought and fires.

To assess the impact of experiencing a given risk, results reveal that the p-value is significant only in the case of wildfire risk.

In conclusion, the findings of this study provide a robust evidence base for designing tailored communication strategies that enhance awareness among interested parties regarding the specific risks to which they are exposed. By identifying perception gaps, these results enable the development of targeted messaging that is both relevant and actionable.

Effective risk communication must extend beyond the general public to encompass all stakeholders, including institutional actors, technical operators, policymakers, and community representatives. It should operate at every level of coordination—local, regional, and national—to ensure coherence, transparency, and shared understanding across governance structures.

By integrating these findings into structured communication frameworks, organizations can strengthen risk preparedness, foster informed decision-making, and promote a culture of shared responsibility in risk management processes.

21.5. Tailored communication for flood evacuation models through a simplified probabilistic approach

River floods are among the most severe natural hazards affecting urbanized areas (Guo et al., 2021; Blöschl, 2022; Cea & Costabile, 2022; Jiang et al., 2023; Blöschl et al., 2024; Turconi et al., 2024; Ridolfi et al., 2025). In many regions worldwide, vulnerability is shaped not only by environmental conditions but also by socio-economic dynamics, urban development patterns, and infrastructural limitations. These intertwined factors increase the complexity of disaster risk management and highlight the need for integrated, non-structural approaches.

Within this framework, effective risk communication becomes a fundamental component of evacuation planning and broader disaster risk reduction strategies. Beyond defining procedures and routes, tailored communication strategies are essential to enhance awareness among exposed populations and to support informed decision-making before and during flood events. Risk communication must therefore be designed to address different target groups — from citizens and vulnerable communities to institutional stakeholders — ensuring that information is clear, accessible, and actionable.

At the same time, communication efforts must extend across all coordination levels, fostering collaboration among the actors responsible for emergency management, including maintenance personnel, firefighters, civil protection authorities, and critical infrastructure operators. This requires the analysis and adoption of standardized methods and dedicated IT services that enable efficient information and knowledge sharing, particularly in scenarios involving critical infrastructures. Integrating technological tools with established operational protocols enhances situational awareness, supports timely decision-making, and strengthens the overall resilience of urban systems in the face of rapidly evolving flood events.

The core methodological contribution of this study is the development of a simplified probabilistic framework that combines spatial mobility, routing uncertainty, and hazard propagation. Instead of attempting to reproduce detailed individual behaviors, the model generates large ensembles of plausible evacuation trajectories, accounting for variability in route selection, travel speed, and flood arrival times. This ensemble-based approach, consistent with stochastic methods widely adopted in environmental modelling, enables the derivation of probability distributions rather than single deterministic outcomes.

Such probabilistic representations are essential given the intrinsic uncertainty that characterizes flood emergencies. Available warning times are often based on hydrological forecasts affected by considerable uncertainty. At the same time, human responses under stress can vary significantly, and transportation networks may be partially disrupted as flooding progresses, with accessibility conditions changing dynamically. A robust evacuation assessment must therefore explicitly incorporate uncertainty as a structural element of the modelling process.

The proposed framework was applied to Ostia, a coastal district of Rome (Italy), selected for its complex risk profile. The area is exposed to both fluvial and pluvial flooding, features high population density, and presents a highly articulated infrastructural layout. Its location between the sea and the Tiber River creates potential interactions among hydrological processes, which may accelerate flood propagation and reduce drainage efficiency. In addition, local topographic depressions and a dense street network complicate the identification of reliable evacuation routes. These characteristics make Ostia a particularly relevant case study for testing and evaluating simplified probabilistic modelling strategies.

The primary aim of this study is to develop a simplified modelling framework capable of supporting evacuation assessments in flood-prone urban environments while remaining operationally practical and accessible to decision-makers. The research is structured around four main objectives:

- Develop a probabilistic evacuation model able to generate distributions of evacuation times for any location within an urban network. By running thousands of simulations per node, the framework moves beyond single deterministic estimates and captures the variability associated with uncertain route choices and movement conditions.
- Formulate a simplified flood arrival model based on an approximate hydraulic representation. Rather than relying exclusively on fully resolved hydrodynamic simulations, although these may be incorporated when available, the approach estimates flood propagation through probabilistic velocity distributions, offering a physically consistent yet computationally accessible alternative.
- Assess the interaction between evacuation dynamics and hazard evolution by quantifying the probability of pedestrians encountering floodwaters. This probabilistic measure of interaction provides an integrated indicator of safety, combining mobility uncertainty with the temporal progression of the hazard.
- Validate the methodology through application to a real-world case study, generating operationally relevant insights for emergency planning and exploring its potential integration within Urban Digital Twin (UDT) frameworks.

21.6. Data

The modelling framework relies on four primary datasets: (i) the road network derived from OpenStreetMap (OSM); (ii) officially designated shelter areas from the Civil Protection Plan of the Municipality of Rome; (iii) national Flood Hazard Area (FHA) maps provided through IdroGEO/ISPRA; and (iv) a digitised polyline representing the riverbank. For flood hazard classification, the H2 scenario was adopted, corresponding to events with a 100–200 year return period.

To ensure transparency and ease of application, all datasets were consolidated into a lightweight spreadsheet structure. From the road network, 609 nodes were extracted, each representing either an intersection or a significant change in direction. A topological matrix was constructed in which each node includes the following attributes:

- Planimetric (X–Y) coordinates.
- Up to three admissible outgoing neighbouring nodes, defining feasible pedestrian movement directions at each step. Links oriented toward the river were excluded to maintain evacuation consistency. The option labelled Choice1 corresponds to the principal, safest, or shortest route, identified based on local morphology and the official evacuation logic.

- A binary shelter flag (1 = designated shelter node; 0 = non-shelter node), ensuring that evacuation paths terminate upon reaching a safe location, provided no prior flood interaction occurs.
- A binary hazard flag (1 = inside the selected FHA; 0 = outside), identifying nodes potentially subject to pedestrian–flood interaction along multi-segment paths.
- The Euclidean distance from the left riverbank, used as a proxy for hydraulic distance. For nodes outside the FHA (hazard flag = 0), this value is set to −9999.

21.7. Probabilistic modelling of pedestrian velocity

We model pedestrian velocity as an AutoRegressive model of first order (AR(1), Box and Jenkins 1976; Stockis and Tong 2002):

$$v_l = \mu_v + \phi \cdot (v_{l-1} - \mu_v) + \epsilon \quad (1)$$

where:

- v_l is the pedestrian velocity along the i-th segment (chosen by a pedestrian) of a polyline which connects a starting node with a shelter,
- v_{l-1} is the pedestrian velocity corresponding to the previous (i-1)-th segment,
- μ_v is the mean value of pedestrian velocity
- ϕ is the autoregressive persistence parameter, with the well-known property $|\phi| < 1$ for the respect of stationarity (Box and Jenkins 1976), and

$\epsilon \sim \mathcal{N}(0, \sigma^2)$ is a zero mean gaussian noise, characterized by a standard deviation σ.μ_v,ϕ,σ are assumed as constant along a polyline. Obviously, they are context-dependent parameters, usually on i) density of walking/corridor population, ii) panic-like conditions, iii) presence of elderly / mobility-limited population, iv) presence of obstacles, slope and step along the path, and so on.

The autoregressive model generates evacuation time distributions with smoother transitions, reflecting realistic persistence in movement speed. This mirrors behavioural inertia documented in empirical evacuation studies (Alqahtani et al. 2025; Duan 2024; Peacock et al 2011; Wang et al 2021), in which evacuees rarely change velocity abruptly between successive segments.

Due to the significant uncertainty associated to these AR(1) parameters, we considered μ_v,ϕ,σ as random variables, uniformly distributed inside specific ranges, according to literature review (Arrighi et al. 2017; García Diéguez et al. 2021; Giannoulaki and Christoforou 2024). In detail:

μ_v~U(0.5 m/s;1 m/s)

ϕ~U(0;1)

σ~U(0.05 m/s;0.25 m/s)

For each plausible starting node (i.e., characterized by Flag = 0) we generated 1,000 3-parameter sets of values for (μ_v,ϕ,σ); for each set we carried out 1,000 simulations of plausible polylines towards any shelter node (i.e., with Flag = 1).

As well-known from the theory of stochastic processes (Box and Jenkins 1976), for a specific parameter set of values for (μ_v,ϕ,σ) associated to a polyline, v_l~N(μ_v,σ^2/(1- ϕ^2)). However, to avoid unrealistic negative or excessive values for pedestrian velocity, we furtherly applied the following filter:

$$v_l = \begin{cases} 0.01\ m/s & if\ v_l < 0.01\frac{m}{s} \text{ from Eq. (1)} \\ \mu_v + \phi \cdot (v_{l-1} - \mu_v) + \epsilon & if\ v_l\ \in \left[0.01\frac{m}{s}; 2\frac{m}{s}\right] \text{ from Eq. (1)} \\ 2\ m/s & if\ v_l > 2\frac{m}{s} \text{ from Eq. (1)} \end{cases} \tag{2}$$

Application of Eq. (2) for the above-mentioned simulations ensemble allows to obtain (without considering interaction with floodwater) the probability distribution of evacuation times for each node (with Flag = 0) considered as starting point towards any shelter area. Obviously, for each simulated path, the evacuation time T (associated to a k-th starting node) corresponds to the summation of the times associated to all the involved segments belonging to the simulated path:

$$T = \sum_{l=1}^{m} \frac{d_l}{v_l} \tag{3}$$

where m is the total number of involved segments for the simulated path, d_l and v_l are the length and the pedestrian velocity (from Eqs. 1-2) of the i-th segment.

The proposed framework adopts a simplified probabilistic representation of flood-wave evolution, based on the following assumptions:

- Starting from the Euclidean distance d_k of each k-th node inside the FHA map (i.e., with FlagINSIDE = 1) from the left riverbank, the associated hydraulic distance d_(w,k) was randomly evaluated in each simulation. Specifically, d_(w,k) was set equal to:

$$d_{w,k} = d_k \cdot (1 + \delta) \tag{4}$$

where δ~U(0;1). From Eq. (4) it is clear that, due to above-mentioned uncertainty related to the specific hydraulic directions in a flat flood plain (like in Ostia), in each simulation d_(w,k) could be at most two times its Euclidean value d_k;

- in each simulation, flood water velocity v_w in the flood plain is assumed as spatially constant and generated from a statistical uniform distribution, according to ranges from literature (Li et al. 2025b and references herein), i.e. v_w~U(0.5 m/s;v_(w,max)), in which v_(w,max)~U(1.5 m/s;3 m/s)

Thus, in each simulation the flood arrival time for any k-th node with FlagINSIDE = 1 is evaluated as:

$$T_{w,k} = \frac{d_{w,k}}{v_w} \tag{5}$$

With this simplified approach we cannot furtherly assess potential flood effect on pedestrian (sliding, toppling) but only evaluate potential interaction with floodwater.

21.8. Probability of pedestrian-floodwater interaction

Starting from the procedures described, for each k-th node with Flag = 0 and considered as starting point for a pedestrian, the Probability of pedestrian-floodwater interaction P_(w,k) is evaluated as:

$$P_{w,k} = \frac{N_{T_{k,j} > T_{w,j}}}{N} \tag{6}$$

where N is the total number of simulations, and N_(T_(k,j)>T_(w,j)) is the number of simulations for which the evacuation time T_(k,j), from the k-th node to any j-th node along the path, is greater than flood arrival time T_(w,j) related to the same j-th node.

If a warning time T_warning (which allows population to anticipate the evacuation) is considered, Eq. (6) is modified as:

$$P_{w,k} = \frac{N_{T_{k,j} > (T_{w,j} + T_{warning})}}{N} \tag{7}$$

21.9. Results

As expected, the random-choice scenario yields systematically higher mean evacuation times, particularly in the north-western sector, which is characterised by greater distance from the designated shelter areas. Results indicate an average increase, with respect to the deterministic routing assumption, of approximately 25 min in evacuation time and 700 m in travelled distance.

The same comparison is also analysed from a probabilistic perspective. Distances travelled in all simulations from each node to any shelter area are reported along the horizontal axes, while the vertical axes represent the probability that evacuation times exceed selected thresholds (15, 30, 45, 60, 90 and 120 min). Under random routing, a pronounced variance in the distance–probability relationship emerges, reflecting the cumulative effects of branching decisions along the network. Conversely, the deterministic routing scenario exhibits a null variance, as expected from its fixed-path assumption.

It is worth noting that a warning time of one hour is sufficient to reduce interaction probabilities below 25%, even for the most critical nodes in the north-western sector. Longer warning times of 2–3 hours further reduce interaction probabilities below 10% across the entire study area, Figure 2.

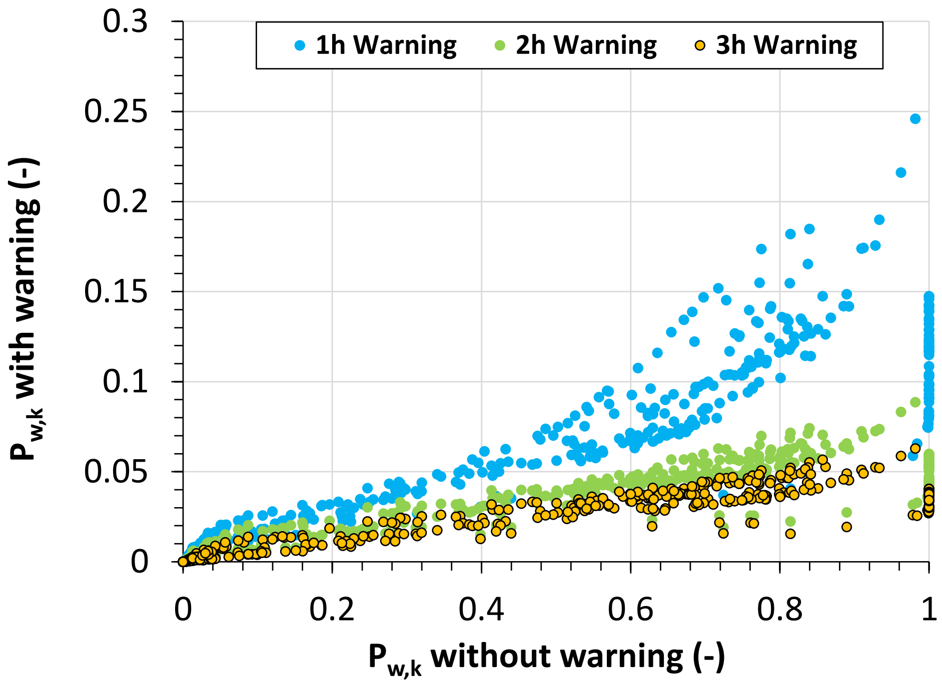

Figure 2. Floodwater–pedestrian interaction probability, comparison among without and with warnings.

The simplified framework developed in this study, despite requiring minimal input data, successfully reproduces patterns typically captured by more complex evacuation models while offering additional insight through its probabilistic structure.

The results indicate that evacuation feasibility is driven primarily by urban network topology and branching uncertainty rather than by Euclidean distance to safety. This aligns with agent-based modelling (ABM) literature, which emphasises the importance of decision points. Whereas ABMs attribute route divergence to perception, cognition, or panic dynamics, the present model embeds behavioural variability implicitly through stochastic node selection. This suggests that simplified probabilistic models can be adequate for preliminary identification of structural weaknesses, reserving behaviourally detailed models for refined analyses.

Path inefficiency emerges as a structural property of complex networks rather than an anomaly. In highly branched areas with geometrically similar alternatives, small directional deviations accumulate across intersections, generating substantial detours and large variance in evacuation times. Uncertainty is therefore central. Traditional evacuation models often rely on deterministic assumptions—single travel times, hazard scenarios, and network representations—thereby narrowing outcome ranges and underrepresenting worst-case conditions. In contrast, this framework incorporates stochastic path generation, speed variability, and simplified flood-arrival perturbations (extendable via hydrodynamic outputs). The ensemble-based approach is consistent with probabilistic risk assessment and reveals vulnerabilities masked by deterministic methods. Heavy-tailed evacuation-time distributions demonstrate how low-probability, high-impact outcomes—extended detours, slow movement, delayed departure—can materially affect risk even when mean outcomes appear acceptable.

Overall, the findings reinforce that evacuation planning cannot rely solely on static routing or prescriptive maps; it must account for variability arising from both network structure and human behaviour. Where inefficiencies persist, planners should prioritise interventions such as enhanced signage, improved wayfinding, real-time routing support, and strengthened communication—particularly in highly branched sectors. In cases where evacuation times remain incompatible with flood propagation, alternative measures, including vertical evacuation, should be evaluated.

The framework nonetheless has limitations inherent to its simplified structure. First, in the absence of hydrodynamic simulations, flood propagation is represented only approximately through arrival times, without capturing water depth variability, topographic effects, surface roughness, hydraulic connectivity, or fluvial–pluvial interactions. While sufficient for feasibility screening, this approximation cannot replace detailed hydrodynamic modelling when precision is required; when available, such simulations enable assessment of pedestrian and vehicle instability (e.g., sliding, toppling, flotation).

Second, the routing scheme assumes uniform random choice among outgoing links and does not explicitly model behavioural tendencies such as following signage, choosing familiar shortest paths, imitating others, or avoiding perceived hazards. This may overestimate detours where guidance exists, though the framework allows straightforward modification of transition probabilities.

Third, congestion and heterogeneous population groups (children, elderly individuals, tourists, persons with disabilities) are not explicitly represented. In reality, crowd density and vulnerability significantly influence effective speeds and route accessibility. These effects are only indirectly captured through stochastic variability in pedestrian velocity.

Finally, vehicle dynamics are excluded, despite their potential to both facilitate and obstruct evacuation. Mixed pedestrian–vehicle interactions can substantially alter timing; consequently, traffic-restricted scenarios prioritising emergency access should be explicitly considered in planning practice.

21.10. Conclusive remarks

In conclusion, the proposed framework is not intended solely as a technical support tool for evacuation assessment, but as a decision-enabling instrument to strengthen risk awareness and coordination capacity. By identifying structural vulnerabilities, uncertainty-driven criticalities, and sectors exposed to disproportionate evacuation delays, the model provides an evidence base for developing tailored communication strategies targeted to specific categories of exposed populations.

Effective risk communication must extend beyond generic public warnings. It should differentiate messages according to spatial exposure, network complexity, and expected evacuation performance, thereby increasing individual and collective awareness of actual risk conditions. At the same time, communication efforts must be structured across all coordination levels, ensuring that stakeholders—including maintenance personnel, firefighters, civil protection authorities, infrastructure operators, and other emergency managers—share a consistent operational picture.

Within this perspective, the analysis of standard procedures and IT services for information and knowledge exchange becomes central. Interoperable platforms, real-time data sharing, and structured information flows are essential when events involve critical infrastructures (CIs), where cascading effects and interdependencies can amplify consequences. A probabilistic, scenario-based modelling approach supports this process by clarifying uncertainty ranges and potential worst-case evolutions, thereby enabling informed decision-making under stress conditions.

Ultimately, integrating simplified but robust modelling tools with coordinated communication protocols enhances preparedness, supports adaptive response, and contributes to a more resilient emergency management system.

This work has been submitted to International Journal of Disaster Risk Reduction.

22. Conclusions and recommendations

The project achieved significant results, successfully meeting its objectives of developing a comprehensive emergency management platform capable of integrating heterogeneous data, providing advanced analytical tools, and ensuring an effective and transparent communication channel among all stakeholders involved. The added value lies in the platform's ability to combine technological innovation with operational impact, offering authorities and citizens a tool designed to enhance territorial resilience and improve both the speed and quality of decision-making processes.

The main scientific and technological contributions include the integration of artificial intelligence modules for the automatic analysis of texts and reports, the adoption of participatory approaches based on crowdsourcing to enhance the role of citizens, and the development of advanced interfaces for the dynamic representation of data through multi-actor dashboards. These elements demonstrate how the platform is not just a technological prototype, but a flexible and evolving ecosystem, capable of adapting to different emergency contexts and scenarios.

The journey was not without challenges. The complexity of integrating pre-existing systems, often characterized by legacy technologies and heterogeneous standards, represented a significant test. Likewise, continuous alignment between stakeholders with different interests and priorities required a methodological approach based on mediation and co-design. The platform's performance under high load conditions also raised critical issues, which led to the identification of room for improvement in scalability and process optimization.

The technical limitations encountered specifically concern the management of scenarios with extremely high data volumes and the reliance on external artificial intelligence services, aspects that can impact the system's autonomy and overall robustness. These elements were analyzed in depth and form the basis for defining future development priorities.

The evolutionary prospects are clear:

- On the one hand, the focus is on enhancing mobile functionality and user interfaces, with the goal of making the platform even more accessible and intuitive;
- On the other, the aim is to strengthen analytical capabilities, particularly through predictive techniques that enable the anticipation of critical scenarios and the development of proactive intervention plans. Increasing attention will also be paid to integrating with new data sources, including IoT sensors and social media feeds, to further expand information coverage.

A key aspect of the project's long-term sustainability is the platform's replicability in different contexts. To make this possible, it is necessary to plan activities to adapt the system's configuration to local regulatory and operational frameworks, targeted training programs for various stakeholders, and integration procedures with existing technological infrastructures. Only in this way will it be possible to ensure the transferability of the results, consolidate the project's European impact, and strengthen the platform's role as a reference tool for integrated emergency management.

In conclusion, the project has demonstrated the feasibility and relevance of the proposed solution, paving the way for a path of technological and organizational maturation that could lead, in its future evolutions, to a substantial change in the response capacity of institutions and in the resilience of communities.

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