

MULTI-TWIN: AI-based Digital Twins for Multi-Risk Analysis of Historic Centers

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Abstract

Historic urban centers and critical facilities increasingly face cascading, interdependent hazards—seismic ground motion, fault displacement, rainfall-triggered slope instability and river flooding—that challenge traditional single-risk workflows. This paper introduces MULTI-TWIN, an ongoing research project funded under the Italian National Recovery and Resilience Plan (PNRR), which aims to develop an integrated, web-based platform coupling advanced sensing, visual and geospatial data acquisition, AI-driven pattern extraction, and physics-based digital twins to support multi-risk assessment and planning at both territorial and building scales. This work outlines the project’s objectives, methodological framework, and expected outcomes, using the pilot implementation in Popoli Terme (Abruzzo, Italy) as an illustrative case study. Popoli Terme is a medieval town located within the 2009 L’Aquila seismic crater and subject to multiple hazards, specifically seismic, hydraulic, and hydro-geological risks. The contribution is twofold: (i) a replicable architecture integrating AI pattern recognition with structural/hydro-geological simulation under one operational workflow; (ii) a cultural-heritage-aware design that supports conservation-grade documentation, monitoring and planning strategies.

Keywords

Multi-risk, Digital Twin, Artificial Intelligence, Monitoring, Interdependent Natural Hazards, Built Heritage, Critical Facilities, Urban Environments 1

1. Introduction

Recent catastrophic earthquakes worldwide—such as the 2004 Sumatra event, the 2009 L’Aquila earthquake, the 2016 Central Italy sequence, and the 2018 Sulawesi earthquake—have demonstrated how natural hazards tend to occur in cascading chains. Earthquakes frequently generate secondary effects such as tsunamis, landslides, and soil liquefaction, which may cause greater losses than the seismic shock itself. In Italy, the 2023 floods in Romagna affected 44 municipalities, mostly in the province of Ravenna, where intense rainfall caused the overflow of 23 rivers, more than 250 landslides, and weeks-long disruption of rail transport. This example highlights the growing fragility of inhabited territories and the inadequacy of single-risk approaches. A transition toward integrated multi-risk assessment frameworks is required to equip local administrations with prevention policies, civil protection planning, and resilience strategies.

Since the early 2000s, Italy has introduced territorial planning instruments to mitigate natural risks such as landslides, floods, and earthquakes, mostly at the municipal scale. However, these frameworks tend to address hazards independently, often overlooking cascading or interacting events. Internationally, early-warning systems still focus on real-time monitoring and forecasting of

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specific hazards (e.g., rainfall-induced landslides, earthquake-triggered landslides, floods, active fault rupture) [1].

Risk evaluation approaches span from qualitative–quantitative methods, such as expert brainstorming and SWOT matrices [2], to fully quantitative frameworks, which become significantly more complex when multiple hazards are considered simultaneously. Typically, individual hazards are modelled independently, and their outputs are later overlaid, as exemplified by the U.S. Hazus MH software [3]. Hazus relies on the General Building Stock database, which aggregates building attributes for American territories to estimate the impact of natural events (earthquakes, floods, tsunamis, hurricanes). Notably, the database can be updated by citizens, though hazard interactions remain outside its scope.

The scientific literature not only lacks a systematic multi-risk approach, but also an integrated digital-twin framework supported by artificial intelligence aimed at enhancing disaster risk management. Projects such as DTCC (Digital Twin Cities Centre, <https://dtcc.chalmers.se/>), HARMONIA (Development of a Support System for Improved Resilience and Sustainable Urban areas to cope with Climate Change and Extreme Events, <https://harmonia-project.eu/>) and DESTINE (Destination Earth, a digital model of the Earth <https://destination-earth.eu/>) have demonstrated the potential of virtual replicas of the built environment to support real-time monitoring, predictive modelling, and emergency response. Despite their relevance, most of these platforms focus on single-hazard scenarios or on modern urban infrastructures, whereas the integration of multi-hazard analyses in historic urban fabrics – characterized by heterogeneous construction techniques, limited data availability, and strong conservation constraints – remains largely underexplored.

This state of the art highlights the need for a **comprehensive multi-risk approach** capable of jointly assessing the different natural hazards that interact within the same territory. Such an approach must overcome the current fragmentation of methods and scales, integrating seismic, hydrogeological, and environmental analyses within a unified and continuously updated framework.

The **MULTI-TWIN project** addresses this methodological gap by developing a replicable system that links territorial-scale hazard assessment with building-scale vulnerability evaluation. Through the combination of real-time monitoring, structural and territorial modelling, and data-driven analysis, MULTI-TWIN enables a coherent interpretation of cascading effects and supports informed decision-making for the protection and resilience of historic towns.

The medieval town of Popoli Terme (PE, Abruzzo) represents a paradigmatic testbed for developing these challenges [4-6]. Its historic center is within the seismic crater of the 2009 L'Aquila earthquake and directly above a segment of the active and capable Sulmona normal fault. The town rests on Quaternary continental deposits exceeding 400 m in thickness, carried by the Pescara and Sagittario rivers, and is overlooked to the west by Mount Morrone. This geo-morphological setting exposes Popoli Terme to multiple hazards, including seismic shaking, fault rupture, floods, and slope instability. Despite its rich architectural and cultural heritage, no comprehensive multi-risk study has yet been conducted for this historic and strategic built environment.

This paper presents the framework of the ongoing MULTI-TWIN project: *“Artificial intelligence supporting MULTI-risk analysis through digital TWINS”*, funded under the Italian National Recovery and Resilience Plan (PNRR), Spoke 5 *“Environment & Natural Disasters”*. The paper is organized into six sections: Section 1 introduces the problem and related needs; Section 2 illustrates the structure of the project; Section 3 describes the case study; Section 4 presents the scientific methods employed and the IT platform; Section 5 discusses the preliminary results; and Section 6 provides the conclusions and outlines future developments.

2. Project structure

The project, with a duration of 12 months, is structured into eight Work Packages (WP), each addressing a specific set of objectives and tasks. Their main contents, which define the overall project structure, are summarized below and illustrated in Figure 1.

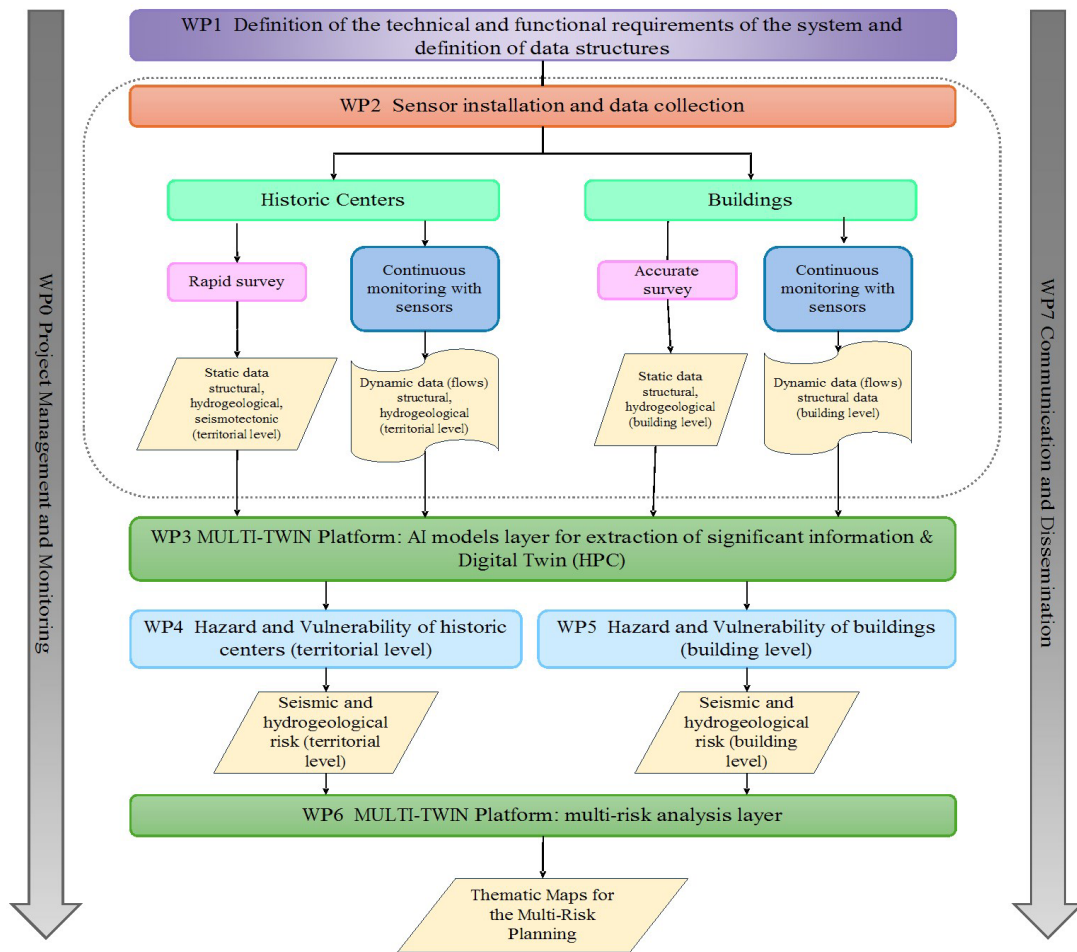


Figure 1: Work breakdown Structure of the MULTI-TWIN project.

WP1 – Definition of Technical and Functional Requirements. This WP establishes the system architecture, which is structured across five layers: (i) sensors, (ii) backend, (iii) AI models and digital twins, (iv) multi-risk analysis algorithms, and (v) the frontend interface. Functional specifications are defined in collaboration with end-users and domain experts, while particular attention is given to data modelling and formats, in order to ensure consistency with subsequent acquisition activities.

WP2 – Sensor Deployment and Data Collection. Advanced sensor networks are installed for telemetry purposes to capture vibrations, structural displacements, and geo-environmental parameters. In parallel, rapid surveys of historic centers and detailed surveys of critical facilities are conducted, combining traditional and advanced vision-based techniques. The resulting static and dynamic datasets provide the input for the AI models developed in WP3.

WP3 – AI Models and Digital Twin Platform (HPC). This WP delivers the first layer of the MULTI-TWIN platform, integrating AI models with finite element (FEM) digital twins. Sensor data are processed through deep and machine learning algorithms, while FEM models simulate the structural behaviour of monitored assets. The combined approach enables anomaly detection, interpretation of discrepancies between observed and simulated responses, and quantification of structural damage. The backend infrastructure and HPC resources ensure the scalability of the platform.

WP4 – Hazard and Vulnerability Assessment of Historic Centers. At the territorial scale, vulnerability assessments of historic centers are performed using proxies and approximate methodologies, enabling rapid yet informative screening of large urban areas.

WP5 – Hazard and Vulnerability Assessment of Buildings. At the building scale, detailed analyses are carried out, with the aim of deriving seismic fragility and vulnerability curves. This allows the identification of weaknesses and the prioritisation of strengthening strategies.

WP6 – MULTI-TWIN Platform: Multi-Risk Analysis Layer. This WP integrates the outputs of previous activities into a comprehensive multi-risk analysis environment, applicable at both territorial and building scales. Algorithms for automated risk determination are implemented, and results are displayed through thematic maps, dashboards, and interactive reports.

As shown in Figure 1, the project adopts two different levels of analysis: the **territorial scale** and the **single-building scale**. At the territorial level, risk assessments are carried out for the entire city or for homogeneous areas (e.g., the historic center). At the single-building level, on the other hand, specific analyses are performed on selected structures. The information needed to carry out these analyses is provided by rapid and accurate surveys conducted through a combination of traditional techniques and innovative tools, such as drones and vision-based systems, which are particularly valuable for mapping historic centers and sensitive structures.

Central to the project is the deployment of advanced sensor networks, designed to provide continuous information on vibrations, displacements, and environmental conditions, thus creating a constant flow of data both at the scale of individual assets and across the urban fabric. The collected data feeds the development of artificial intelligence models, where new Deep Learning solutions are trained, or existing ones refined, to process large and heterogeneous data streams. These models are able to generate significant indicators for multi-risk assessment, supporting the detection of hazardous situations and supplying the input needed to construct detailed digital twins. These digital twins, conceived as dynamic virtual counterparts of buildings, enable real-time simulation and prediction of structural vulnerability, offering a powerful tool for anticipating potential risks. All the collected data and resulting outputs converge within the MULTI-TWIN web platform, which serves as the project's central tool.

The platform enables operators to upload, visualize, and modify alphanumeric and cartographic datasets, integrating them with AI-derived information and digital twin simulations. In this way, it supports hazard and vulnerability assessments across different scales and offers the possibility to run algorithms for multi-risk analysis (focusing particularly on seismic and hydrogeological hazards), with results made available through thematic maps and reports. Individual knowledge of potential risks is combined to develop a dedicated multi-risk planning activity. A multi-risk analysis is an integrated assessment that simultaneously considers different types of hazards and their potential interactions. In this project, the planned integration is between seismic, hydraulic and hydrogeological risks. These strategies will provide valuable support for urban and territorial planning, improving the effectiveness of civil protection measures and strengthening resilience against multiple risks.

The MULTI-TWIN project is currently under implementation, and the results presented here are to be understood as expected outcomes rather than finalized achievements. The project aims to deliver a set of web-services that will be directly accessible to local administrations, supporting multi-risk urban planning at both territorial and building scales. These services will provide thematic maps and vulnerability estimates, enabling informed decision-making for civil protection and resource allocation.

To reach these objectives, the project distinguishes between intermediate results, which serve as essential building blocks, and final results, which represent the fully operational deliverables of the MULTI-TWIN platform. Intermediate products include datasets from sensor installations, rapid and detailed surveys, archetype-based fragility curves, and prototype modules of the platform. While valuable in themselves, these outputs primarily function as inputs for the final integrated system. The defined duration, measurable outputs, and intermediate deliverables for each WP ensure continuous progress tracking and provide a quantitative basis for project feasibility assessment.

The following table shows the intermediate and final objectives stated in the project:

Table 1. Output to be achieved for each WP.

WP	Description	Intermediate Outputs	Final Outputs
WP1	Definition of the technical and functional requirements and data structures	– Report on the technical and functional requirements – Report on data structures	(same as intermediate outputs)
WP2	Sensor installation and data collection	– Static dataset from rapid surveys on buildings and the territory – Data streams from sensors. – BIM models (vision-based) of buildings	Final report on the operation of the continuous monitoring system for long-term operation and maintenance
WP3	MULTI-TWIN platform: AI model layer for extraction of meaningful information & Digital Twin (HPC)	– Prototype of the first system layer, including backend, DBMS, AI models, and Digital Twin	(same as intermediate outputs)
WP4	Hazard and vulnerability assessment of historic centres (territorial scale)	– Seismic and hydro-geological hazard map at territorial scale – Vulnerability map at municipal/sub-municipal scale	(same as intermediate outputs)
WP5	Hazard and vulnerability assessment of critical structures (building scale)	– Seismic and hydro-geological hazard assessment for selected buildings – Vulnerability assessment of individual buildings	(same as intermediate outputs)
WP6	MULTI-TWIN platform: multi-risk analysis layer	– Prototype of the second system layer, including algorithms for multi-risk calculation and frontend	– Multi-risk maps based on site-specific natural hazards in Popoli Terme – Digital Twin of buildings using HPC systems – MULTI-TWIN platform
WP7	Communication and dissemination	– Workshop – Project events	(same as intermediate outputs)

The final results of MULTI-TWIN are fourfold. First, the project seeks to develop a replicable methodological and technological model that can be extended to other urban and suburban contexts facing similar multi-risk conditions. Second, it will generate thematic multi-risk maps at the territorial scale, aligned with instruments such as municipal civil protection plans, emergency limit conditions, and evacuation strategies. Third, it will implement digital twins of selected historic and critical buildings, which will support local administrations in extraordinary maintenance and structural improvement. Finally, the project will deliver the MULTI-TWIN platform itself, conceived as a dynamic and flexible tool for monitoring, simulating, and planning multi-risk scenarios, with potential applications beyond seismic and hydro-geological hazards.

The principal outcome of the project is thus represented by the MULTI-TWIN platform, an AI-enhanced digital environment capable of collecting, integrating, and analyzing data from historic centers and critical facilities. The platform enables seismic, hydro-geological, and multi-risk analyses in support of civil protection strategies, risk mitigation policies, and the preservation of cultural heritage. Its flexible architecture is designed to be easily extendable to additional risk domains, such as industrial or fire hazards, and applicable to both Italian and international contexts.

In the pilot case of Popoli Terme (PE, Abruzzo), the platform demonstrates its effectiveness in a territory characterized by complex geo-morphological conditions and exposed to multiple interacting hazards. Here, intermediate and final outputs are validated in collaboration with local authorities, ensuring the direct usability of the system for urban resilience planning. Beyond the local case study, the project aspires to establish a replicable reference model that combines technological innovation, scientific rigor, and cultural heritage awareness in the management of natural risks.

3. Case study

The choice of the case study of **Popoli Terme** (PE, Italy) was carefully considered during the drafting of the project, as it exemplifies a territory where multiple natural hazards converge. The town is directly exposed to the very risks that the project seeks to address seismic hazard, faulting, flooding, and slope instability. Its setting, both geomorphological and tectonic, makes it a particularly meaningful location for the analysis.

As illustrated in Figure 2, the municipality of Popoli Terme is situated in a uniquely complex position:

- It lies within the **seismic crater** (Figure 2a), as evidenced by the widespread damage sustained in the historic center (Figure 3), where poor-quality masonry buildings triggered collapse mechanisms.
- The municipality is directly overlain by the **Sulmona Fault** [7][8], a major NW–SE trending tectonic structure that stretches for approximately 23 km along the western slope of Mount Morrone (Figure 2b).
- It occupies the central part of the **Aterno–Pescara basin**. Within the framework of the Flood Risk Management Plan (PSDA) (<https://www2.regione.abruzzo.it/content/psda>), the study area—and particularly the built-up core of Popoli—is identified as containing a high-hazard flood zone, which develops along the western sector of the settlement (Figure 2a).
- Finally, the **geomorphological configuration** of the municipal territory highlights the controlling influence of steep slopes and marked elevation differences. These morphological characteristics strongly affect the landscape and play a critical role in shaping natural processes such as erosion, landslides, and slope stability (Figure 2b).

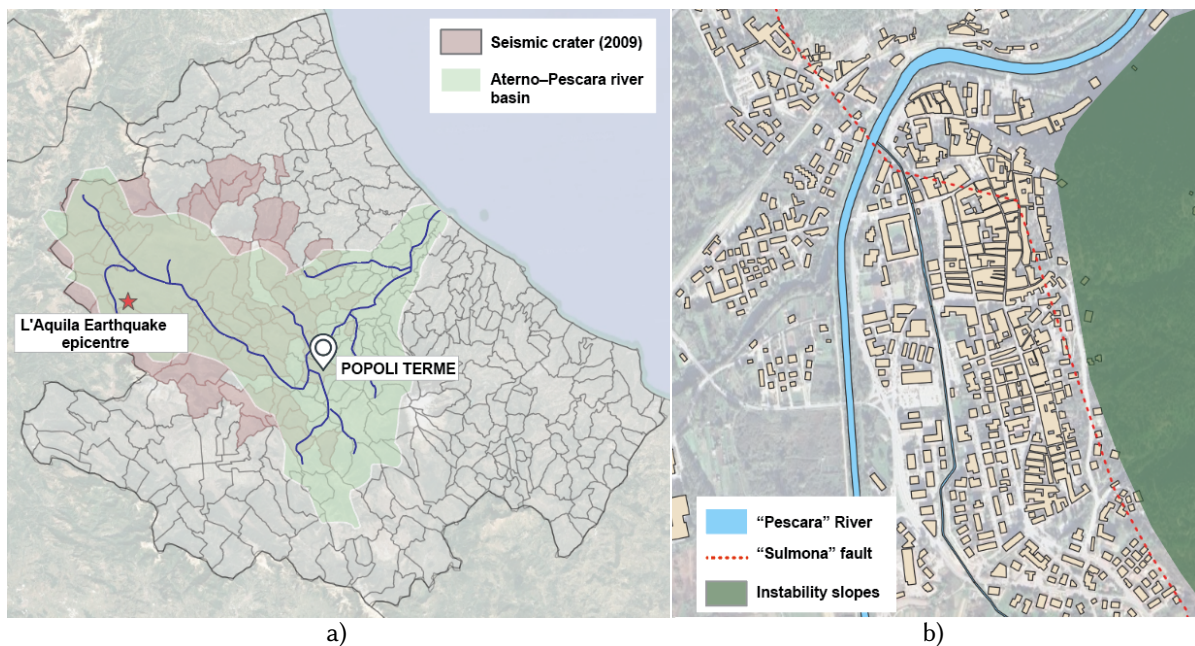


Figure 2: Risks identified in the municipality of Popoli Terme

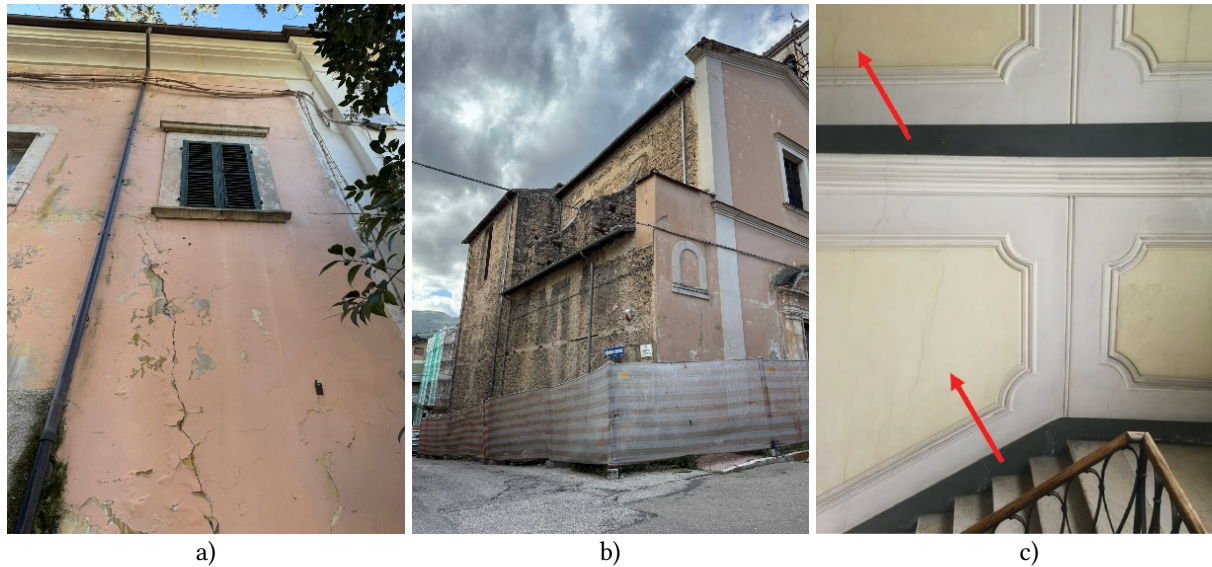


Figure 3. Damage following the 2009 earthquake: a) municipal building; b) Church of St. Dominic; c) private building known as ‘Palazzo Ducale’. All buildings are currently still unusable.

4. Multi-Twin platform

The challenges of the MULTI-TWIN project are conceived to address the intrinsic complexity of multi-risk scenarios affecting historic towns and buildings. Natural hazards rarely act in isolation: seismic shaking may be coupled with fault rupture or trigger slope instability, while intense rainfall may simultaneously induce floods and landslides. For this reason, the project adopts a holistic and multi-scale approach that integrates hydraulic, hydro-geological, and seismic analyses with advanced data acquisition and artificial intelligence techniques. Figure 4 shows the proposed interface for the platform, highlighting the main sections covered by the project.

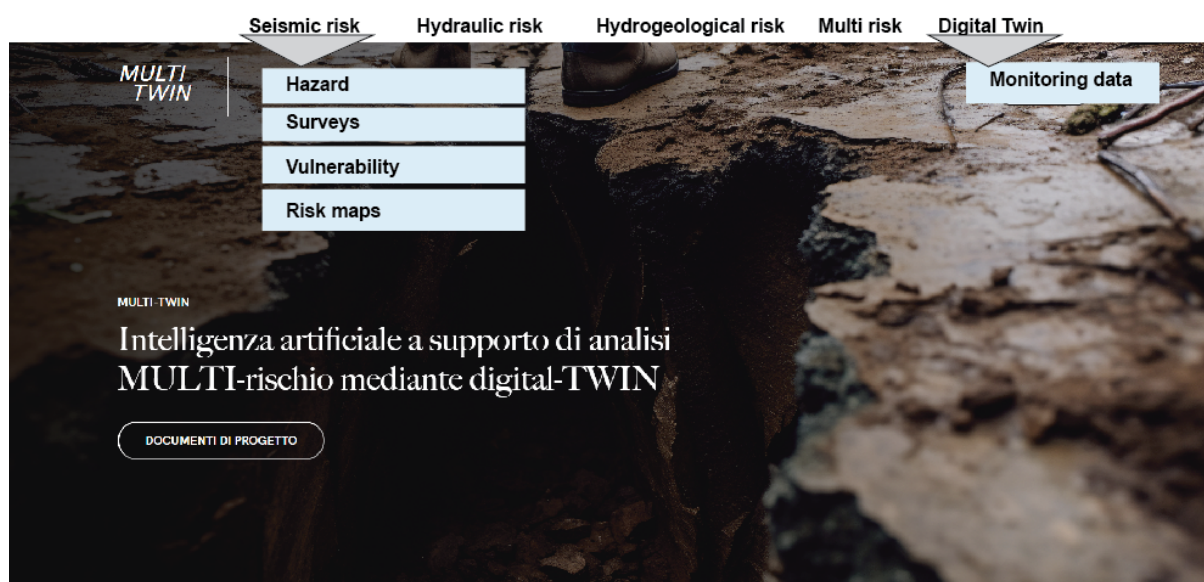


Figure 4. Proposed interface for the MULTI-TWIN platform.

The first component concerns the quantification of the **seismic hazard**, based on national [7] and regional seismic catalogues [8], complemented by direct and indirect investigations of the subsoil (geognostic, geotechnical, and geophysical tests). These data enable the execution of **local seismic**

response analyses, which are crucial to determine site-specific ground-motion amplification. In parallel, the project addresses **hydrogeological hazards**, with particular attention to slope stability and flood risk [9]. Moreover, the proximity of Popoli Terme to the Pescara and Sagittario rivers requires explicit consideration of **hydraulic hazards and flood scenarios**, in which rainfall intensity and groundwater level fluctuations must be regarded as potential triggering factors.

The survey section contains all the data collected on the case study. In fact, MULTI-TWIN platform is based on a **metadata catalogue** that allows for the standardization of information. The adoption of a dataset-based model makes the system highly scalable: new metadata can be added, existing classifications can be updated, or information sections can be expanded without altering the core structure. Moreover, this approach enables efficient integration with other **territorial information systems** (GIS, municipal databases, monitoring systems), thereby ensuring both interoperability and data reusability.

The metadata catalogue supports vulnerability analyses, which in turn inform the resulting risk assessments. Within the multi-risk framework, **vulnerability assessment relies on the implementation of fragility curves**, which allow the expected damage percentage to be calculated as a function of hazard intensity. Specifically, for **seismic vulnerability**, a parametric method is applied to estimate the expected damage, where the parameters considered (e.g., number of storeys, position within the cluster, presence of arches and vaults, geometric irregularities, etc.) are derived from a literature-based methodology validated on Italian towns similar to Popoli Terme [10]. For **hydraulic vulnerability**, the most representative parameter is the expected water depth in flooded areas, $h(\text{Tr})$, obtained through hydraulic simulations and varying according to the return period. Finally, for **hydrogeological vulnerability**, the key indicator is the average translational and rotational kinetic energy of the blocks involved in collapse events. Together, these models provide a harmonized and transferable framework for quantifying damage across different hazard types, supporting **multi-risk assessments**.

For **risk assessment**, the key parameter adopted is the **Expected Annual Loss (EAL)** [11], which represents the average annual economic losses and is calculated as the area under the site-specific loss curve. The procedure adopted to determine the loss curves for a site in order to derive the EAL is as follows. First, **damage probability curves (DPCs)** are defined [12]. Then, the **economic loss (L)** is estimated through specific correlations: (i) for seismic risk, it is expressed as a percentage of the reconstruction cost (%RC) for each damage level, following the values provided by [13]; (ii) for other hazards, it is estimated from the building area (m^2) and its use category. These **typological loss curves** are then converted into **site-specific loss curves** by linking the intensity measure—**Peak Ground Acceleration (PGA)**—with its occurrence frequency, $\lambda(\text{IM})$, derived from the site's hazard curves. The resulting risk metrics are visualized as **thematic maps** within the MULTI-TWIN platform, allowing for the spatial interpretation of expected economic losses.

Among the various components contributing to multi-risk, **surface faulting hazard** has been included. This phenomenon, characterized by ground surface displacement during a strong earthquake due to fault slip, can directly damage structures and generate seismic risk. At the same time, it may alter topography and disrupt river networks, thereby increasing hydrogeological risk.

Finally, the structural integrity of a critical infrastructure in the municipality of Popoli Terme is being monitored. Specifically, a steel footbridge connecting two wings of the local hospital has been equipped with sensors to continuously record its dynamic response. Structural and environmental monitoring data are continuously assimilated into seismic and hydrogeological hazard models. This dynamic updating process enables the generation of scenarios that explicitly account for exposure and vulnerability within the **digital twin environment**, thereby yielding more reliable predictions of cascading effects. The data streams recorded by the sensors are used to train an artificial intelligence (AI) model that learns the normal operational conditions of the structure, corresponding to its undamaged or 'healthy' state. Once the training phase is complete, the model is employed in inference mode, analyzing new incoming signals. If the model receives signals that deviate from those observed during training, they are classified as anomalous. The occurrence of such anomalies may potentially indicate damage to the structure. The adopted model is an **autoencoder**, an

unsupervised neural architecture designed to reduce the dimensionality of the input signal through an encoder and reconstruct it via a decoder. As it is exposed only to standard signals during training, it learns to accurately reconstruct normal conditions alone. When analyzing anomalous signals, the model fails to reconstruct them accurately, resulting in a high reconstruction error that serves as an indicator of anomaly. The model chosen for the analysis is a simple autoencoder consisting of two hidden layers. The layers are connected using ReLU (first layer) and linear (second layer) activation functions, while the chosen loss function is the Euclidean norm.

The MULTI-TWIN platform implements **automated algorithms** for vulnerability, and multi-risk assessment, which are executed directly on continuously updated datasets. These procedures generate **quantitative indicators and thematic maps** without requiring manual post-processing, ensuring that the evaluation of cascading hazards remains consistent and up-to-date. Within the same environment, **real-time data acquired from the sensors** are automatically stored in a shared geospatial database and exchanged with analytical and numerical models. This organization allows the **digital twin** to dynamically update structural and environmental parameters, reflecting the current condition of the monitored assets and enabling proactive management of interdependent risks.

In summary, the MULTI-TWIN scientific methodology couples traditional engineering approaches—such as seismic response analyses and slope stability modelling—with innovative AI-driven pattern recognition and digital twin technologies, thereby creating a replicable framework for understanding and managing multi-risk conditions in heritage centers.

5. Preliminary results

This section presents the preliminary outcomes achieved. Several surveys and studies were carried out to collect information across the entire municipal area. These activities allowed for the definition of the urban and territorial context, highlighting the morphological and geographical features of the study area. Three main types of activities were undertaken:

Cartographic surveys (Static data)

These surveys represent the first level of investigation and provide the foundation for subsequent analyses. In particular:

- i. **Digital Terrain Model (DTM)** was generated, describing the elevation distribution of the ground surface without anthropogenic or vegetational elements;
- ii. **Cartographic data** were collected for monitoring watercourses, based on the Fiducial Telemeasurement Network of the Abruzzo Region (GIS Map – Regione Abruzzo);
- iii. **Geological and land-use maps** were analyzed.

On-site surveys (Static data)

Buildings in the historic center were analyzed to identify their main structural characteristics. These data will be used to calculate the seismic vulnerability of both individual buildings and the historic center as a whole. Site inspections were also conducted to define and validate the hydraulic model and to analyze the slopes surrounding the built-up area of Popoli Terme, with the aim of identifying the main physiographic, geological, and geomorphological features of the area.

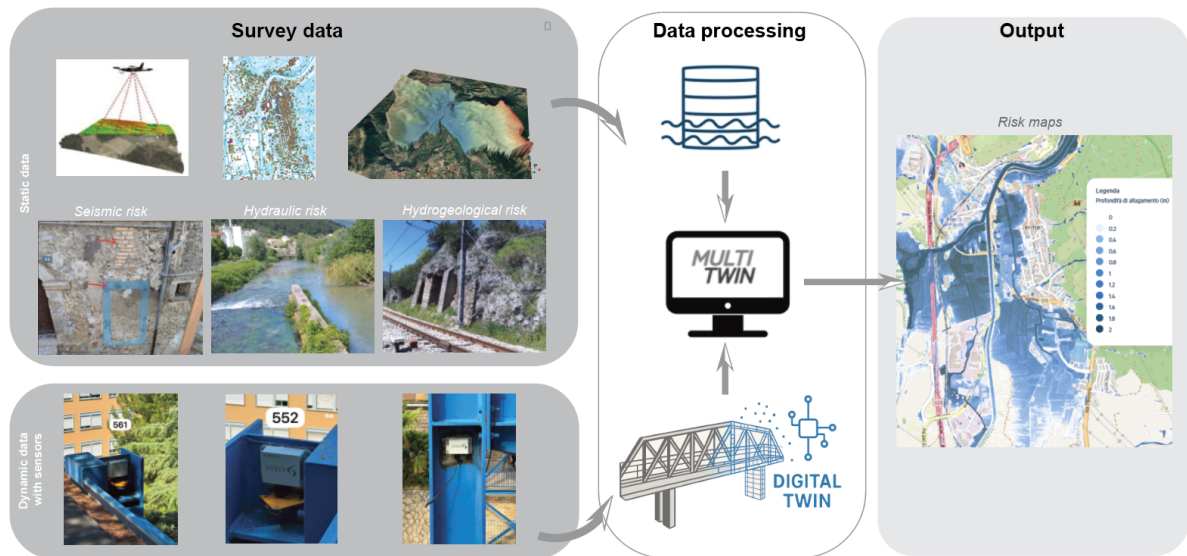


Figure 5. Studies carried out on the municipality of Popoli Terme.

Sensor installation (Dynamic data)

At the same time, a **sensor network** was installed to monitor the steel pedestrian bridge of the Popoli Terme Hospital. The bridge was equipped with eight high-sensitivity devices, each integrating a high-performance triaxial accelerometer. The installation followed an engineering-based criterion aimed at maximizing the dynamic information collected; the sensors were therefore positioned at structurally critical locations, including supports, mid-spans, discontinuity nodes, and areas prone to stress accumulation.

All the static data collected have already been uploaded to the platform, while the dynamic data are still being processed and integrated. The first risk models have already been developed based on the information acquired. Figure 5 illustrates the overall workflow of the activities carried out for the case study of Popoli Terme.

As the project is currently in progress, the results presented are intentionally limited to methodological and organizational aspects. Quantitative validation and comparative analyses with existing baselines will be performed in the next development phase, once the platform and monitoring system become fully operational.

6. Conclusions

This paper presents the framework, methodological approach, and expected results of the ongoing **MULTI-TWIN project**, an initiative funded under the Italian National Recovery and Resilience Plan (PNRR). The project addresses the increasing complexity of cascading and interdependent hazards affecting historic centers, with a specific focus on seismic and hydrogeological risks. Its methodological design integrates advanced sensing, rapid surveys, AI-driven pattern recognition, and digital twin technologies into a web-based platform that operates across both territorial and building scales. Through the pilot case of **Popoli Terme (Abruzzo, Italy)**, the project demonstrates how such an integrated approach connects territorial-scale vulnerability mapping with building-specific digital twins, thereby providing local administrations with actionable tools for risk-informed planning, conservation, and emergency management.

The outcomes of MULTI-TWIN go beyond technological innovation, with significant implications for both policy and practice. At the institutional level, the project contributes to improving municipal civil protection plans, offering more accurate forecasts and risk management strategies. At the community level, it enhances the resilience of historic centers, particularly through improved monitoring of slope stability and river flooding in valley environments. By integrating exposure and

vulnerability into dynamic multi-risk scenarios, the platform reduces the socio-economic impact of natural disasters, enabling faster recovery of urban functionality after disruptive events.

MULTI-TWIN also provides direct support to local authorities, enabling the prioritization of maintenance and strengthening interventions, the scheduling of public expenditures, and the management of emergency measures based on continuous monitoring. This capacity is complemented by the potential for cost reduction in structural consolidation and maintenance, thanks to refined calculation models that integrate real-time sensor data.

The project further generates positive territorial and economic impacts. By promoting demand for specialized interventions, it supports the development of local enterprises and professionals, while also stimulating wider economic circulation through the presence of new workforce activities. In the medium and long term, a safer and more sustainable built environment also enhances the touristic attractiveness of Popoli Terme and similar heritage towns.

Finally, the project's pilot implementation in Popoli Terme serves as a **living laboratory** to test and refine the methodology under complex geo-morphological and multi-hazard conditions. The results provide **transferable practices** that can be adapted to other Italian and international contexts, while combining scientific research, technological innovation, and heritage awareness in the management of natural risks.

As this represents a preliminary implementation, the current version of MULTI-TWIN still reflects the inherent limitations of early-stage data availability and model calibration. Moreover, the multi-risk approach itself faces methodological challenges in harmonizing heterogeneous datasets and uncertainty sources, which will be further explored and refined in future developments.

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Declaration on Generative AI

During the preparation of this work, the authors used ChatGPT5 in order to: grammar and spelling check. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

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