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# An Open-Source Framework for Geospatial Data Management in the Built and Natural Environment

Thesis of

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# Abstract


In the current era of digital transformation, the fields of Geomatics and Geospatial Information Science are facing a significant paradigm shift. While the increasing availability of high-resolution 3D data ranging from technologies like Terrestrial Laser Scanning to Unmanned Aerial Vehicle photogrammetry allows for documentation of the physical world with unprecedented accuracy, it has simultaneously created a "data silo" problem. The management, integration, and dissemination of this information remain largely fragmented, often trapped in proprietary software or accessible only to specialized technicians. This challenge is particularly acute in three critical domains: cultural heritage, where the focus is on public engagement and accessibility; the natural environment, where climate change necessitates long-term monitoring and multi-disciplinary data sharing; and civil infrastructure, where recent structural failures have highlighted the urgent need for optimised, interoperable asset management systems.

To address these challenges, this research proposes the development of a modular, web-based, open-source framework designed to act as a "common ground" for multidimensional geospatial data. The core of the project is the creation of a unified environment that integrates heterogeneous data sources, including massive point clouds, BIM/IFC models, GIS layers, and oriented drone imagery, into a single, accessible web interface. By leveraging standards and open-source engines such as CesiumJS and Potree, the framework enables users with varying levels of technical expertise to interact with, annotate, and analyse spatial data without the requirements of high-end hardware or expensive software licenses.

The framework design's efficacy was validated through multidisciplinary case studies across the three target domains. In the context of cultural heritage, it provided a platform for immersive storytelling and high-resolution documentation of the Farnese Castle in Piacenza, making it accessible to the larger public. In the natural environment, the framework supported the monitoring of dynamic alpine environments, such as glaciers and landslides, by facilitating the dissemination of 4D time-series data of the Belveder Glacier monitoring project. For civil infrastructure, it was applied to customisation of the P.O.N.T.I. platform for the management of 2D/3D inspection geodata in the context of the documentation of bridges in the Province of Piacenza in Italy. These applications demonstrate the framework's versatility in handling diverse scales, from specific structural elements to entire landscape-level datasets.

The primary potential of this work lies in its scalability and its role as a precursor to full-scale Digital Twins, with an architecture designed to eventually incorporate IoT sensor data and VR/AR interfaces. In addition, the research also acknowledges the technical trade-offs inherent in web-based streaming, specifically the balance between performance and centimetric precision for massive datasets. Furthermore, while the open-source nature of the framework promotes transparency and collaboration, its broader adoption requires a cultural shift within public administrations and private firms to move away from proprietary ecosystems. Ultimately, this thesis provides a roadmap for more democratic and integrated geospatial data management across the built and natural environment.



**Keywords:** 3D data management, WebGIS, free and open source, geospatial solutions

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# Acronyms

ADE – Application Domain Extension

AEC – Architecture Engineering and Construction

AI – Artificial Intelligence

API – Application Programming Interface

AR – Augmented Reality

BIM – Building Information Modelling

BMS – Bridge Management System

CAD – Computer Aided Design

CH – Cultural Heritage

CityGML – City Geography Markup Language

CP – Check Point

CRUD – Create, Read, Update and Delete

CSS – Cascading Style Sheets

CSV – Comma Separated Values

DSM – Digital Surface Model

DOI – Digital Object Identifier

DT – Digital Twin

ERD – Entity Relationship Diagram

FAIR – Findable, Accessible, Interoperable and Reusable

FOSS – Free and Open Source Software

GCP – Ground Control Point

GIS – Geographic Information System

glTF – graphic library Transmission Format

GNSS – Global Navigation Satellite System

GPL – General Public License

GUI – Graphic User Interface

HBIM – Historical BIM

HTML – HyperText Markup Language

HTTP – HyperText Transfer Protocol

ICP – Iterative Closest Point

ICT - Information and Communication Technology

IFC – Industry Foundation Classes

IOT – Internet of Things

JS – JavaScript

JSON – JavaScript Object Notation

LiDAR – Light Detection And Ranging

LoD – Level of Detail

ML – Machine Learning

MMS – Mobile Mapping System

OGC – Open Geospatial Consortium

OSM - OpenStreetMap

PHP – Hypertext Preprocessor

SQL – Structured Query Language

RDN2008 – Rete Dinamica Nazionale 2008

REST – Representational State Transfer

RTK – Real-Time Kinematic

SaaS – Software-as-a-Service

SDG – Sustainable Development Goal

SDK – Software Development Kit

SfM – Structure-from-Motion

SHM – Structural Health Monitoring

SLAM – Simultaneous Localisation And Mapping

SPARQL – Protocol And RDF Query Language

TIFF – Tagged Image File Format

TLS – Terrestrial Laser Scanning

UAV – Unmanned Aerial Vehicle

UTM – Universal Transverse Mercator

UX – User Experience

VR – Virtual Reality

W3C – World Wide Web Consortium

WebGL – Web Graphic Library

WGS84 – World Geodetic System 1984

WFS – Web Feature Service

WMS – Web Map Service

XR – Extended Reality

# 1

# Introduction

## 1.1 Motivation and relevance

The current era of digital transformation has equipped the fields of Geomatics and Geospatial Information Science with an unprecedented capacity for high-resolution reality capture. From Terrestrial Laser Scanning (TLS) to Unmanned Aerial Vehicle (UAV) photogrammetry, the ability to document the built and natural environment with sub-centimetric precision is now an industrial standard (Gorgoglione et al., 2023; Papadopoulos et al., 2025; Porcelli et al., 2020). However, this technical maturity in data acquisition has birthed a significant paradox: while the volume of 3D documentation is growing exponentially, its operational utility is still largely restricted to a small number of expert users, who are often the sole producers of the original data (Bill et al., 2022).

Traditional geospatial practices have historically focused on the production of static deliverables, such as 2D plans, 2.5D maps or isolated 3D models, often archived in disconnected information silos or fragmented memory systems (Lei et al., 2024). These memoryless datasets capture a real-world state at a specific point in time but lack the persistence and interactivity required for modern management workflows. In the context of the digital transition, this has resulted in the problem of data silos, where high-fidelity geomatic documentation is frequently trapped in proprietary software environments (Dihan et al., 2024). This documentation is accessible only to specialised technicians and is excluded from the broader decision-making process, hindering also the control over dataset produced in-house.

Managing massive 3D data poses a particular challenge across three interconnected yet heterogeneous domains: cultural heritage, the natural environment and civil infrastructure. Despite their different scientific objectives, these domains are united by a technological bottleneck: a lack of a unified architectural foundation capable of converting raw spatial data into actionable, enduring knowledge. While the widespread adoption of low-cost sensors and devices has democratised reality capture and digital modelling, ensuring flexible access, collaborative management and optimised rendering remains challenging (La Guardia and Koeva, 2023). This is often limited to unwieldy combinations of distinct software, whose usage is hindered by technological and economic barriers.

Current state-of-the-art solutions often force stakeholders to choose between two options: stateless specialised data viewers or proprietary ecosystems. Indeed, web-based tools offering excellent visualisation performances often lack a persistent database state, preventing the recording of users' interactions, temporal updates, or administrative metadata. At the same time, closed black-box Digital Twin solutions impose significant financial barriers and risk technical vendor lock-in, particularly for small and medium-sized public administrations and entities, often binding users to all-in-one over dimensioned solutions with no room of simplification or customisation. This fragmentation hinders digital sovereignty, intended as the full control over data and products of public institutions, communities and businesses, and limits the scientific reproducibility of geospatial research in academia. There is, therefore, a critical need for a modular, documented, and open-source framework that can bridge the gap between high-fidelity 3D rendering and state-aware data management.

Beyond its technical scope, the framework presented in this thesis acknowledges that broadening access to highly structured spatial data carries a non-trivial challenge: non-specialist users, encountering rich visualisations without sufficient understanding of the underlying data quality, acquisition limitations, and processing assumptions, may draw conclusions that exceed what the data can actually support. The research therefore treats user-facing documentation and training as integral components of each implementation rather than as accessories.

## 1.2 Research objectives and contributions

The primary objective of the research is to design, implement and validate a modular open-source framework for the integrated visualisation and management of direct-from-survey geospatial data in the built and natural environments. The framework aims to prototype a scalable common ground where visualisation, monitoring and management functions are unified within a single web-based user-friendly environment.

To achieve this goal, the research addresses the following key questions:

- How can a web-based architecture handle the streaming of massive multi-source 3D products while maintaining high quality performance and accessibility for non-expert users?
- To what extent can a single modular system support diverse operational goals, ranging from public dissemination to operational asset management, without domain-specific software fragmentation?
- How can the maturity of a geospatial platform be quantified to provide a readiness roadmap for institutions entering the digital transition?

The original contributions of this thesis are both architectural and methodological:

1. The modular framework: the development of a full-stack open-source engine designed for cross-domain scalability.
2. The multi-domain validation: the deployment and testing of the framework across three high-impact case studies: a restricted cultural heritage site (Farnese Castle), a dynamic natural environment (Belvedere Glacier), and a critical civil infrastructure (P.O.N.T.I. prototype for bridge inspection data management).

## 1.3 Structure of the thesis

The thesis is organised to reflect the progression from theoretical gaps to technical validations with three dedicated case studies:

- **Chapter 1** provides the motivation and relevance of the current research, outlining the problems in current geospatial data management approaches and defining the objectives for creating a modular, open-source framework for the built and natural environment, with special focus on applications in the cultural heritage, natural environment and civil infrastructure domains.

- **Chapter 2** frames the work within the activities of the Politecnico di Milano LabMGF and the industrial partnership with TECNE – Autostrade per l'Italia as part of the PNRR scholarship funding the author's research. It introduces the case study contexts in needs of cross-domain harmonisation.
- **Chapter 3** gives an overview of the state of the art in web-based management technologies and applications towards the adoption of digital twin infrastructures. It identifies the research niche by analysing current trends and commonalities in visualisation and management requirements across different domains, framing the research into a user engagement maturity model adapted from literature.
- **Chapter 4** describes the logical and physical architecture of the developed platform, explaining the selection of the Free and Open Source Software (FOSS) stack and modular logic.
- **Chapter 5** presents the practical realisation of the framework across the three case studies. It details the specific customizations for the Farnese Castle (Cultural Heritage), the Belvedere Glacier (Natural Environment), and the P.O.N.T.I. prototype (Civil Infrastructure), illustrating the adaptation of the database and interface to meet distinct stakeholder needs.
- **Chapter 6** elaborates a cross-domain comparative analysis using the user engagement maturity model, validating the framework's flexibility and identifying the path toward digital twin full adoption.
- **Chapter 7** outlines the longer-term research roadmap. It discusses the transition toward autonomous and predictive geospatial ecosystems, exploring the feasibility of the integration of Internet of Things (IoT), Artificial Intelligence (AI), and immersive Extended Reality (XR) interface in the developed framework.
- **Chapter 8** synthesises the research findings and reflects on the broader impact of the work. It concludes with a discussion on the importance of open dissemination and the role of transparent geospatial frameworks in supporting the digital governance of the built and natural environment.

# 2

# Research context and case studies

## 2.1 Research setting, laboratory context, and institutional collaborations

The author's research project is deeply embedded within the active collaborations of the Geodetic and Photogrammetric Laboratory (LabMGF) at the Politecnico di Milano, part of the Department of Civil and Environmental Engineering. The group's primary research focuses on cultural heritage documentation, environmental monitoring, and civil infrastructure inspection through applied geomatics approaches. This work is specifically situated at the intersection of academic research and public administration, as the laboratory develops applied geomatics solutions tailored for real-world applications.

In particular, this thesis was conceived and developed as part of a scholarship co-financed by Ministerial Decree no. 352 of 9 April 2022, based on the National Recovery and Resilience Plan (NRRP)—funded by the European Union–NextGenerationEU, and by the company TECNE, the engineering branch of Autostrade per l'Italia, an Italian company specialised in the management of highway and related maintenance activities. This partnership frames the study within industrial needs for optimised highway management and maintenance, moving towards more automated and interconnected geospatial ecosystems.

Beyond industrial funding, the project's development relied on close interaction with diverse stakeholders to ensure functional relevance. These include:

- Cultural associations: collaboration with Ente Farnese in Piacenza (Italy) was fundamental for identifying storytelling priorities and points of interest for digital heritage exhibits.
- Educational initiatives: development of innovative teaching activities for multi-disciplinary students interested in mapping climate change effects to a real-world scenario (Belvedere glacier in the Italian Alps), as part of a long-term environmental monitoring project.
- Provincial administrations: developing practical solutions for innovative road asset inspection management in collaboration with the Province of Piacenza, responding to specific needs for periodic visual inspections and data traceability required by national regulations.

These collaborations demonstrate that the three cases and domains are part of a unified research trajectory aimed at supporting decision-making through 3D/4D monitoring and integrated geospatial data management, overcoming single domain-specific setup.

Hence, the decision to address Cultural Heritage, Natural Environments, and Civil Infrastructure within a single research framework is an intentional response to the fragmentation of the geospatial data lifecycle affecting diverse contexts and domains. While these domains are often treated as isolated silos in academic curricula and industrial practice, they share a fundamental technological bottleneck: the transition from geometric documentation (the survey) to operational knowledge (the information system).

## 2.2 Case studies description

The research activity focused on three main case studies, encompassing applications and collaborations across different domains and scales. In particular, Castello Farnese in Piacenza was chosen for testing in the cultural heritage domain; Belvedere Glacier in Macugnaga represented a super site for application in the natural environment and the bridge assets of the Piacenza Road Cadastre were the case study for decision-making support in the civil infrastructure domain.

### 2.2.1 Castello Farnese

In recent decades, there has been a significant rediscovery of Piacenza's military and architectural heritage, with the Farnese Castle (locally known as the *Castello Farnese*) emerging as a primary example of historical stratification and urban defence in Northern Italy (Figure 1). Despite its high historical value, the site remains largely inaccessible to the general public due to its continued role as a military-restricted area and the presence of structural safety limitations (Gentile, 1990). This physical barrier creates a distinct "narrative gap," where the architectural complexity and the historical evolution of the fortification are hidden from the community (Palloni, 2017). Consequently, the site represents an ideal case for the challenge of how reality capture can transform restricted physical spaces into accessible digital and explorable environments for a broad audience.

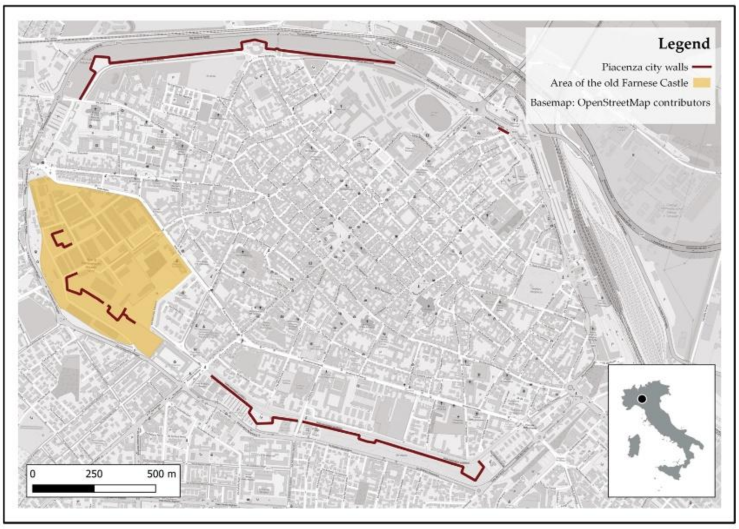


*Figure 1. Map of the city of Piacenza showing the ancient city walls that are still visible. In the Farnese Castle area, only 3 of the 5 bastions remain, with short sections of the curtain wall (Gaspari et al., 2024a).*

The historical evolution of the Farnese Castle is characterised by its strategic role within the defensive system of Piacenza (Giarelli, 1889; Soldini, 1991). Built upon a pre-existing medieval core, the fortification underwent significant transformations during the 16th century under the Farnese dynasty, who integrated the site into a sophisticated bastioned perimeter designed to withstand the advancements in modern artillery (Figure 2) (Rocchi, 1894; Adorni, 1889). The architectural complex effectively mirrors the transition from medieval defensive logic to the "alla moderna" fortification style, making it a critical asset for understanding the military history of the Po Valley (Guidoni and Marino, 1982). Throughout the 19th and 20th centuries, the castle transitioned from a purely defensive outpost to a state-owned military facility, a change that ensured the preservation of its external volumes but prevented the development of traditional museum or public-facing functions (Bertacchi, 2013). It was only in recent years that military authorities and local historians began a concerted effort to document the internal structures and the complex network of underground passages that characterize the site (Broglia, 2020). This historical layering ranging from 14th-century masonry to 20th-century functional adaptations produces a fragmented geometric record that requires a unified, flexible digital environment to be properly visualised and interpreted.

Currently, the cultural valorisation and scientific visits to the site are managed and coordinated by the Ente Farnese, a cultural association dedicated to the preservation of Piacenza's heritage. The association identified a critical need for a digital platform that could bypass physical access restrictions, allowing visitors and researchers to explore the site remotely. Within this research, the Farnese Castle serves as a test site for geospatial interactive storytelling tools' needs, using high-resolution 3D products and historical timelines to create an engaging and informative "virtual exhibit" that bridges the gap between the restricted military reality and the public's need for cultural access.

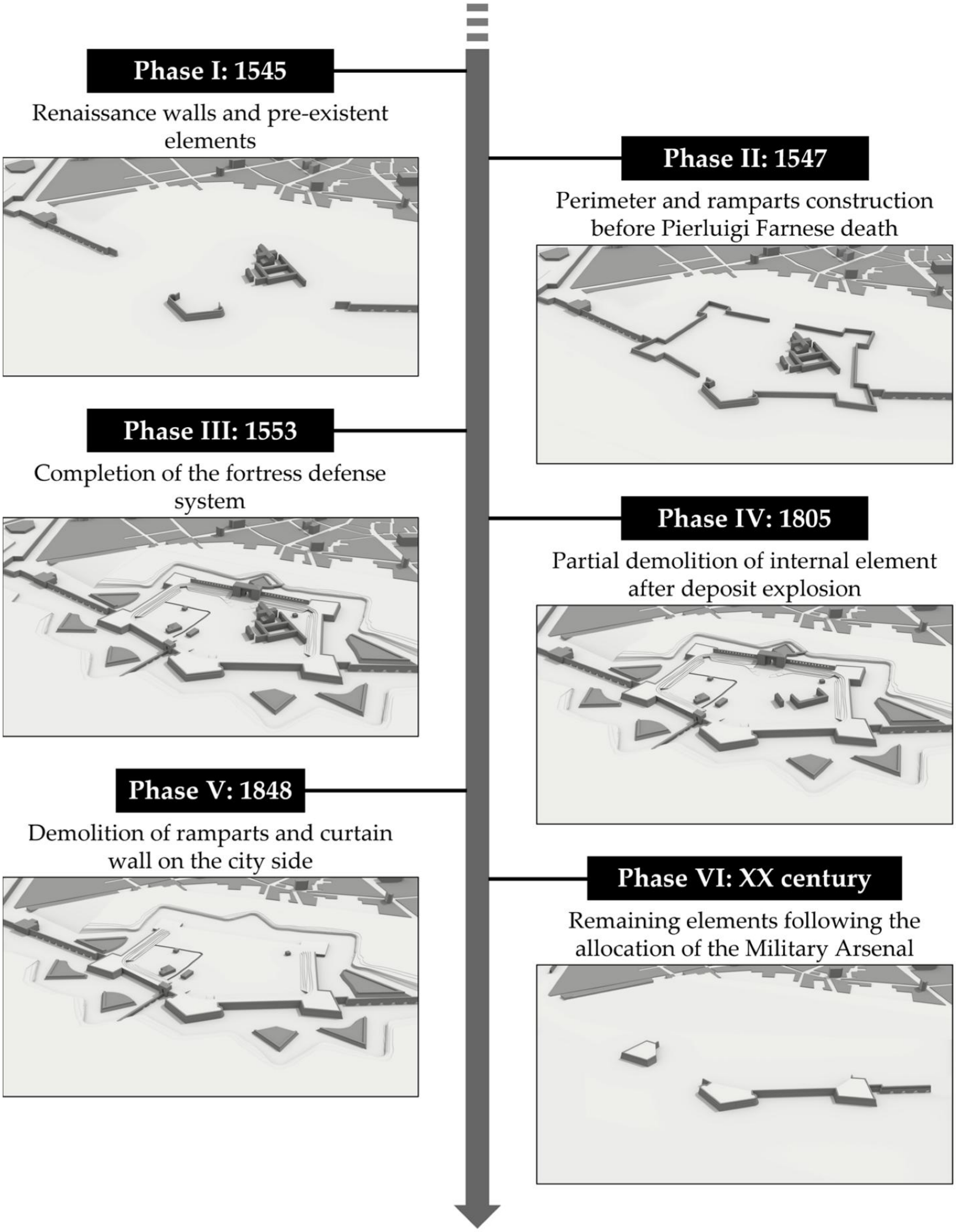


*Figure 2. Timeline of the evolution of the Castle Farnese site, showing the main historical phases concerning its construction and gradual destruction (from Gaspari et al., 2024a).*

### 2.2.2 Belvedere Glacier

The second case study represents the natural environment pillar of the research, focusing on the Belvedere Glacier, located in the Anzasca Valley at the base of the east face of Monte Rosa in the Italian

Alps (Figure 3). As a debris-covered glacier characterised by unique dynamic phenomena, including past surging events and the formation of supra-glacial lakes, the Belvedere serves as a critical indicator for climate change impact and morphological evolution in high-altitude alpine environments (Diolaiuti et al., 2003). Within the context of this thesis, the site represents the test site for solutions dedicated to the management of time-series data and multi-temporal 3D models, with monitoring capabilities as well as communication strategies across a wide range of end users.

Since 2015, the glacier has been at the centre of a long-term monitoring project led by LabMGF of Politecnico di Milano. This initiative aims to document the glacier's surface variations, velocity, and volume changes through the annual acquisition of high-resolution geospatial data. Over a decade of monitoring, the project has generated a massive 4D dataset (3D geometry + time) consisting of UAV photogrammetric surveys, GNSS measurements, and terrestrial laser scanning. This longitudinal approach creates a significant data management challenge: the information must be stored and queried in a way that allows for the comparison of different years and the integration of heterogeneous scientific products.

The project does not limit its reach to a single technical objective but addresses a multidisciplinary scientific community with diverse needs. To reflect this complexity, the digital solution logic for the Belvedere Glacier was designed to accommodate three distinct user groups:

- researchers and glaciologists requiring high-precision data, raw survey products, and technical metadata for quantitative analysis.
- students and trainees using the data for educational purposes, focusing on learning geomatics workflows and environmental interpretation.
- the general public seeking informative and accessible but quantitative visualisations to understand the impacts of climate change on the alpine landscape.

This user-group logic was heavily shaped by the ongoing collaboration between research and higher education, particularly through the annual summer schools organised on-site. For the Belvedere Glacier case study, the proposed research acts as a scientific repository and monitoring dashboard, ensuring that a decade of environmental documentation is not only preserved but remains queryable and accessible to both the scientific community and the public.


*Figure 3. Map of the Belvedere Glacier displaying the RGB orthophotomosaic from a 2023 UAV survey from the long-term monitoring project and surrounding topography derived from SWISS Topo. The inset shows the location within the Italian Alps. All maps are presented in the RDN2008/UTM Zone 32N global reference system (EPSG: 7791) (from Gaspari et al., 2025a).*

### 2.2.3 Bridges of the Piacenza Province

The third case study addresses the critical domain of civil infrastructure, focusing on the management and inspection of bridge networks. Unlike the previous examples, where the primary goals were dissemination or environmental monitoring, the infrastructure sector requires solutions that are explicitly operational and decision-oriented. Consequently, this case study serves to validate the capabilities of the cross-domain framework as a digital environment not only able to visualise 3D geometry but also to host legal documentation, inspection reports, and real-time annotations of defects from structural inspectors and civil engineers.

The management of bridge infrastructure in Italy is currently undergoing a significant regulatory shift with the release of the "Guidelines for Risk Classification and Management, Safety Assessment, and Monitoring of Existing Bridges" (MIT, 2025; ANSFISA, 2022), following a series of dramatic collapse and failures of bridges. The implementation of such regulations demands a transition from paperbased or flat-database inspection records to integrated systems that ensure the traceability and spatial localization of defects: for a bridge manager, the ability to pinpoint a crack or a carbonation area directly onto a 3D point cloud is essential for maintaining a clear chronological record of structural health.

In this context is developed first the collaboration between LabMGF and the Province of Piacenza, the entity managing the operation and maintenance of the road assets in the relative administrative division (Figure 4). Such a public administration body, managing a diverse portfolio of historical and modern river crossings, required a tool that could harmonise heterogeneous data, ranging from 2D maps to complex BIM (Building Information Modelling) objects, into a single, accessible web interface, building on top of an existent free and open-source stack adopted for their Road Cadastre database.

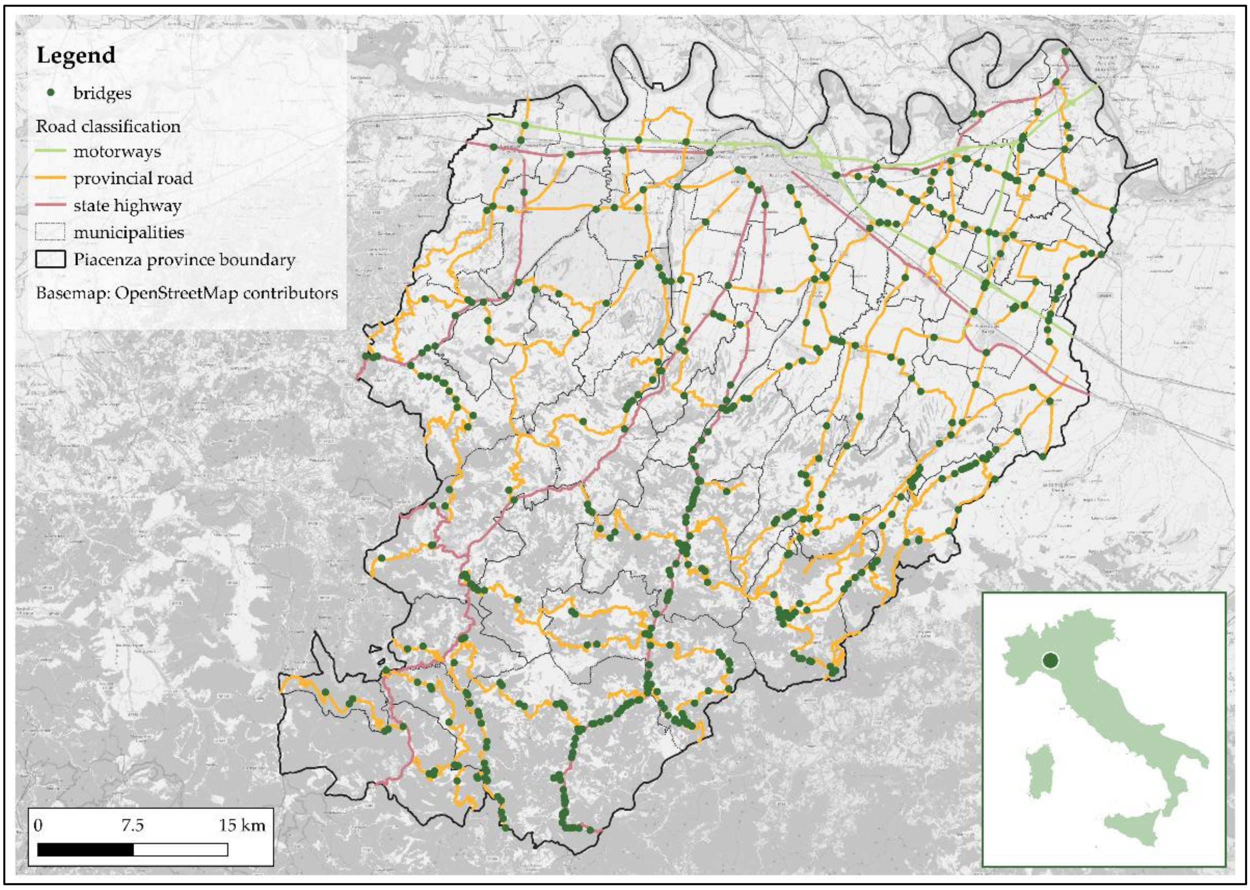


*Figure 4. Distribution of bridge assets managed by the Province of Piacenza overlayed to the network of state and provincial roads.*

The necessity for a new digital solution arose from the limitations of traditional Bridge Management Systems (BMS), which often lack 3D spatial awareness and user-friendly interfaces for field inspectors. By integrating Create, Read, Update, and Delete (CRUD) operations into the 3D viewer, the developed framework should allow engineers to interact with the asset in a "state-aware" environment. Within this research, this case study serves as a validation to demonstrate the functional complexity of a Management System where the geospatial framework becomes a legal and technical ledger for the safety and governance of public infrastructure.

## 2.3 Synthesis of the case studies operational goals

The three case studies detailed in this chapter provide a comprehensive cross-domain scenario of practical challenges in developing flexible solutions to extracting insights from diverse dataset, representing a selection that spans the full breadth of the geospatial data management challenge. Although the stakeholders and physical assets vary significantly from the cultural sensitivity of a XVI-century fortification, to the dynamic complexity of an alpine glacier, to the structural accountability of a regional bridge network, their digital requirements converge on the need for an integrated multi-source information system.

This synthesis confirms that the "fragment data" problem is not a domain-specific limitation but a cross-domain architectural gap. The following chapter will build upon this foundation by reviewing the technological state of the art through the lens of these requirements, identifying the technical benchmarks and tools necessary to transition from reality-captured digital shadows (Kritzinger et al., 2018; VanDerHorn & Mahadevan, 2021), towards interactive, state-aware geospatial environments.

3

# From survey products to digital information spaces

*Overview of the state of the art across the three domains*

## 3.1 From survey products to digital information systems

Over the past decade, the field of geomatics has undergone a fundamental shift, moving from the production of static survey artefacts to the design and development of continuously updated, service-oriented spatial information infrastructures (Figure 5). Such a trend becomes even more relevant with the rise of the Digital Twin concept, intended as a digital infrastructure able to connect in a bi-directional way the real world with its virtual replica (Kritzinger et al., 2018; VanDerHorn & Mahadevan, 2021). Recent geospatial data management research emphasises that geomatics now connects data acquisition, modelling, visualisation, and analysis to ensure the continuous availability and re-use of geospatial data, rather than isolated and fragmented map production (Breunig et al., 2020; Dritsas and Trigka, 2025). Traditional spatial practices, heavily reliant on early geospatial information modelling and Computer-Aided Design (CAD), were dominated by static representations of the Earth, such as 2D plans, 2.5D maps, and isolated domain-specific 3D models (Bill et al., 2022). These digital datasets merely captured a real-world state at a specific time and were often archived in disconnected information silos, severely limiting their capacity for integration, real-time dynamic updates, and comprehensive lifecycle analysis (Masoumi et al., 2023). In contrast, contemporary work shows how multi-sensor reality capture (e.g., mobile mapping systems, terrestrial and mobile laser scanning, UAV photogrammetry) produces dense, high-resolution point clouds. These point clouds form the geometric backbone for reusable and integrated models and information systems, from digital city twins to infrastructure management platforms, where data become informed decision as well as impactful stories (Chang et al., 2024; Gorgoglione et al., 2023; Papadopoulos et al., 2025; Porcelli et al., 2020).

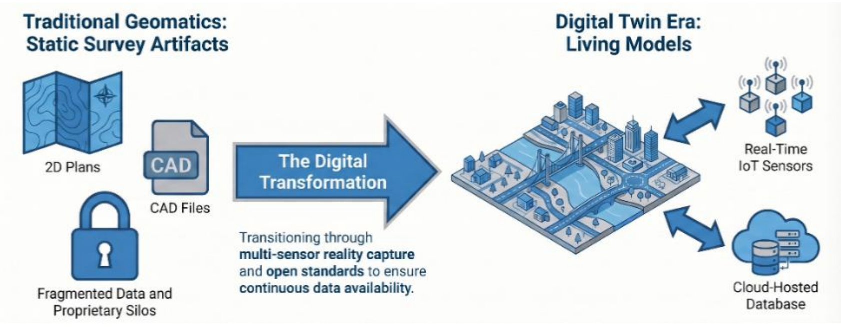


*Figure 5. Infographic summarising the transition from static and fragmented 2D/3D documentation and survey outputs in Geomatics to interconnected multi-source data management and workflows in the Digital Twin era. Image generated by Gemini model based on author-provided prompts.*

In the traditional geomatics framework, documentation typically culminated in representations without temporal depth or connectivity: once produced, maps and models were rarely maintained as living information resources (La Guardia and Koeva, 2023). The transition towards a Digital Twin-oriented geomatics instead introduces persistent 3D/4D environments that act as an "alive" digital counterpart for physical assets, infrastructures, and territories across scales. In these environments, heterogeneous 2D/3D datasets, Building Information Modelling (BIM), and point clouds can be fused within web-based and cloud-hosted platforms, enabling users to navigate, query, and update complex models through standard browsers and interfaces, often explicitly positioned as a first step towards digital twinning in different domains (Adreani et al., 2024; Ramonell et al., 2023). Systematic reviews and cross-sector studies consistently differentiate Digital Twins from conventional 3D models by their higher maturity. Beyond the static visualisation of 3D models, DTs couple rich spatial representations with multi-source integration, IoT sensing, real-time or near-real-time data streams, cloud computing, AI and Machine Learning (ML), and bidirectional human–computer interaction to support simulation, prediction, and data-centric decision-making throughout the design, construction and operation lifecycle (Shahzad et al., 2022; Riaz et al., 2023). Case studies in the built environment, infrastructure and environmental management show how advanced geomatics, sensor networks, and immersive or web-based visualisation can be embedded into platforms that continuously monitor performance and risk indicators, test "what-if" scenarios, and inform operational decisions over time (Aschieri et al., 2024; Bandara et al., 2025; Barrile et al., 2025; Bibri and Huang, 2025). In this context, the persistence of the geomatics representation, especially in the third dimension, with its ability to remain connected, updatable, and accessible to multidisciplinary target users, emerges as a critical requirement. It marks the transition from simple documentation and viewing to complex simulation, optimisation, and decision support across a wide range of applications in the roadmap to achieve Digital Twin status (Ali et al., 2024; Jeddoub et al., 2023; Piras et al., 2024; Sepasgozar, 2021).

However, a significant barrier remains: the data silo problem. In many domains preparing to evolve towards Digital Twins, data is fragmented across heterogeneous systems, proprietary platforms, and discipline-specific tools, which undermines real-time integration and limits the value of twin-based decision-making (Dihan et al., 2024; Jeddoub et al., 2025). Despite the proliferation of high-quality reality capture — such as TLS and UAV photogrammetry, also thanks to the spreading adoption of low-cost devices — the resulting point clouds and 3D meshes are often framed within closed, "black-box" software ecosystems or locked in project-specific workflows (Lei et al., 2024). This creates an expert-only bottleneck: high-fidelity documentation is trapped in specialised formats and interfaces, inaccessible to non-experts and difficult to reuse across disciplines, multi-disciplinary team projects, and lifecycle phases (Chheang et al., 2024; Piras et al., 2024).

Addressing these silos requires the establishment of a common ground: a technological framework that can host diverse reality-capture products and operational data within a shared, interoperable, and semantically rich environment, adaptable to different user needs (Al-Sadoon et al., 2025). Recent work on digital twins emphasises that such environments must support open standards, graph- or web-based data interaction, and lifecycle data integration, rather than isolated BIM, Geographic Information System (GIS), or sensor platforms (Gao et al., 2024; Hildebrandt et al., 2025; Koirala et al., 2024). At the same time, several reviews highlight that the successful use of digital-twin and XR-based systems is limited not only by interoperability, but also by gaps in user knowledge and skills, from data literacy and model interpretation to the ability to interact with immersive and IoT-enabled interfaces in routine practice (Kliestik et al., 2024; Kostadimas et al., 2025).

Against this background, the purpose of this chapter is to provide a concise overview of how the literature addresses the management of 3D survey data in digital environments across three fields that are central to this thesis: cultural heritage, natural environments, and civil infrastructure, with particular attention to bridges. Rather than reviewing all acquisition techniques in detail, the chapter focuses on the transition from data production to data management, with emphasis on platform purposes, user access, interoperability needs, and current fragmentation. This overview provides the conceptual basis for Chapter 3, where these needs are translated into the design requirements of the proposed modular framework.

## 3.2 Domain-specific state of the art

While data acquisition technologies are often shared across fields, the functional purpose of the resulting digital space dictates its architectural requirements. Whether the goal is to tell a historical story, track climate change impacts on the natural landscape, or manage infrastructure safety, the digital environment must be tailored to these specific functional objectives.

### 3.2.1 Cultural heritage

The field of cultural heritage documentation is experiencing significant transformation due to rapid advancements in digital technologies (Figure 6). Established geomatics techniques such as TLS, UAV photogrammetry, mobile mapping, and other geospatial sensors now provide highly accurate, multi-scale 3D documentation that underpins conservation, monitoring, and analysis workflows (Ulvi, 2021; Jo & Hong, 2019; Maté-González et al., 2022; Agapiou & Skarlatos, 2023). These methods increasingly serve as the reality-capture layer feeding web platforms and digital twins rather than as stand-alone outputs (Xing et al., 2025).

In this context, web-based platforms have become the primary infrastructure for documenting, interpreting, and disseminating digital heritage, replacing siloed desktop tools with centralised, accessible environments (Leka et al., 2025; Spettu et al., 2024). Platforms designed around Software-as-a-Service (SaaS) and cloud or VPS architectures relieve institutions from heavy local hardware and long-term storage burdens while enabling diffused access to 3D and multimodal documentation (Angheluță et al., 2023). Their purposes extend from basic visualisation to supporting the full digital life cycle of collections: creation, curation, preservation, versioning, and public access (Dragoni et al., 2017). A distinctive feature of the heritage domain is that platform value is often measured not only in terms of metric fidelity but also in terms of accessibility, narrative capacity, and the ability to link metric data to historical and interpretive content.

Cultural dissemination platforms act as large public repositories, offering certified assets, narratives, and educational resources to global audiences (e.g. Europeana, Google Arts & Culture, Smithsonian Open Access, CyArk) (Abate et al., 2017; Boutsi et al., 2019; Lian & Xie, 2024). Beyond dissemination, multi-purpose data management and collaboration systems provide workspaces for expert users, supporting ingestion, semantic enrichment, annotation, and shared analysis of 3D and imaging datasets (Achille et al., 2019, Quintilla-Castán et al., 2022, Néroulidis et al., 2024; Spadafora & Saccone, 2025). General-purpose 3D visualisation and sharing platforms host and embed models within wider communication strategies, often functioning as lightweight front-end to more structured back-end repositories (García-Bustos et al., 2023, Vennarucci et al., 2021). Embedded and facility-management ecosystems developed by hardware and software vendors integrate capture, processing, and BIM/Architecture, Engineering and Construction (AEC) workflows, increasingly aligning with digital twin paradigms in museums and heritage sites (Luther et al., 2023; Bounouioua et al., 2025).

At the same time, specialised heritage platforms combine 3D, WebGIS, and semantic components to support sustainable site management, tourism planning, and participatory decision-making, as in the Web-GIS platform for the Archaeological Park of Dion (Iliodromitis et al., 2025) or 4D hubs that link metric models with temporal and historical information for multiple user groups (Ioannidis et al., 2020).

Across these categories, eXtended Reality (XR) applications and digital twin concepts are central to the experiential purposes of platforms. Virtual Reality (VR), Augmented Reality (AR) and Web Graphic Library (WebGL)-based viewers are used to create virtual museums, immersive tours, and interactive exhibitions that enhance engagement, learning, and identity construction (Güvercin et al., 2024; Jin et al., 2022). Platforms like Angheluță et al.'s web-based 3D viewer demonstrate how multimodal imaging and optimised 3D models can be combined in open-access environments aimed at both specialists and the public. Similarly, AI-based cultural heritage platforms integrate digital archives, semantic graph analysis, and generative content tools to support research, exhibition design, digital restoration scenarios, and interactive educational uses (Baek et al., 2025).

User interaction strategies are therefore integral to platform's purpose. Taxonomies derived from recent literature distinguish content-centric, communication-centric, collaboration-centric, and user-centric platforms, depending on whether the primary goal is knowledge management, multi-stakeholder collaboration, or visitor engagement (Luther et al., 2023; Dragoni et al., 2017; Spadafora & Saccone, 2025). Digital storytelling and hyper-storytelling methodologies are implemented through hotspots, guided tours, gaming mechanics, and emerging AI-driven narrative systems, turning repositories into interpretive environments rather than static databases (Trichopoulos et al., 2023; Okanovic et al., 2022, Ishar et al., 2022).

Finally, there is a crucial and accelerating drive towards semantic data and interoperability to avoid fragmented, siloed datasets (Nishanbaev et al., 2021, Caffarri et al., 2026). Semantic Historical BIM (HBIM) and digital twin frameworks structure content for conservation, research, and public reuse (Li et al., 2025; Javier et al., 2025; Liu et al., 2023). Linked Open Data, standardized ontologies, and Findable, Accessible, Interoperable and Reusable (FAIR)-aligned platform designs aim to ensure that digital heritage data remain findable, accessible, interoperable, and reusable across institutions and over time (Barzaghi et al., 2025). Within this ecosystem, web platforms evolve into shared, multi-purpose environments that simultaneously support expert workflows, institutional governance, and broad public engagement with cultural heritage (Maietti, 2023).

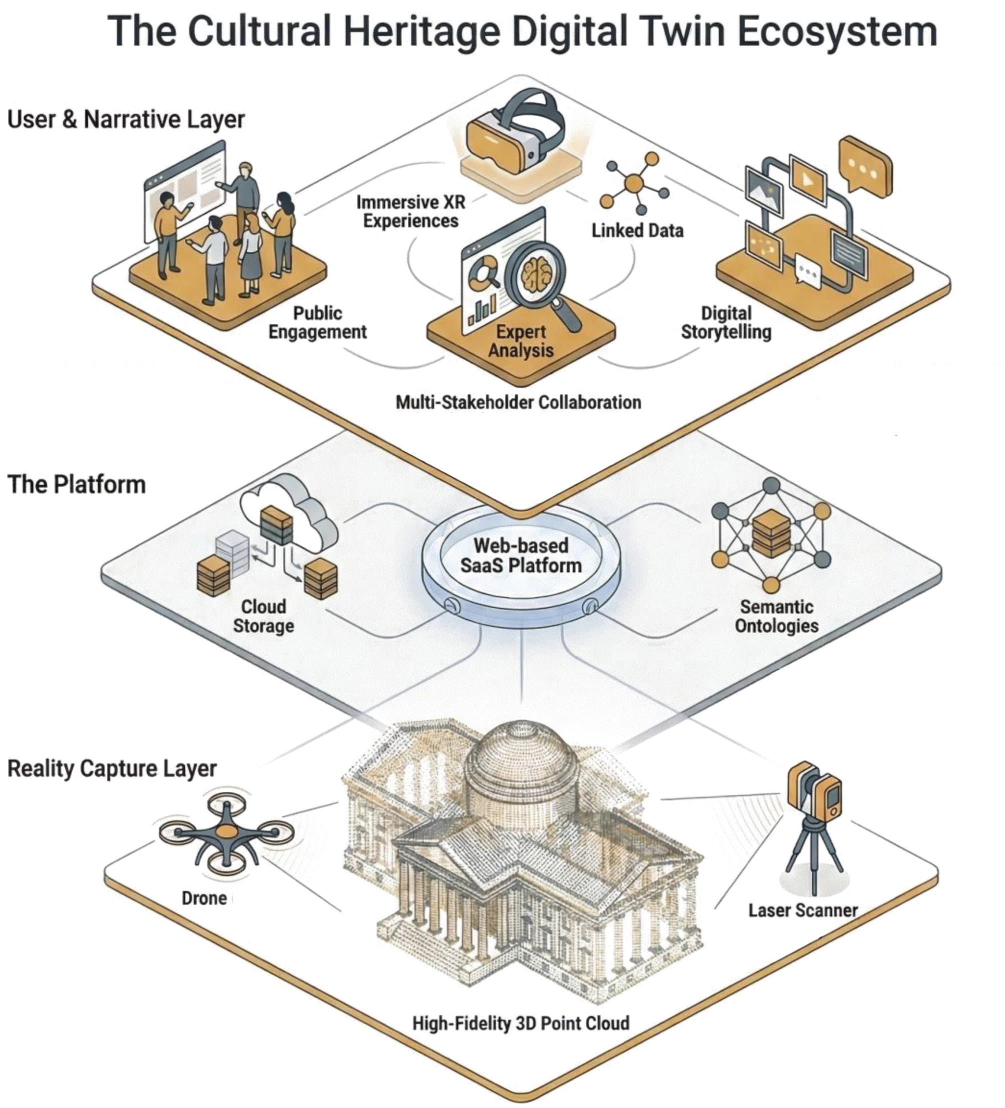


*Figure 6. Graphical summary of the Geomatics technologies and tools involved in different layers of the development of an up-to-date information system in the Cultural Heritage domain. Image generated by Gemini model based on author-provided prompts.*

### 3.2.2. Natural environment

In natural environments, the dominant purpose of 3D survey data is typically observing change over time, often in support of environmental monitoring, scientific communication, and risk awareness. Compared with cultural heritage, where the object of interest is often relatively stable, natural systems such as glaciers, landslides, river corridors, and mountain slopes require repeated surveys and temporal comparison. Here, digital platforms are especially valuable when they allow multi-epoch datasets to be organised, compared, and communicated to different categories of users (Figure 7).

High-resolution 3D documentation of natural environments increasingly relies on integrated remote sensing workflows that combine satellite imagery, aerial and UAV photogrammetry, and laser scanning (TLS, UAV-Light Detection And Ranging (LiDAR)) to derive dense point clouds, orthomosaics, and digital elevation models across scales (Paul et al., 2002; Bamber & Rivera, 2007; Ioli et al., 2022; Ioli et al., 2023a, Ioli et al., 2023b, Di Rita et al., 2020). These techniques now underpin detailed analyses of glacier retreat, river and coastal morphology, forest structure, and other ecosystem changes, forming the primary reality-capture layer that feeds geospatial databases and analysis pipelines rather than remaining stand-alone visual products (Marty et al., 2025; Kükenbrink et al., 2022; MacDonell et al., 2023; Jackson et al., 2020). While such workflows extend a long tradition of multitemporal imagery in glacier monitoring, their rapidly growing data volumes and temporal density make structured management, documentation, and visualisation crucial for making outputs accessible and meaningful to diverse audiences (Kaufmann, 2012; Kropácek et al., 2024; Streuff et al., 2022; Marta et al., 2021; Lützow et al., 2023; Senger et al., 2021a).

Since the early 2000s, images of melting ice have played a central role in climate-change communication, initially focusing on remote polar ice and more recently on mountain glaciers that are culturally and economically embedded in local communities (O'Neill, 2020; Gaia et al., 2025; Salim et al., 2023; Nesur et al., 2022; Ramirez et al., 2020). Yet most visual communication still privileges emotional and aesthetic narratives over representations that integrate quantitative 3D data and socio-cultural context (Johannsen et al., 2018; Buhr, 2024). Addressing this gap calls for multidisciplinary and multimedia approaches in which maps and change visualisations serve as bridges between science and society. These approaches move beyond static images towards locally relevant, interactive tools that capture both spatial and temporal dynamics and lay foundations for robust environmental digital twins (Schroth et al., 2014; Fish, 2020; Tsang, 2023; Fissore et al., 2023; Skopeliti et al., 2025; Pasquaré Mariotto et al., 2023).

In this context, WebGIS, web platforms and 3D web technologies have become central infrastructures for environmental and climate-related monitoring and dissemination. Open-source WebGIS frameworks built on CesiumJS, PostGIS, and geospatial web services integrate heterogeneous monitoring datasets and 3D models, providing interactive 3D exploration, time-enabled map views, and analytical tools to support applications ranging from glacier and coastal monitoring to urban wellness analysis, often framed as early digital-twin structures (Riaz et al., 2023; Tsakiridis et al., 2023; Qiu et al., 2022; Park et al., 2020). Systematic reviews show rapid growth in WebGIS for natural-hazard management. These platforms support real-time monitoring, early warning, decision support, and multi-stakeholder collaboration, and increasingly converge with digital-twin paradigms and cloud infrastructures that couple simulations, sensor data, and visual interfaces (Kussul et al., 2025; Lu et al., 2025a). 3D WebGIS platforms for dynamic precipitation mapping and hydro-hydraulic simulations demonstrate this convergence. They combine real-time sensor data, 3D terrain models, and scenario visualisations to inform civil protection, infrastructure planning, and climate-related risk management (Riaz et al., 2023; Lu et al., 2025a).

Building on these geospatial backbones, dashboards, visual analytics, and 3D viewers are being designed explicitly as communication and education tools for climate change. Interactive climate dashboards built with GIS technologies and business-intelligence tools integrate maps, charts, indicators, and narrative elements to convey historical trends, emission scenarios, and localised climate impacts to students, policymakers, and the general public (Jackson et al., 2020; De Miguel González et al., 2025). Visual-analytics frameworks that couple 2D and 3D representations with simulation modules enable exploratory analysis of urban microclimates, floods, stormwater dynamics, and other environmental processes, translating complex spatio-temporal data into decision-support environments. At different scales, interactive 3D web platforms and business-intelligence dashboards link 3D models with real-time or curated datasets, acting as accessible front ends that bridge research workflows and public awareness. They represent the first operational steps towards digital twins for environmental and climate-change communication and for visualising links between climate, health, attitudes, and demographic factors (Vuckovic et al., 2022;

Mahajan et al., 2022; La Guardia et al., 2025; Andreassen & Babic, 2025). Together, these developments point towards modular, web-based ecosystems where traditional 3D geomatics outputs are embedded in interactive, multi-audience platforms that support monitoring, analysis, and climate-change quantitative communication in an integrated manner.

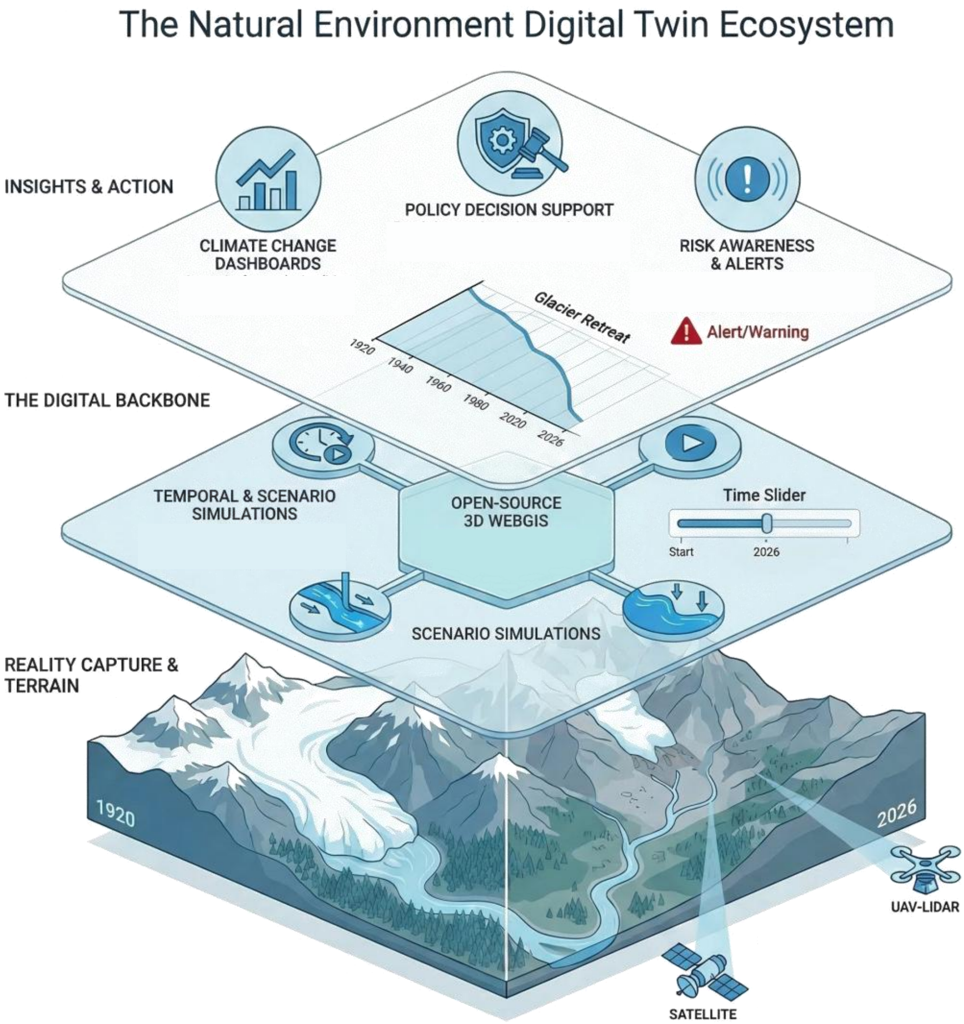


*Figure 7. Graphical summary of the Geomatics technologies and tools involved in different layers of the development of an up-to-date information system in the Natural Environment domain. Image generated by Gemini model based on author-provided prompts.*

### 3.2.3 Civil infrastructures

In the domain of civil infrastructure, particularly within bridge management, 3D survey data have evolved from static documentation into operational assets essential for inspection support, condition assessment, and long-term maintenance planning (Figure 8). This transition marks a shift from mere geometric representation towards decision-oriented data organization, where survey-derived products must support temporal queries, annotations, and structured information retrieval. While traditional inspections relied on manual visual surveys, which are frequently characterised by high costs, safety risks, and subjectivity (Mandirola et al., 2022; Belloni et al., 2023), contemporary geomatics techniques provide an objective foundation for structural diagnosis and remote analysis. Multi-source reality capture now enables the accurate acquisition of both geometric and material-pathological data. The toolset includes UAV photogrammetry for inaccessible sites (Panigati et al., 2025), high-speed laser scanning via TLS and SLAM for deformation monitoring (Mohammadi et al., 2022; Urban et al., 2024), and satellite remote sensing such as GNSS and InSAR for displacement detection (Bianchi et al., 2023; Tonelli et al., 2023). When fused with non-destructive testing (NDT) and Structural Health Monitoring (SHM) sensor networks (Pozzer et al., 2025; Quaglini et al., 2023), these technologies form the metric and parametric backbone of the digital asset. However, as this acquisition phase reaches technical maturity, the primary challenge shifts towards the effective management and visualization of these massive, heterogeneous datasets, transforming raw measurements into a synchronized information system for infrastructure governance.

To ensure that infrastructure owners, engineers and decision makers have a complete and up-to-date understanding of the assets to be maintained, it is crucial to adopt interoperable systems that can integrate different data sources. In this context, digital platforms that consolidate geometric and parametric, visual and physical datasets have become one of the focuses of both research and practice. Currently, BIM models are often managed within the same authoring software used to develop them, where geometric, semantic, and asset data are integrated (Salzano et al., 2023; Chelaru et al., 2024). However, dependence on proprietary solutions can limit the system's interoperability, as accessing and modifying information usually requires the same software environment. To overcome this, BIM models are increasingly being exported in the open Industry Foundation Classes (IFC) format and displayed using free desktop viewers, which allow users to visualise the model without commercial licensing (Santos et al., 2025; Moyano et al., 2022). Nevertheless, it is now recognised that BIM/openBIM models alone cannot encompass the full range of data required for the long-term management of assets: overloading the model with heterogeneous information would reduce its usability and increase the complexity of the system.

With the recognised limitations of standalone BIM models, the challenge of effective infrastructure management is increasingly being overcome by WebGIS solutions (Mangiameli et al., 2024; Vinueza-Martinez et al., 2024) which integrate GIS with web technologies, allow users to access, visualise, and analyse complex spatial data through a simple web browser. This architecture emerged to overcome the limitations of traditional Bridge Management Systems (BMSs), which often suffered from flat graphics, user-unfriendly interfaces, and a limited capacity to visualise geospatial data (Liu et al., 2018; Giuffrida et al., 2025). In this model, the WebGIS platform becomes a centralized cloud-based environment that supports advanced geospatial visualization and data integration. To address the need for comprehensive and decentralized access, research has focused on developing multiscale WebGIS-based management systems for roads (Pascucci et al., 2025; Zhu et al., 2021), railways (Xu et al., 2026) and power and supply networks (La Guardia et al., 2021; Amović et al., 2025). These platforms typically feature an upper level to manage the overall bridge network using 2D vectors, and a lower level designed to handle 3D spatial information and real-time data streams for single structures. The ability of the 3D component to rapidly convey bridge features and exploration scenarios is essential for managers (Liu et al., 2018).

Consequently, some infrastructure managers and researchers have adopted more advanced, integrated commercial management system solutions: these platforms enable the combination of digital models with inspection data (Salzano et al., 2023; Ciccone et al., 2022), summary graphs of asset conditions (Spallarossa and Bonicelli, 2024), and condition records via analytical outputs such as degradation mapping (Buggiani et al., 2024). Additionally, emerging commercial cloud-based solutions (Aglietti et al., 2023) or game-based solutions (Fawad et al., 2025) are being used to visualise sensor data via digital devices such as computers or immersive devices. This enables real-time condition monitoring and augmented reality interactions in situ (Fawad et al., 2025, Martins et al., 2024). Despite their capabilities, these commercial systems often have limitations in terms of dashboard customization and are inherently proprietary, raising issues about long-term flexibility, cost, and data ownership.

Due to the increasing complexity and heterogeneity of data, some authors have begun developing customised solutions using open source software: these systems aim to provide a flexible and scalable environment for managing structured data, overcoming the limitations imposed by commercial platforms. In this context, some authors have proposed BMSs based on FOSS platforms for defining their architecture: in fact, in this framework, data are usually organized through relational databases, which allow efficient storage and retrieval, while spatial mapping of infrastructure assets is managed through GIS systems, which can provide a complete overview of the infrastructure network (Mangiameli et al., 2024). Finally, visualization of individual assets is performed using dedicated open-source viewers, which support consultation of BIM/IFC models, point clouds and other surveys, and monitoring outputs (Gao et al., 2024). This integrated, modular approach enables the creation of an interoperable, extensible, and accessible digital eco-system for infrastructure monitoring and management. Based on the overview and key points highlighted, it is crucial to develop a comprehensive framework for creating a visualization platform suitable for bridge management. This system should be able to integrate diverse data sources and adapt to a wide range of real-world scenarios, from environments with large amounts of data to those requiring the incorporation of entirely new information.

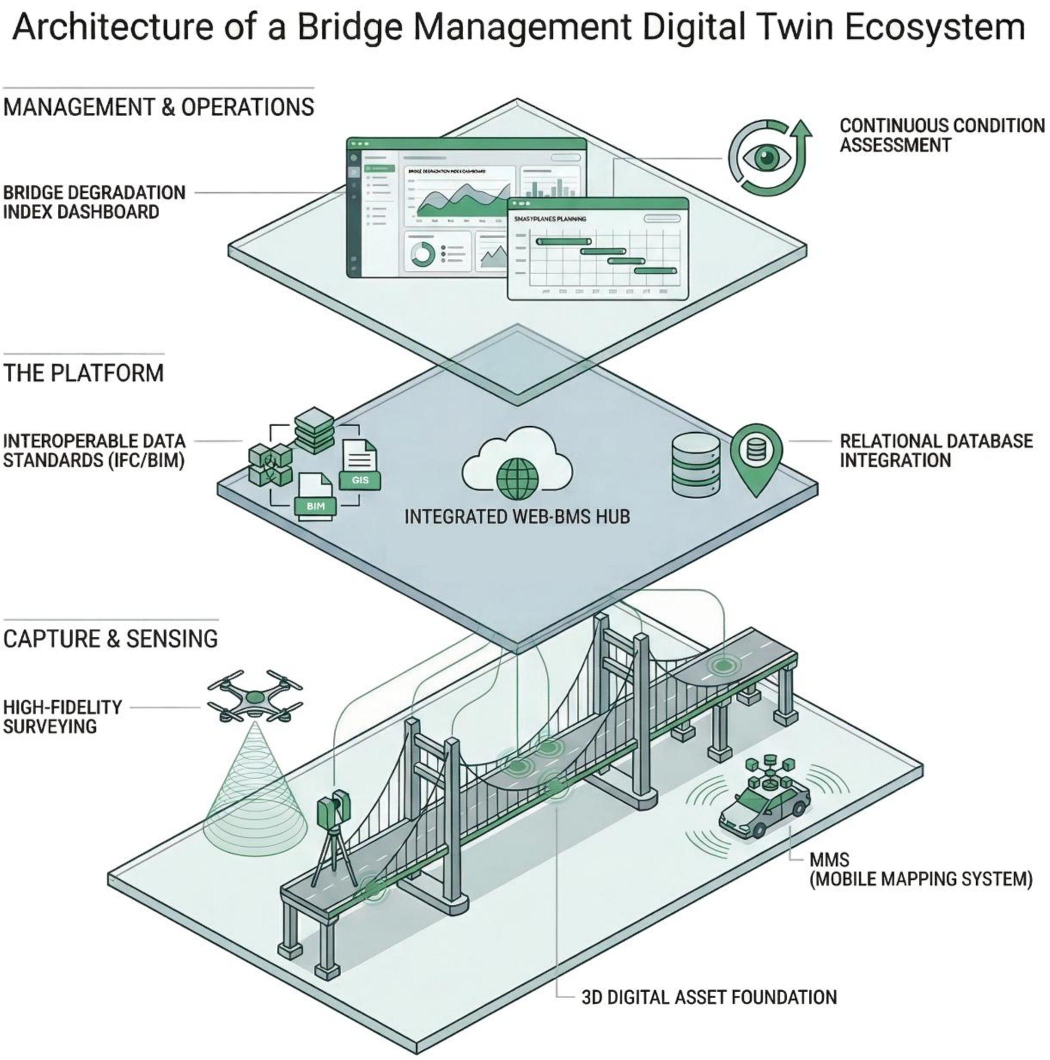


*Figure 8. Graphical summary of the Geomatics technologies and tools involved in different layers of the development of an up-to-date information system in the Civil Infrastructure domain. Image generated by Gemini model based on author-provided prompts.*

## 3.3 Cross-domain challenges in 3D geospatial data management

Understanding the commonalities across cultural heritage, the natural environment, and civil infrastructure is essential for the design of a cross-domain framework. Although the end-users and their specific operational objectives vary significantly across these fields, the underlying digital needs are remarkably consistent. The overview of the current trends described in Section 3.2 reveals that this consistency is built upon three shared technological requirements.

A first issue is heterogeneity of data and formats. Indeed, point clouds, meshes, orthophotos, BIM models, GIS layers, inspection records, and time-series measurements are often generated through different workflows and stored in separate software environments (Lu et al., 2025b). The core difficulty is therefore not simply the volume of data, but their coexistence as heterogeneous objects with different spatial structures, semantic depth, and update logic. This creates barriers to integrated consultation and reuse, especially when platforms are expected to serve multiple user groups rather than a single specialist community.

Interoperability and persistence, also, represent crucial requirements for a platform and its adoption. Across domains, the value of 3D survey data increases when they can remain connected to metadata, derived products, and later observations (Berlato et al., 2025). However, many existing solutions still rely on project-specific pipelines or proprietary ecosystems that make long-term access and exchange more difficult. In this sense, the literature repeatedly moves from the problem of data production to thata of data continuity: how to ensure that 3D survey outputs do not remain isolated deliverables but become persistent components of a broader information environment.

Finally, these systems necessitate the development of user-friendly interfaces, providing intuitive environments that empower non-experts to meaningfully interact with highly complex geomatics data (Lian and Xie, 2024, Parrinello and Picchio, 2023). In particular, the three domains all show a tension between high-fidelity documentation and practical usability. Highly detailed point clouds and models are valuable for expert analysis, but they may be difficult to access, interpret, or manipulate for non-specialists. Conversely, platforms designed for broad dissemination often simplify the data to such an extent that management and analytical potential are reduced (Lucchi, 2023). The design problem is therefore not only one of visualisation performance, but one of calibrated user agency: different users need different degrees of access, interaction, and interpretive support.

Ultimately, the literature suggests a broader structural limitation: a fragmentation between visualisation-oriented solutions and management-oriented solutions. Many platforms are effective in showing 3D data online, but fewer support structured annotation, database connectivity, lifecycle traceability, or iterative updates. This distinction is crucial for the present research, as it marks the threshold between platforms that merely publish survey products and platforms that can support actual geospatial management workflows, validating applications for distinct purposes ranging from dissemination to operation management passing through scientific monitoring.

### 3.3.1 A maturity 5-level roadmap

To address these challenges, the design and implementation strategy of the framework proposed in this thesis is conceptualised through the lens of a five-level user engagement maturity model. Rather than serving as a retrospective performance grade, this model provides the methodological blueprint for an incremental evolutionary roadmap (adapted from Liu et al., 2024 and Chen et al., 2021). It recognises that achieving a Digital Twin is not a singular technological acquisition but a socio-technical learning process, where the platform's architectural complexity must evolve in tandem with the user's operational readiness.

Prescriptively, the model acts as a technical compass, guiding implementers in identifying the architectural components, such as database orchestration or server-side logic, required to satisfy escalating domain needs (Table 1). By emphasising upskilling, the model evaluates how the system supports and enhances the knowledge of the target users, ensuring that technology serves as an enabler of human agency rather than a replacement for it.

*Table 1. Definition of capabilities and application focus for the 5 distinct maturity levels adapted from the literature.*

| Level | Definition | System capability | Focus |
|---|---|---|---|
| 1 | Digital exhibition | Stateless WebGL viewer | Visualisation: accessibility and spatial navigation |
| 2 | Scientific monitor | Read-only DB integration, information multiple overlay | Exploration: data retrieval, querying and monitoring |

| | | | |
|---|---|---|---|
| 3 | Management system | Heterogeneous data integration, full CRUD operations | Interaction: filtering, updating for decision-support and accountability |
| 4 | Digital Twin | Real-time bi-directional data flows and predictive simulation | Prediction: live synchronisation and “what-if” scenarios computation |
| 5 | Autonomous infrastructure | Regional/national networks integration. | Autonomy: self-updating hybrid network of sensors (authoritative and/or crowdsourced) |

With the first level of digital exhibition the system serves as a static viewer, mostly focused on high-resolution rendering of a virtual interactive scene and on its accessibility to users without specific technical background through a standard web browser. The prototype operates in a stateless mode, meaning it lacks a persistent connection to a relational database in its backend. It is a memoryless architecture where user interactions are transient, prioritising zero-distance accessibility and historical storytelling over data persistence.

The second level, defined as scientific monitor, introduces state-awareness by integrating a relational database behind the 3D viewer interface. The system enables one-way communication with the server, allowing users to query and retrieve geolocated 4D time-series measurements. This phase was critical for testing the framework’s capacity to handle the "data silo" problem, transforming the 3D scene from a static model into a searchable contextual data repository.

The third level of maturity, the management system consists of a fully operational data management platform that support complete operational agency. The system architecture supports full CRUD operations, creating a bidirectional link between the user interface and the database. In this stage, the platform functions as a backbone for the advanced development of a Digital Twin environment where user actions are permanently archived, ensuring traceability and accountability in their management.

The fourth level, defined as the Digital Twin, marks the transition from historical and periodic monitoring to real-time synchronisation between the physical asset and its digital representation (Kritzinger et al., 2018; Fuller et al., 2020). At this stage of maturity, the system capability evolves to support continuous, bi-directional data flows, where the virtual model is updated dynamically by live data streams. The focus shifts towards prediction, enabling the framework to perform complex "what-if" simulations and predictive maintenance scenarios based on target users’ requests. This level allows stakeholders to move beyond observing what has happened to forecast structural or environmental behaviours before they occur.

The fifth and final level of maturity is characterised as automated infrastructure, representing the ultimate stage of a self-updating, autonomous geospatial ecosystem. At this level, the platform scales from individual assets or sites to integrated regional or national networks. The system’s capability is defined by its autonomy, where data updates, structural health assessments, and environmental simulations are triggered automatically by a hybrid sensor network. This ecosystem incorporates not only traditional IoT devices but also crowdsourced "human sensors" (Goodchild, 2007), creating a distributed and highly resilient geospatial infrastructure.

## 3.4 Implications for the thesis and research niche

The overview presented in this chapter shows that the management of 3D survey data has become a central issue across cultural heritage, natural environments, and civil infrastructure. In all three domains, advances in reality capture have made high-resolution and multi-source spatial datasets increasingly available. However, the literature also shows that the capacity to acquire data has advanced faster than the capacity to organise them into accessible, interoperable, and reusable digital environments.

A recurring limitation is the fragmentation of current solutions. On one side, there are platforms mainly oriented towards online dissemination and 3D visualisation; on the other, there are more structured, but often domain-specific or proprietary systems focused on peculiar operational tasks. What is still less common is a modular and transferable framework able to connect heterogeneous survey products, progressive levels of user interaction, and different management needs within a coherent web-based architecture. This gap becomes especially visible when comparing domains: the same family of data types may support storytelling in cultural heritage, temporal analysis in environmental monitoring, and inspection workflows in bridge management, yet current solutions are often developed separately and with limited reusability across contexts.

Within this scenario, the relevance of open-source approaches is not only economic, but methodological. Open technologies can facilitate transparency, reproducibility, adaptability, and reduced dependence on closed software ecosystems, which is particularly important when public institutions or research groups need long-term control over their own datasets and workflows. The issue is therefore not to oppose proprietary and open solutions in abstract terms, but to recognise that modularity, inspectability, and reusability are essential qualities for a framework intended to evolve across domains and over time with maturity roadmap.

Rather than proposing yet another domain-specific application, the research illustrated in this thesis aims to define and validate a modular open-source framework for geospatial data management that can be adapted to different contexts while preserving a common architectural logic. The framework is conceived as a common ground for heterogeneous 2D and 3D survey data, enabling different levels of user agency and supporting the transition from static documentation to more persistent and interactive digital environments. In this sense, the contribution of the thesis is not limited to data visualisation: it concerns the design of a reusable structure for organising, accessing, and progressively enriching survey-derived information across the built and natural environment.

# 4

# Platform design

*A modular framework for progressive user agency and data integration*

Understanding the geomatics-based practices currently adopted and explored by researchers and practitioners for managing natural and built environments provides a basis for analysing the specific needs of each group of stakeholders across different domains. Indeed, requirements analysis enables the identification of specific goals and the functionalities required to achieve them within a flexible data management platform. This chapter details the main steps that led to the design and development of a modular architecture for an open-source platform for geodata management, where heterogeneous survey or historical inspection products can coexist and be interacted with through a simple web browser. In particular, the design of the proposed framework is intended as a response to the heterogenous needs of different group of users in three distinct dedicated case studies in the domains of cultural heritage, natural environments, and civil infrastructures. To ensure the system's effectiveness, the development followed an inductive logic, where the technical requirements were distilled from the specific challenges of real-world scenarios.

This chapter is organized as follows:

- Section 4.1 provides a requirement analysis based on targeted domains of application, identifying the specific needs in relation to user technical background and operational goals.
- Section 4.2 details the design of the platform architecture, outlining the interaction between the visualisation engines, the relational database, and the user interface.
- Section 4.3 explores the peculiarities of integrated libraries and tools and the necessary transitions from survey-ready to web-ready data.
- Section 4.4 summarises the different customisation and readaptation of the framework functional modules for the implementations of the Farnese Castle, the Belvedere Glacier and the bridges of Piacenza.

## 4.1 Requirement analysis

In order to define the requirements for a unified geospatial platform, this research employs an inductive methodology. The system's functional requirements were synthesised through a comparative analysis of three diverse case studies in different fields: the Castello Farnese (cultural heritage), the Belvedere Glacier (natural environment) and the P.O.N.T.I. prototype (bridges). While these fields use different data acquisition techniques, their operational needs converge on a single requirement: the transformation of static, massive 3D datasets into manageable, interactive geospatial knowledge.

### 4.1.1 Target users' profile across domains

The framework is designed as a common ground for a diverse spectrum of users that can be customised according to varying technical backgrounds and operational goals. Hence, to build a scalable architecture, it was essential to identify the specific needs and engagement levels for each of the three target domains summarised in Table 2.

*Table 2. Summary of target user profiles, operational goals, and technical requirements across the three application domains.*

| Domain | Main goals | Key user roles | Needs and engagement level |
|---|---|---|---|
| Cultural heritage | High-resolution 3D documentation and dissemination for public engagement, managing structural fragility and accessibility. | Simple readers: General public and students.<br>Experts: Conservators. | Needs: Interactive storytelling, immersive experiences (VR/AR), and accessible WebGL exploration.<br>Engagement: Primarily passive for outreach, active for expert analysis. |
| Natural environment | Monitoring dynamic changes (e.g. glaciers, landslides) in remote terrain to address climate change challenges. | Technical users: Multidisciplinary researchers and geomatics technicians.<br>Learners: Students in field programs.<br>General public: citizens and/or simple visitors of the area of interest. | Needs: Open data sharing, 4D (time-series) visualisation of volume/velocity changes, and scientific transparency.<br>Engagement: Active data production and quantitative analysis. |
| Civil infrastructure | Structural health monitoring, inspection data and lifecycle management to optimise maintenance. | Managers: Road asset managers and small/medium administrations<br>Operators: Field inspectors and specialists.<br>System administrators: IT responsible for the operation of the operability of administration systems | Needs: Integration of fragmented data, defect annotation on 3D models, and BIM/GIS data management for decision-making.<br>Engagement: High active interaction for maintenance planning and monitoring. |

In the context of cultural heritage domain, user requirements are shaped by the dual need for public dissemination and scientific documentation. The research identifies two primary stakeholder profiles whose needs dictate the platform's functional design. For the general public the primary requirement is the democratisation of access to sites that are physically inaccessible, vulnerable, or located in restricted zones, such as the military area housing the Castello Farnese chosen for the case study described in Chapter 4. These users require immediate and simplified accessibility that prioritises intuitive navigation and interactive digital storytelling. This approach reduces technical barriers, such as specialised hardware requirements or software installations, traditionally associated with the direct use and rendering of raw geomatics products. At the same time, the platform, if re-adapted for different cultural heritage sites of local relevance whose managers plan not only to disseminate their stories but also to develop maintenance and conservation strategies, should consider the usage of conservation experts and professionals. This additional group of technical users requires the platform to also expose essential high-resolution metric tools. Their needs extend beyond the virtual visualisation of a 2D/3D scene to the extraction of measurements and the comparison of site conditions across epochs, achieved by integrating multi-source objects in a single, collaborative viewer. Hence, the framework should be able to combine the need for a lightweight and intuitive interface easy to explore with the integration of basic tools for more technical routine operations.

Within the natural environment domain, particularly in areas experiencing rapidly changing topographies, user requirements are shaped by the urgent need to document and communicate the effects of climate change, as in the case of the Belvedere Glacier on the Italian Alps detailed in Chapter 5. Traditional monitoring methods frequently produce fragmented geospatial data that non-experts find challenging to interpret. Consequently, the framework delineates three stakeholder profiles with increasing technical demands. The general audience requires an intuitive interface to the latest qualitative and quantitative research on climate change documentation. Multi-disciplinary researchers seek to export 2D and 3D products for advanced autonomous processing and to adapt the platform for use at comparable sites. Students aim to learn field data acquisition techniques and accessing real-world research resources as active contributors of insights. Hence, the platform architecture should allow multiple access points to interactive interface where users of different groups, with the support of dedicated user guides, can query data dynamically, without relying exclusively on predefined scenes or exploration paths statically defined in the source code.

In the civil infrastructure domain, the primary focus is on the structured management of data across the structure's lifetime and the optimisation of maintenance workflows for ageing infrastructure networks. In this case, the requirements are driven by a need for a systematic, secure and collaborative system to retrieve and update structural information, specifically addressing the challenges faces by road asset managers in small and medium-sized administrative divisions (e.g. the Italian Provinces) (Figure 9). As observed through the collaboration with the Province of Piacenza, these entities are now mandated by national regulations (MIT, 2020; ANSFISA, 2022) to perform periodic inspections and assign so-called "Attention Classes" to managed structures. Currently, the transition to digital workflows is hindered by limited internal resources and technical expertise, often resulting in inspection multi-source data - ranging from visual observations to complex laser scans and BIM models – being stored fragmentarily on personal disks or disorganised local folders (Gaspari et al., 2023a). This dispersion leads to data loss and the proliferation of inconsistent formats. Consequently, the framework must bridge the gap between on-site observations and virtual inspections, providing a single queryable space where road cadastre staff (already familiar with GIS/DB operations) and structural assessment engineering groups (handling defect recognition) can collaborate. To ensure data integrity and long-term sustainability, the system design identifies three core functional roles: IT technicians for system maintenance, GIS specialists for geospatial data orchestration, and bridge engineers/inspectors for technical assessment and defect annotation. For these users, the platform must support full CRUD operations, allowing them to accurately locate, quantify, and version structural defects directly on the 3D survey products, ensuring traceability and administrative accountability.

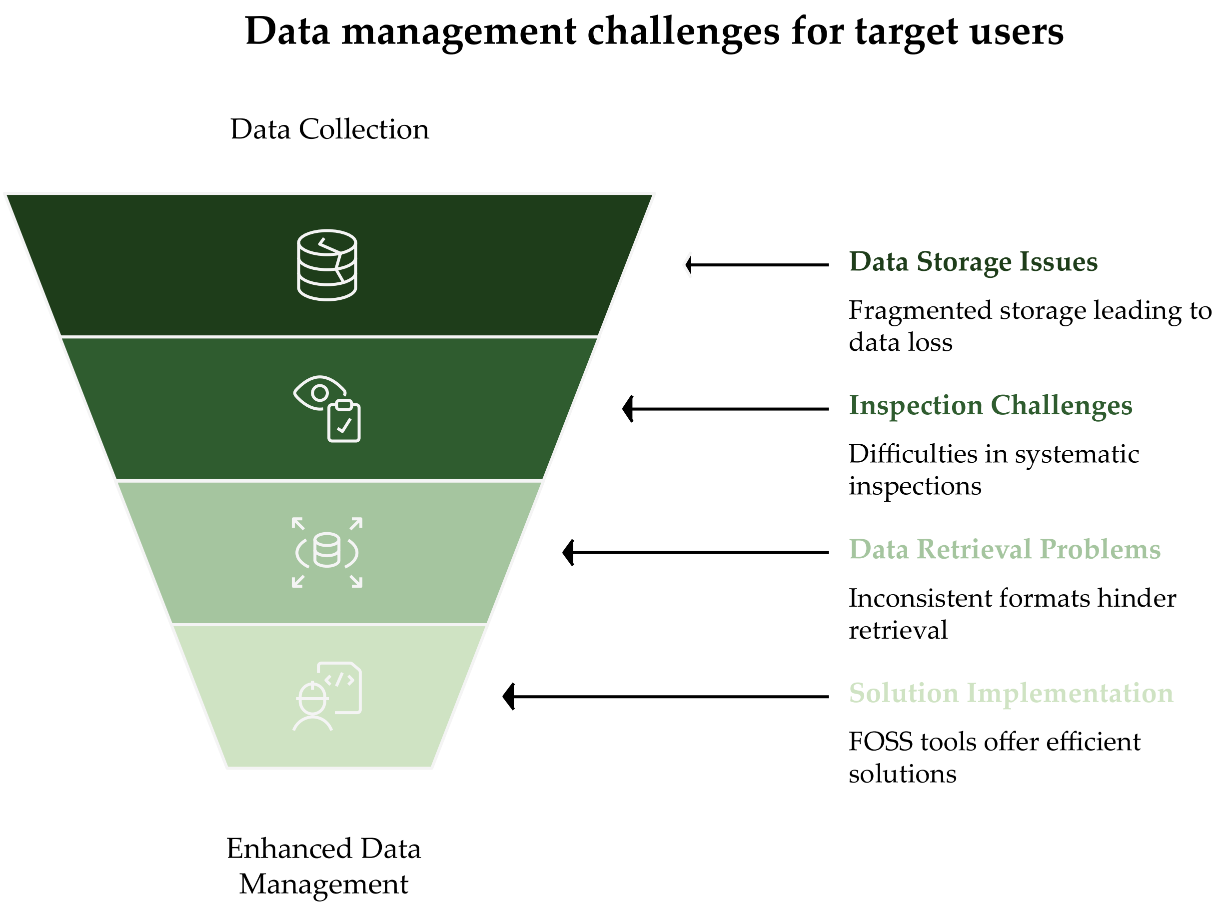


*Figure 9. The inverted pyramid visualises a progressive refinement from broader issues—data storage, inspection, and retrieval—down to the core solution implementation phase. This structure reflects the priorities and practical needs expressed by infrastructure stakeholders and guides the system design from problem identification to functional response.*

## 4.2 Software architecture and functionalities

The technical realisation of the proposed framework is based on a three-tier web architecture designed to ensure modularity and cross-domain interoperability. It is validated iteratively through case studies. As illustrated in Figure 10, the system orchestrates interactions among a client-side interface, a multi-service server layer, and a persistent data storage tier. This structure decouples data storage from user interaction, allowing the system to scale its capabilities according to the user specific needs.

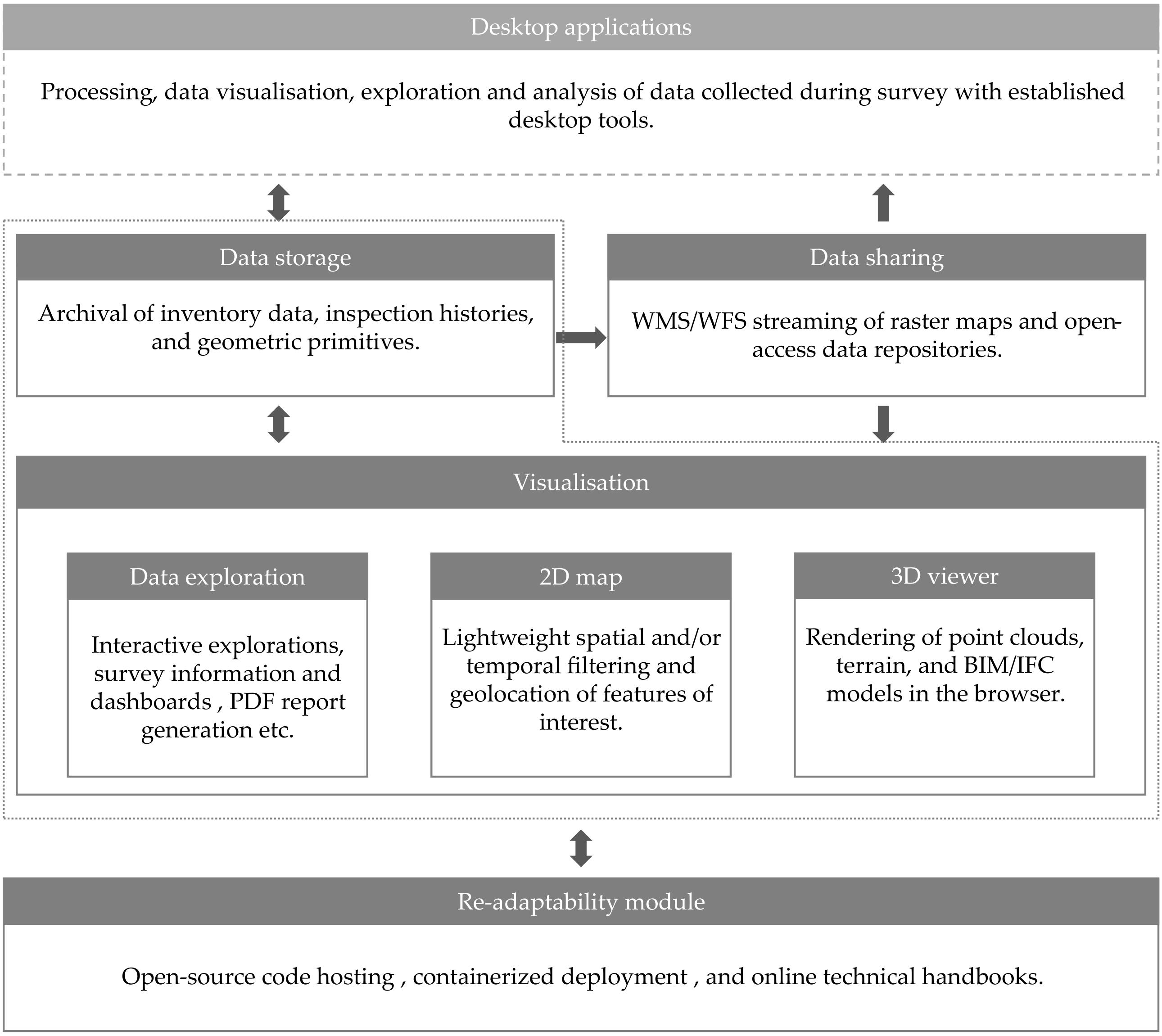


*Figure 10. Proposed three-tier web architecture of the modular framework, illustrating the interaction between the persistent data storage, the server-side orchestration, and the client-side presentation tier.*

### 4.2.1 Data tier and server-side orchestration

Based on the needs of heritage and infrastructure stakeholders, the system must handle massive data while remaining accessible. Hence, the responsibility of the data tier is to ensure data persistence, structural integrity, and spatial indexing while allowing for flexible access as summarised in Figure 11. This layer indeed acts as the "memory" of the framework. Its role is to handle in a flexible way relational queries, manage associations across different domains, and provide a state-aware environment.

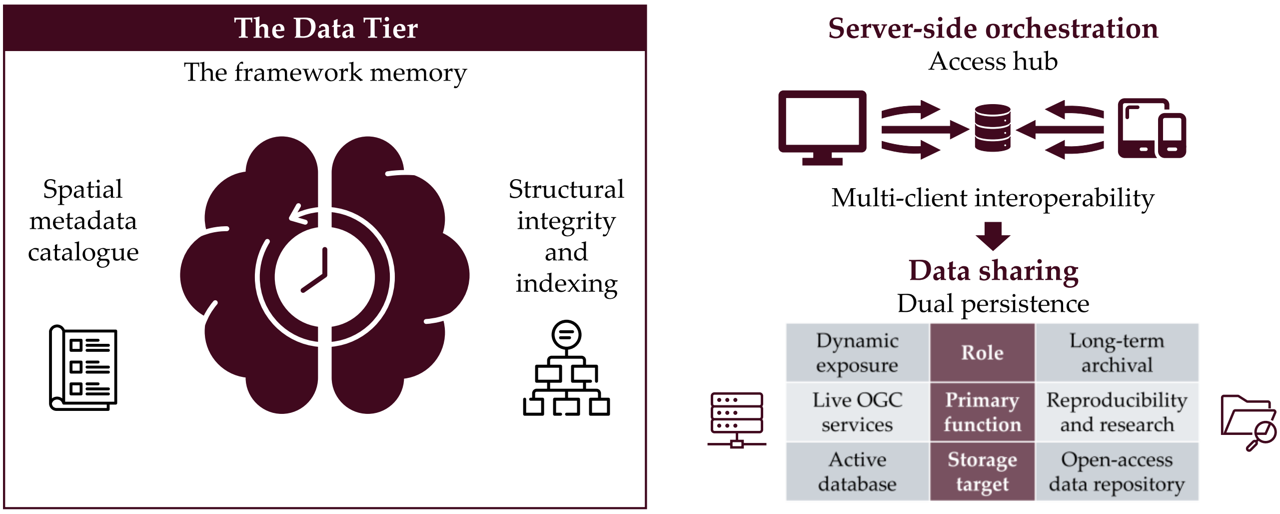


*Figure 11. Overview of the Data Tier (Persistence Layer): a hybrid architecture orchestrating the coexistence of active relational-spatial data management via PostgreSQL/PostGIS and long-term scientific archiving via Zenodo.*

A key feature of this design is the use of the database as a spatial metadata catalogue. Rather than storing massive products (high-resolution images, point clouds, meshes, or BIM files) physically within the database, which would cause significant latency and scalability issues, the system stores them on the web server's file system. The data tier maintains the logical links between these external files and their semantic attributes, ensuring that every geometric asset remains queryable and contextually enriched.

It is worth noting that database-centric solutions, storing for instance point clouds as PostGIS objects, can in principle offer stronger transactional guarantees, unified access control, and simpler backup semantics for large geospatial assets. However, for the data volumes typical of UAV/TLS surveys in the three case studies (tens to hundreds of GB per epoch), it was preferred to avoid in-database storage that could introduce latency in random spatial access, disrupts real-time web streaming of tiled features and affect backup. The hybrid approach adopted here keeps massive geometric assets on the server filesystem in tile-ready formats (octree, 3D Tiles), reachable via path references stored in tables, while semantic and lightweight vector data remain inside the database. The filesystem hierarchy mirrors the database schema: one directory per asset, sub-directories per epoch, immutable filenames linked to the asset's unique identifiers. The main limitations of this design are the lack of native transactional rollback on the file layer, mitigated by Zenodo snapshots for archival epochs, and two access-control surfaces (DB user roles + filesystem access and control list), mitigated by wrapping most write operations behind the PHP transaction layer. As the framework matures towards higher maturity, migration of selected mid-size assets into PostGIS could be evaluated.

The server-side orchestration further incorporates a sharing and persistence component intended to maximise the utility and longevity of the geospatial assets. This component fulfils two distinct operational roles. First, it manages the dynamic exposure of spatial data through standardised map services: this ensures that processed layers are not only rendered within the framework's internal interface but are also fully interoperable with external, industry-standard GIS systems. By acting as a multi-client hub, the framework supports the rigorous, Open Geospatial Consortium (OGC)-compliant data access required for expert-level spatial analysis alongside efficient web-based visualisation.

Second, the architecture integrates a long-term archival strategy to ensure the reproducibility of research and the preservation of historical states. While the active database handles real-time queries and current implementations, a secondary persistence mechanism provides access to static raw datasets and historical product backups. By decoupling the high-frequency operational data from the scientific records stored in dedicated open-access repositories, the framework ensures system performance without sacrificing data transparency. This dual-purpose orchestration, balancing live service delivery with permanent archival access, affirms the framework's status as a robust, open infrastructure capable of supporting the entire data lifecycle from initial survey to public dissemination.

### 4.2.2 Client-server communication

The communication layer serves as the bridge between the data tier and the presentation interface. Its primary responsibility is to manage the bidirectional flow of information through two distinct communication strategies, optimised for the specific nature of the geospatial assets involved.

For massive geometric assets, the framework employs a spatial indexing and streaming logic. This ensures that high-resolution 3D datasets are not downloaded in their entirety but instead, data is delivered in discrete, hierarchical tiles based on the user's real-time field of view. This view-dependent rendering minimises initial loading times and eliminates the hardware barriers traditionally associated with 3D Geomatics, allowing for a more flexible visualisation even on low-bandwidth connections.

For semantic data and interactively generated user contents, the communication layer facilitates asynchronous data exchange. This logic allows the presentation tier to request specific attributes or update the database state (Creade, Read, Update and Delete (CRUD) operations) through dedicated server-side transactional scripts. By mediating these requests independently from the geometric streaming, the framework ensures that the interface remains responsive during complex data operations. This dual-path communication logic effectively decouples the heavy visualisation tasks from the targeted database transactions, ensuring a stable and contextually enriched experience for both public and expert users.

### 4.2.3 Presentation tier and client-side logic

The presentation tier represents the front-end environment where all different data streams converge into a unified, interactive experience (Figure 12). This layer is responsible for the transition from raw data delivery to spatial reasoning and digital storytelling, acting as the primary interface between the complex back-end orchestration and the end-user. By relying on browser-native graphics protocols, this tier eliminates the historical need for proprietary plugins or specialised local hardware, fulfilling the requirement for immediate accessibility across diverse user profiles.

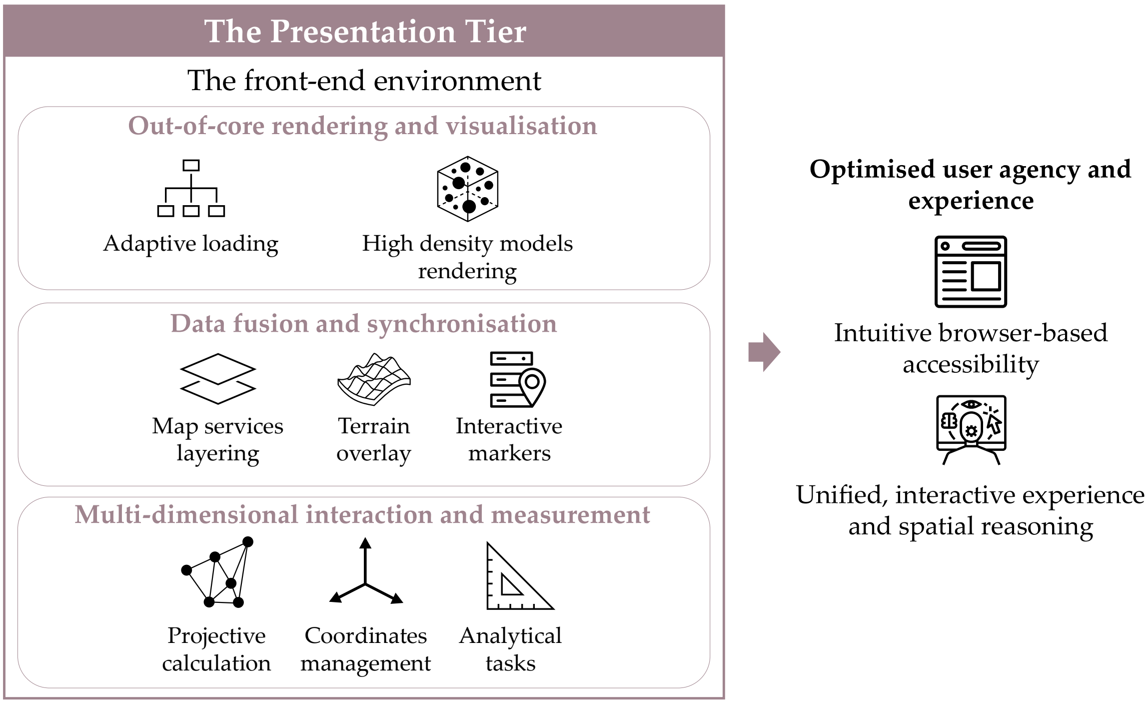


*Figure 12. Core elements of the Presentation layer in the designed framework, ranging from optimised rendering of 3D products to geospatial features management to enhance user agency and experience.*

The core responsibility of the presentation tier is the orchestration of out-of-core rendering. This logical approach ensures that the browser remains responsive even when managing massive geospatial datasets. The client-side logic manages the adaptive loading of hierarchical data structures, requesting higher levels of detail only for specific nodes or tiles within the user's immediate field of view. This optimisation minimises memory consumption while maximizing visual fidelity, allowing for the seamless exploration of high-density point clouds and territorial-scale 3D models.

Beyond visualization, this tier hosts the functional components that enable progressive user agency, intended as the capacity for intentional action and control over the system and its functionalities. The client-side engine performs the real-time synchronization of diverse data sources, effectively "fusing" layers from different origins. For example, the viewer must overlay dynamic raster map services onto the 3D terrain while simultaneously displaying interactive markers retrieved from the relational database. This ensures that the user interacts with a contextually enriched environment where geometric accuracy and semantic information are perfectly aligned.

In more advanced scenarios, such as structural inspections or environmental monitoring, the presentation tier handles the geometric and projective calculations required for multidimensional interaction. This includes the transformation of coordinates between different reference systems, such as the projection of 2D pixel coordinates from oriented imagery into 3D global space. By performing these calculations locally, the framework ensures a high-frequency response rate for analytical tasks—such as measurements, attribute querying, and diachronic toggling. Once an interaction is completed, the logic packages the result into lightweight data objects for transmission back to the server, completing the bidirectional loop of a state-aware management system.

### 4.2.4 Framework distribution and re-adaptability

The final component of the system architecture is not found within the server-side runtime, but in the infrastructure used for its distribution and collaborative development. To ensure that the framework goes beyond the specific case studies presented in this research, a dedicated re-adaptability strategy has been implemented. This involves hosting the source code on public version-control platforms, which serves as the central repository for the platform's development.

The use of a version-control system addresses several critical needs for open-source geospatial research. First, it provides a transparent history of the platform's evolution, allowing for the traceability of code changes and the peer-review of technical implementations. Second, it facilitates modular re-adaptability: the codes of each implemented functionality are structured into distinct modules. This modularity allows other researchers to fork the repository creating an independent copy of the code and adapting specific components to their own hardware configurations or domain-specific needs without having to rebuild the entire framework from scratch.

To support this re-adaptability, the framework technical documentation, handbooks and deployment scripts are shared and made publicly available through repositories (e.g. GitHub, Codeberg). This infrastructure lowers the entry barrier for target users, such as public administrations or research groups, who may lack advanced web-development expertise but wish to deploy the system for their own asset management or environmental monitoring projects. By utilising open-source licensing (such as Massachusetts Institute of Technology (MIT) or General Public Licences (GPL)), the framework ensures that the data silo problem is not replaced by a code silo. Instead, the platform remains an extensible geospatial ecosystem, where the scientific community can contribute, driving the evolution of the tool towards future advancements.

## 4.3 Functional modules

To make the logical roles defined in Section 4.2 operational, a suite of FOSS was selected based on their performance, community support, and adherence to OGC standards.

### 4.3.1 Data storage

The Data Storage Layer acts as the framework's primary repository and state-aware engine, ensuring the persistence of both geometric assets and their associated semantic information. This module is designed as a hybrid storage environment, combining an active relational spatially-enabled database for operational tasks with a persistent archival in parallel for scientific transparency.

The core responsibility of relational and spatial data management is handled by PostgreSQL, an open-source object-relational database management system. It was selected for its high extensibility and ability to handle complex workloads required by multi-user management systems (Stonebraker and Rowe, 1986). To enable geospatial capabilities, the database is extended with PostGIS (Obe and Hsu, 2021), a spatial database extension that allows PostgreSQL to handle geographic objects as native data types. In particular, it adds support for spatial types (such as points, line and polygons) and functions for geometry processing and topological analysis with SQL queriesn (Kaptosv, 2025). Within the designed system, this tool is responsible for the management of tables storing metadata for field survey products (e.g., date, sensor, coordinate system) along with the file path to the web-ready formats.

For long-term scientific transparency, the layer is integrated with Zenodo, a general-purpose open-access repository developed under the European OpenAIRE program and operate by CERN. Unlike traditional databases, Zenodo is designed specifically for the permanent preservation of research outputs. The designed framework uses it as an archival for raw dataset and historical product backups. Each upload is assigned a Digital Object Identifier (DOI), providing a persistent, citable link that ensures the reproducibility of the geomatics workflows described in research documents and projects. By linking the platform to Zenodo, the framework ensures that even if the active web platform is updated or decommissioned, the underlying scientific records remain findable and accessible to the international research community, adhering to the FAIR (Findable, Accessible, Interoperable, and Reusable) data principles.

### 4.3.2 Data streaming and web-ready transition

The main role of this module is to answer the technical challenges in web-based Geomatics affected by the mismatch that occurs when the massive scale of reality-capture products meets the constraints of limited memory and processing power of standard web browsers. Hence, the module is responsible for the data streaming of files into tiled, spatially indexed formats that can be streamed out-of-core, loading only the data relevant to the user's current screen viewpoint and Level of Detail (LOD).

GeoServer is employed as the orchestration engine for standardized map services. It is responsible for exposing vector and raster data through OGC Web Map Service (WMS) protocol, guaranteeing that the framework's internal layers are simultaneously discoverable by external GIS software or other external custom applications. This choice ensures that the framework could be integrated into broader geospatial infrastructures, extending its utility beyond the web platform and facilitating the seamless inclusion of the data in external analytical workflows. Moreover, using WMS, the framework does not force the browser to download monolithic, high-resolution images. Instead, the viewer requests specific bounding boxes of the map at the required resolution. GeoServer processes these requests on the fly, rendering a lightweight image tile that is georeferenced within the viewer scene.

To handle massive survey-derived point clouds, the framework relies on the usage of PotreeConverter, which is responsible for the transition from raw LAS/LAZ formats into a web-ready, multi-resolution octree structure (Schütz, 2015). With this logic, the 3D space is partitioned into hierarchical cells. When the user explores the scene, the client-side viewer requests only the points within the visible partition at a resolution appropriate for the camera's distance. This progressive loading enables the visualisation of datasets containing billions of points without exceeding the browser's hardware-accelerated (WebGL) memory limits. By standardising the point cloud storage in this format, the framework ensures a baseline for dissemination and monitoring, where data is immediately accessible to end users without the need of installing specialised desktop software. For complex 3D scenes produced as meshes and for large-scale digital terrain models, the framework adopts the OGC 3D Tiles standard, primarily rendered through the CesiumJS engine. The standard organises 3D content hierarchically through a spatial data structure (e.g., a quadtree): the viewer automatically switches between low-resolution simplified geometries for distant viewing and high-resolution detailed meshes for close inspection. This approach allows for the integration of large-scale territorial contexts (e.g. terrain and basemaps) with localised detailed reconstruction of structures.

Recognising that BIM data requires a different interaction logic than raw photogrammetry products, the framework incorporates the XEOKIT SDK. While 3D Tiles are ideal for landscape-scale streaming, XEOKIT is specifically adopted for its high-performance handling and querying of IFC-derived models and their properties. Its responsibility within the framework is to manage the semantic granularity of structural assets, especially for the civil infrastructure domain. XEOKIT allows for object-oriented interaction, such as isolating specific bridge pillars, toggling the visibility of internal reinforcements, or querying BIM metadata, while maintaining a high frame rate through specialised geometry compression techniques.

By combining these specialised technologies, the framework ensures that every geomatics product is streamed through the logic most suited to its geometry and intended use.

### 4.3.3 User interface

The graphic user interface is the result of the orchestration environment where disparate data streams converge. The front-end is built using HyperText Markup Language (HTML), Cascading Style Sheets (CSS) and JavaScript (JS), with sub-modules specialised for 2D and 3D geovisualisation, as well as tabular and documental retrieval and dashboard capabilities.

A core component of this layer is the transaction logic mediated by the Hypertext Preprocessor (PHP). PHP scripts act as an asynchronous bridge between the visualisation tier and the data storage layer. Therefore, when a user performs an operation to execute CRUD activities on a specific database record (e.g. recording a structural defect on a bridge), the interface layer packages the request into a JavaScript Object Notation (JSON) object. This lightweight format enables rapid communication, allowing the client to update the database state in real time, visualise additional information relating to an element clicked on a 2D map, print PDF reports with PDFjs integration and access and order all the associated surveys or inspections in a table. It also allows users to load layers of targets measured in an epoch inside a 3D scene, click on them and visualise the associated time series with an ECharts-based panel, leveraging the library's plotting capabilities (Li et al., 2018).

For territorial-scale navigation and 2D data management, the framework adopts LeafletJS, a lightweight and mobile friendly open-source JavaScript library for interactive maps (Crickard, 2014). It can also consume WMS and WFS services provided by GeoServer, allowing for the visualisation of geospatial vector layers and overlay them on standard basemaps like OpenStreetMap or custom ones. This sub-module allows the users like civil infrastructure inspectors, to visualise the distribution of their assets in their cadastre directly retrieved from the underlying database, having an immediate overview of the situation of their managed structures also with custom symbology, filtering, toggling and navigation shortcuts.

The visualization of products and geospatial entities in a 3D georeferenced scene is instead mainly handled by Potree, a WebGL-based renderer specialised for large point clouds. By leveraging the multi-resolution octree structure, Potree enables smooth navigation of billions of points directly in the browser, without the need for plugins, and allows for overlaying with meshes in OBJ or PLY formats, as well as GeoPackage layers. Thanks to its native implementation based on the three.js and PROJ.4 libraries, Potree can manage geodata in different reference systems while ensuring a smooth 3D rendering experience. The 3D viewer sub-module leverages this tool to provide essential metric tools such as distance, area, cross-section extraction and element annotation, supporting the technical needs of expert users. It also supports interactive exploration functionalities such as overlaying oriented 2D images on 3D elements and animations, which are particularly useful for dissemination and storytelling purposes.

To provide a global geospatial context and to render large-scale 3D tiles, the framework integrates CesiumJS. Cesium is an open-source library for globe-based visualisation, capable of handling temporal data (4D) and massive terrain models. Within the framework, Cesium is used to seamlessly load terrain models and meshes. Similar to Potree, its ability to handle different coordinate reference systems ensures that architectural models are perfectly georeferenced within their real-world topography.

For use cases like the civil infrastructure management, the interface incorporates XEOKIT, a high-performance 3D SDK for BIM and engineering visualisation. XEOKIT allows the framework to render complex IFC-derived models while maintaining their semantic hierarchy. Users can interact with the BIM tree, toggle the visibility of structural components (e.g., separating the deck from the piers of a bridge), and access the parametric data associated with each element. This semantic awareness is what transforms the 3D scene from a visual product into a queryable management tool.

## 4.4 Implementation test cases

To demonstrate the inherent flexibility of the proposed modular architecture, this section provides a synthesis of how the framework was configured for the three distinct application domains described in Chapter 2. Table 3 illustrates the activation logic of the functional modules described in the previous sections.

Rather than developing three independent applications, the research implemented a single core engine where specific components were reused (standard features), customised/activated (adapted for domain-specific data). This approach significantly reduces code redundancy and provides a clear roadmap for the rapid deployment of the framework in new geospatial contexts.

The matrix in Table 3 highlights the functional roadmap across the implementations. While the Farnese Castle configuration focuses on high-performance rendering and narrative hotspots to fulfil viewer-only dissemination, the Belvedere Glacier adaptation introduces the 4D temporal dimension and external repository linking for active monitoring and research outputs exploration and querying. Finally, the infrastructure prototype represents the most complex configuration, activating the BIM module and enabling full bidirectional interaction with the database, giving the target users full management capabilities as both writers and consumers of the data.

*Table 3. Detailed overview of the different functional components encompassed by the framework with their responsible tools, role in each case study customisation and type of implementation with respect to the general cross-domain architecture.*

| Functional Component | Library/Tool | Farnese Castle (Heritage) | Belvedere Glacier (Environment) | P.O.N.T.I. (Infrastructure) | Implementation Type |
|---|---|---|---|---|---|
| **2D Mapping Layer** | Leaflet | Active: Site location context. | *Active*: Multitemporal GIS layers. | *Primary role*: Asset network navigation. | Reused / Customised |
| **3D point cloud rendering** | Potree | *Primary role*: High-fidelity documentation. | *Active*: Morphological comparison. | *Active*: Metric support for defects. | Reused |
| **3D Mesh & Terrain** | CesiumJS | *Not active* | *Active*: Contextual surroundings. | *Active*: Contextual surroundings. | Reused / Customised |
| **BIM / IFC Support** | XEOKIT | Not active | Not active | *Active*: Structural logic. | Activated |
| **Spatial Database** | PostGIS | Not active | *Active*: Read-only scientific queries. | *Primary role*: Full CRUD operations. | Customised |

| Functional Component | Library/Tool | Farnese Castle (Heritage) | Belvedere Glacier (Environment) | P.O.N.T.I. (Infrastructure) | Implementation Type |
|---|---|---|---|---|---|
| **Interaction Layer** | PHP / JS API /Potree | *Primary role*: Storytelling & Hotspots. | *Active*: Data download & Charts. | *Primary role*: Defect tagging & Reporting. | Customised |
| **Scientific Archiving** | Zenodo | Not active | *Primary role*: Open-access DOI linking. | Not active | Activated |

The progressive configuration of the framework is further detailed in Figure 13, 14 and 15, which illustrate the specific activated modules and their interactions for each domain. These diagrams show how the core engine, which includes the data storage, streaming, and interface modules, is tailored to transition from the narrative-focused design of heritage sites to the operational management system platforms required for infrastructure.

This modular configuration ensures that the framework remains lightweight: only the necessary libraries and server-side connections are initialised for a specific case, optimising performance while maintaining a common code base and library set. This architectural strategy allows for a scalable digital transition, where a stakeholder can begin with a simple visualisation module and incrementally add management or monitoring features as their organisational needs and technical readiness evolve.

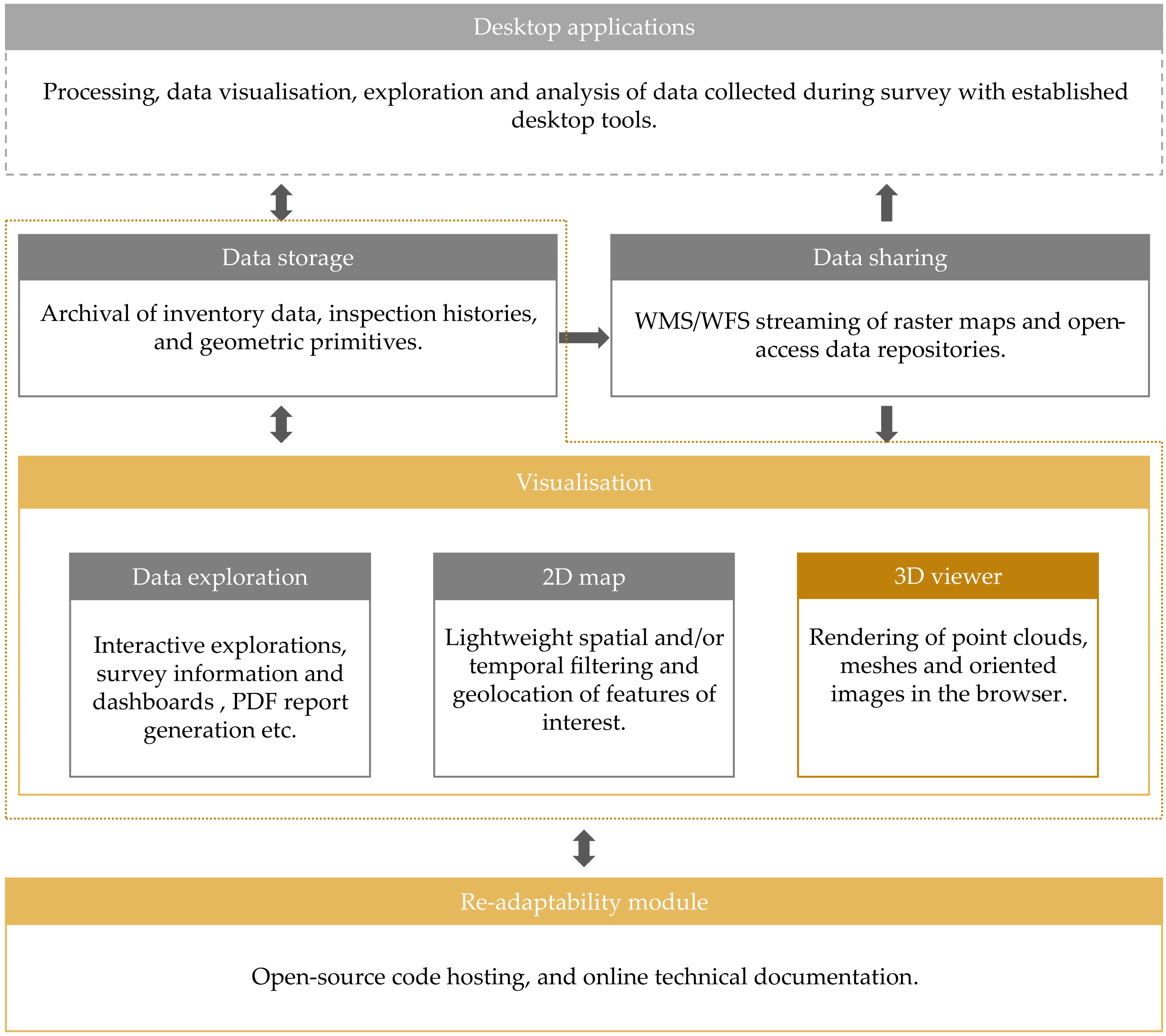


*Figure 13. Updated schema of the proposed three-tier web architecture of the modular framework, with customised and tested component for cultural heritage highlighted in yellow.*

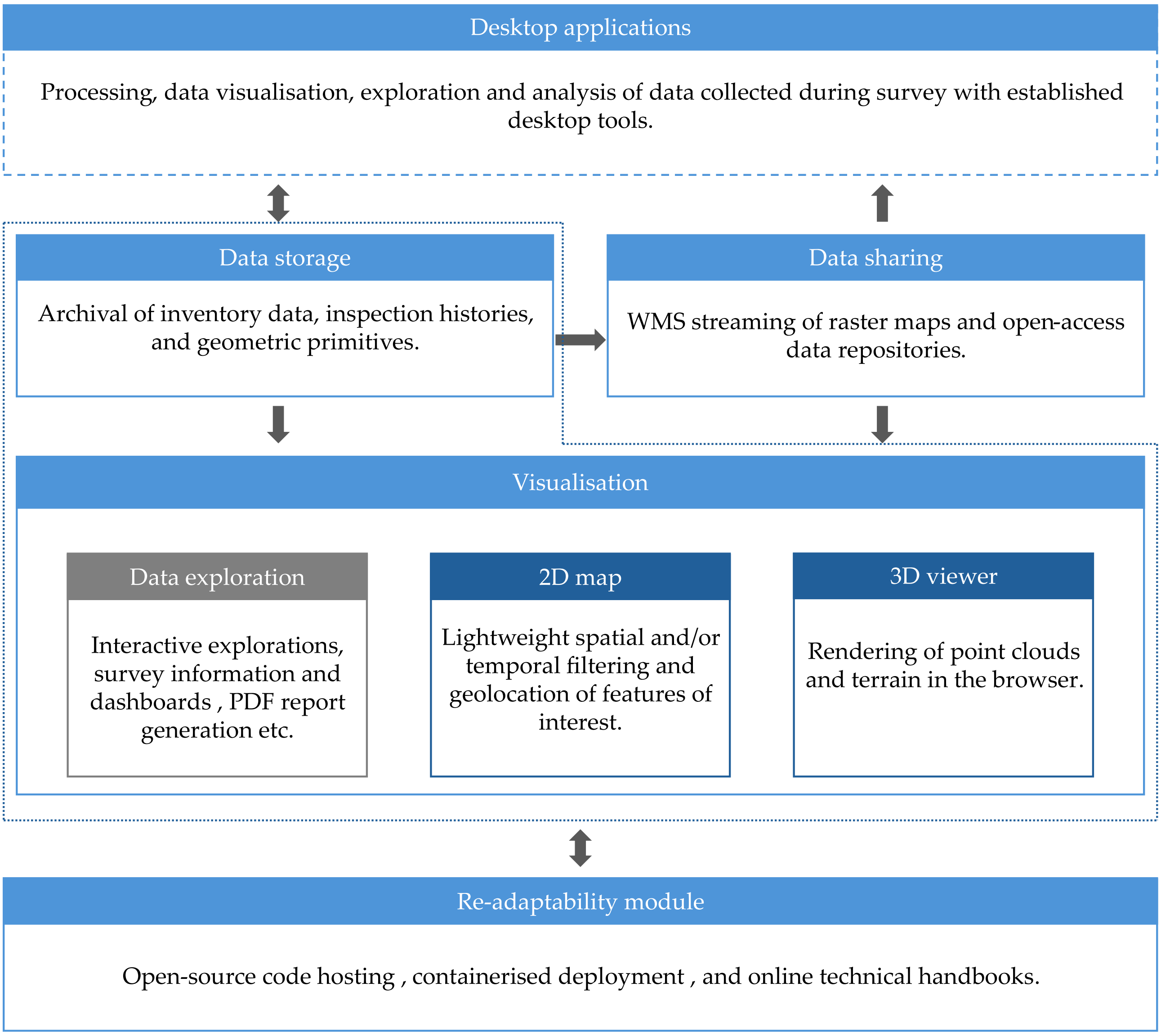


*Figure 14. Updated schema of the proposed three-tier web architecture of the modular framework, with customised and tested component for natural environment highlighted in blue.*

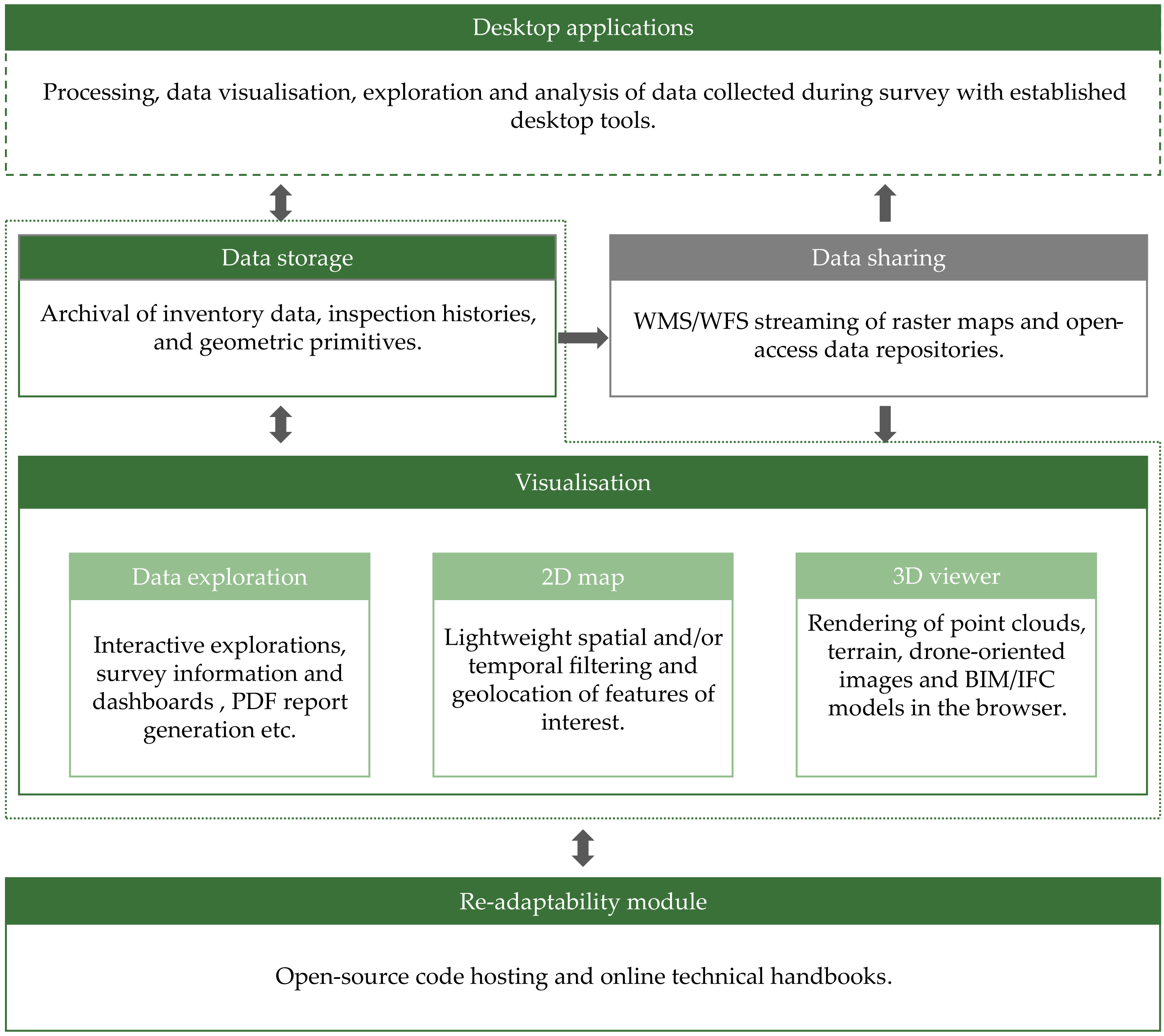


*Figure 15. Updated schema of the proposed three-tier web architecture of the modular framework, with customised and tested component for civil infrastructure highlighted in green.*

# 5

# Implementations

*Implementing and customising the framework for cultural heritage storytelling, glacier monitoring and bridge assets management.*

This chapter is based on:

- **Gaspari, F.**, Barbieri, F., Fascia, R., Ioli, F., & Pinto, L. (2024). An Open-Source Web Platform for 3D Documentation and Storytelling of Hidden Cultural Heritage. Heritage, 7(2), 517-536. https://doi.org/10.3390/heritage7020025
- **Gaspari, F.**, Barbieri, F., Fascia, R., Ioli, F., Pinto, L., & Migliaccio, F. (2025). Strategies for Glacier Retreat Communication with 3D Geovisualization and Open Data Sharing. *ISPRS International Journal of Geo-Information*, 14(2), 75. https://doi.org/10.3390/ijgi14020075
- **Gaspari, F.,** Fascia, R., Barbieri, F., Roman, O., Carrion, D., Pinto, L. (2025). A 3D WebGIS Open-Source Prototype for Bridge Inspection Data Management. *Geomatics*, 5(4), 68, https://doi.org/10.3390/geomatics5040068

This chapter details the practical application and customisation of the proposed open-source geospatial framework across three highly heterogeneous domains: cultural heritage, the natural environment, and civil infrastructure. By moving from theoretical design to real-world deployment, this chapter demonstrates the framework's modularity and capacity to solve domain-specific data silo problems. The implementations shift progressively in terms of user agency and system memory: from a stateless exploratory viewer designed for historical storytelling at the Farnese Castle, to a read-only state-aware platform for 4D environmental monitoring of the Belvedere Glacier, and finally to a fully transactional, bi-directional management system for bridge inspections via the P.O.N.T.I. prototype.

## 5.1 Cultural heritage implementation

### 5.1.1 Objectives and customisation logic

The primary objective of this customisation is to digitally document the current state and construction history of a cultural heritage site with limited accessibility, developing a user-friendly web viewer for 3D exploration. To accommodate both technical experts and non-specialists, the system relies on open-source WebGL solutions (specifically Potree) to create a low-cost, easy-to-implement platform that breaks down the barriers of proprietary software or expensive VR hardware. The customisation logic focuses on interactive storytelling, allowing users to explore the site's architectural evolution dynamically without requiring advanced 3D navigation proficiency. Indeed, the primary requirement is to bridge the gap between high-resolution metric documentation derived from a dedicated survey and public dissemination through a stateless WebGL viewer, making accessible the outdoor scene of the castle remains as well as a portion of the indoor environment of one of its bastions in a virtual low-code environment. Hence, the customisation focuses particularly on the 3D viewer component for data exploration, testing is flexibility for integrating both technical and multimedia features. This involves the integration of massive point clouds and 3D meshes of the historical reconstructions into a single interactive scene, supported by a specialised spatio-temporal storytelling layer composed of interactive hotspots and actions in the 3D scene (Gaspari et al., 2023b). Furthermore, this case study tests the re-adaptability module through the public release of the template code and technical documentation, ensuring that the developed storytelling strategies can be reproduced in other heritage contexts. By prioritising intuitive navigation and immersive exploration, this implementation serves as a common ground where the general public can access hidden heritage, providing a friendly access to digital documentation and site history dissemination. Additionally, expert users can utilise native metric tools to quantify distances, areas and volumes. This leaves open the possibility of using more technical tools in the future, should restoration or renovation interventions involving architects or engineers be planned, who may be interested in a preliminary assessment of the site.

### 5.1.2 Input data and preparation

In order to better understand the context and the evolution of the case study site, in a preliminary phase following the discussion with the Ente Farnese cultural association, an investigation on the historical archives, as well as an in-situ data collection was conducted. These approaches provide the basis for reconstructing the previous and the current conditions of site, associating them to specific epochs. The main steps of the data input and preparation are summarised in Figure 16.

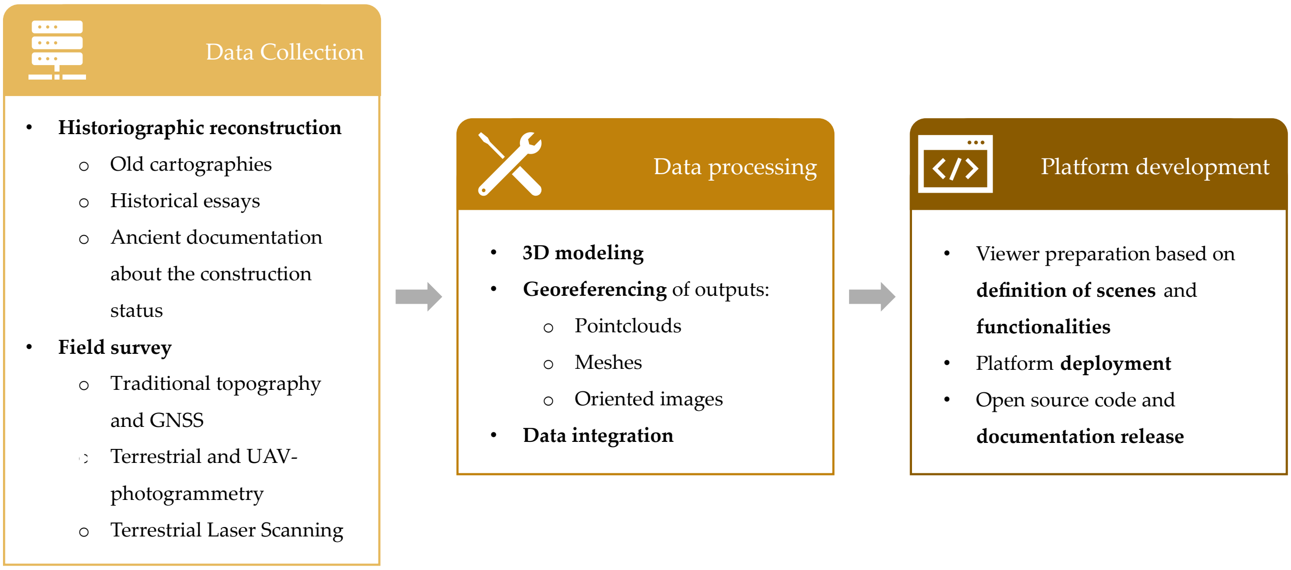


*Figure 16. Workflow with progressive steps of processing from data collection to viewer implementation and deployment.*

The first step aimed to reconstruct the historical development and construction phases of the site. Archival sources, ancient cartography, and historical documentation were analysed to understand the broader cultural context and to identify the main stages of construction as part of the thesis project developed by Architecture students from Politecnico di Milano, Piacenza campus (Dondi and Rivieri, 2021). These sources were used to create 3D models that reproduce the evolution of the site between 1547 and 1553, the epoch of the construction, as well as the partial demolition of some of its parts that began in the 19th century. The models were generated using AutoCAD and SketchUp for 3D modelling and rendering and initially referenced in a local coordinate system.

The current state of the Farnese Castle was reconstructed by integrating different surveying approaches, including UAV and terrestrial photogrammetry and TLS for 3D reconstruction, traditional topography and Global Navigation Satellite System (GNSS) for defining a common reference system and georeferencing of the different datasets. The procedure carried out for the Farnese Castle 3D survey is illustrated in Figure 17.

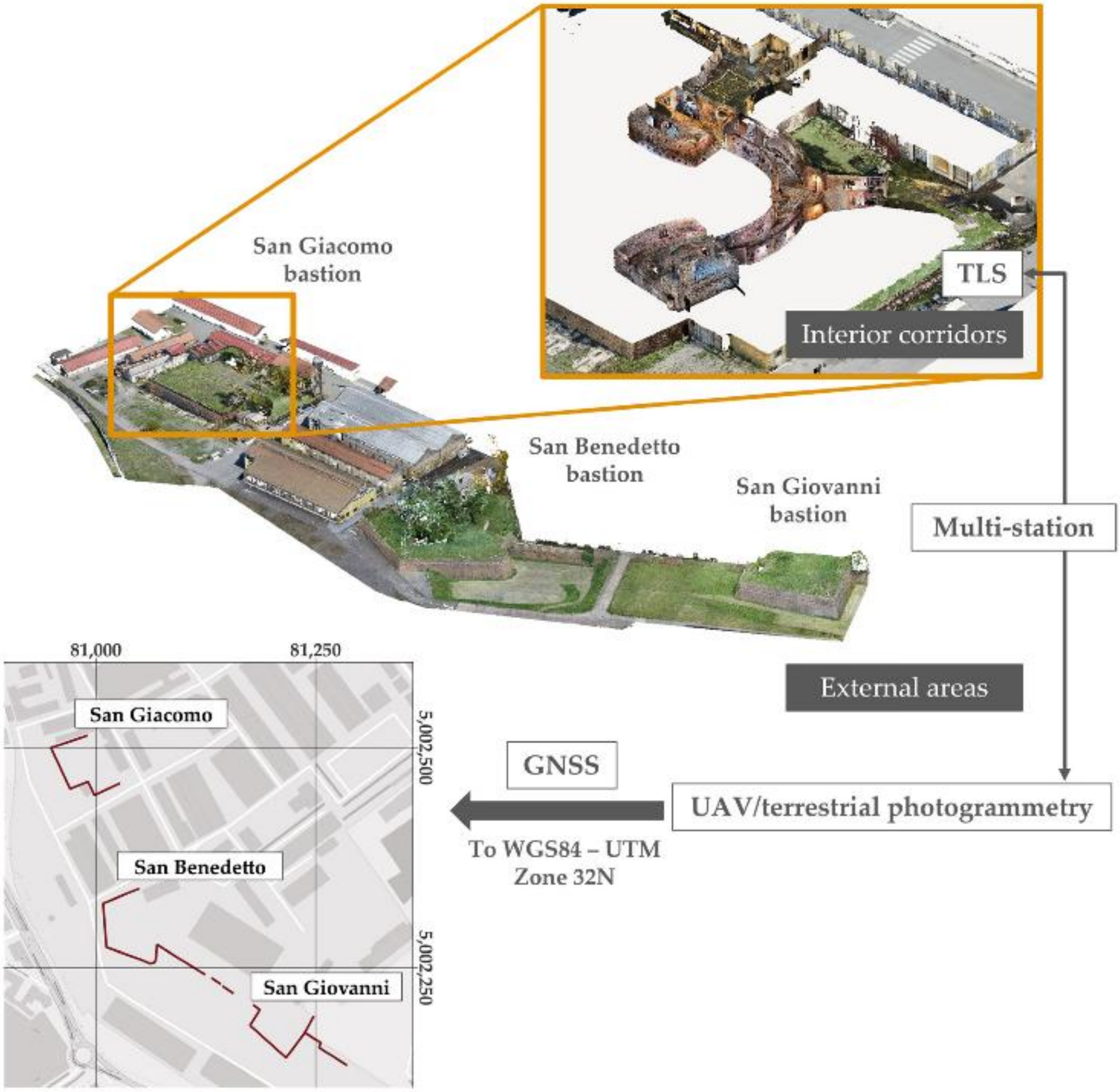


*Figure 17. Scheme of the study areas and distinction of the different survey techniques used for data collection (from Gaspari et al., 2024a).*

To reconstruct the exterior area of the three bastions San Giovanni, San Benedetto and San Giacomo, two UAV photogrammetric surveys were conducted with off-the-shelf quadcopters DJI Phantom 4 RTK and Mavic 2 Pro. Phantom was used for the nadiral flight to cover the entire area, while Mavic 2 was used for the oblique acquisition of pictures closer to the structure. A total of 780 images, including 570 nadiral and 210 oblique images, were acquired to cover an area of ~59 000 m2. In addition to the UAV images, 240 images were acquired by a compact hand-held Nikon Coolpix S3500 camera to gain a closer view of the lower parts of the bastions' walls. To georeference the photogrammetric block, a set of 35 targets was deployed over the site both on the ground and on the walls, to properly constrain both the nadiral and oblique images. The location of the targets was measured in a local reference system by a multi-station Leica MS60. The multi-station was used to build a closed polygonal network covering the whole study site, from which all the targets were measured. Among the 35 targets, 24 of them were used as Ground Control Points (GCPs), while the remaining 9 were used as Check Points (CPs) to evaluate the accuracy of the photogrammetric block (Figure 18). The interior corridors of the San Giacomo Bastion were reconstructed by 14 TLS scans acquired with a Faro Focus M70. To link together the photogrammetric block of the external areas and the TLS scans of the interior corridors, 2 additional targets were strategically positioned on the corridor walls. These targets were placed to ensure visibility from the exterior through the corridor's windows and loopholes and were measured by the multi-station within the same local reference system employed for the photogrammetric block. Additionally, three out of the 14 scans were specifically acquired to provide overlaps with the UAV-point clouds of the outer backyard of the San Giacomo bastion.

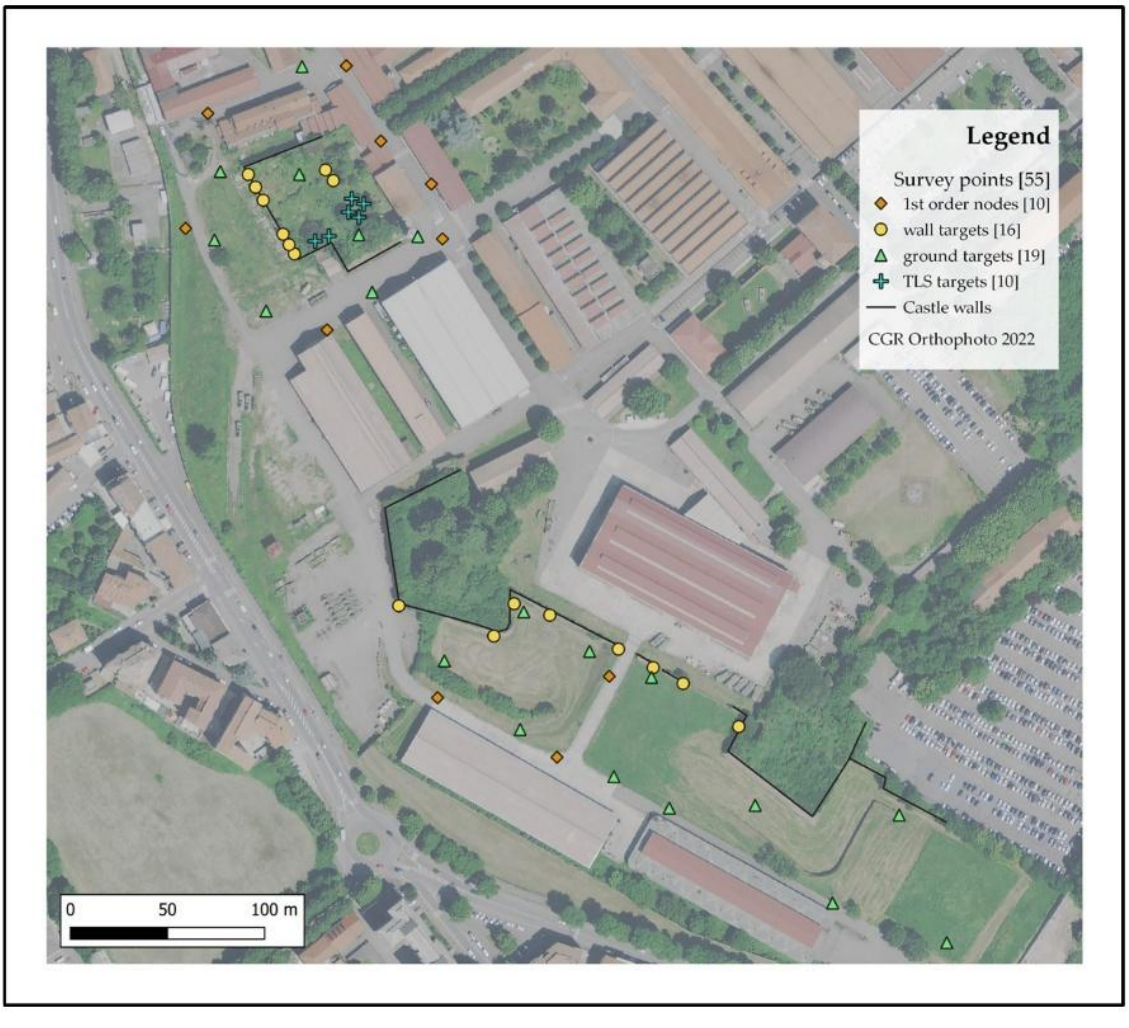


*Figure 18. Orthophoto of the case study area with the survey points. The 1st order nodes of the topographical network represent the positions of the stations from which measurements were taken with the total station of the targets on the*

*ground and on the walls of the structure. Ground targets were also measured with a GNSS receiver. Inside the San Giacomo Bastion a set of additional targets was used to interlink the indoor TLS scans (from Gaspari et al., 2024a).*

The collected datasets – historical 3D models, UAV and terrestrial photogrammetry, TLS scans, and topographic and GNSS measurements – were integrated into a unified georeferenced framework. The processed products included dense point clouds of the current state of the site, 3D meshes for the reconstruction of historical construction phases, and ancillary datasets from the photogrammetric processing such as georeferenced images with their orientation parameters. These outputs formed the basis for the interactive geovisualisation in the web 3D scene.

The full photogrammetric block was processed with Agisoft Metashape to derive a dense point cloud of the exterior areas of the Farnese Castle. For images taken with the DJI Phantom 4 Real-Time Kinematic (RTK), the perspective centre coordinates were used to better constrain the location of the cameras within the bundle block adjustment step in Metashape. All the scans were co-registered by the Iterative Closest Point (ICP) algorithm on overlapping areas (Zhang, 1994) using the scanner's proprietary software, Faro Scene. All the point clouds were roto-translated from the local reference system to the official Italian reference system World Geodetic System 1984 (WGS84) – Universal Transverse Mercator (UTM) Zone 32N by measuring six on-ground targets both with the multi-station and with a topographic-grade GNSS receiver Leica GS14, employed in nRTK mode. Finally, the co-registered point clouds were merged and subsampled to have a homogenous point spacing of ~2 cm. The resulting point cloud was further manually cleaned by using CloudCompare to remove spurious or unnecessary points. Considering as a reference the resulting in-situ survey derived point clouds, the 3D model of the historical phases resulting from SketchUp were georeferenced in CloudCompare through roto-translation by aligning them with the surveyed geometry of the existing remains.

The 3D digital reconstruction of the construction phases resulted in a series of nine meshes representing the evolution of the Castle according to the original plans and maps of Piacenza. This series of 3D objects included both the states of the site corresponding to the main historical phases depicted in Figure 2 as well as additional models with intermediate structural changes reported in the literature and old maps. The originally designed proportions of the bastions and curtain walls were maintained due to the lack of quantitative information on changes during construction. The models were georeferenced into the WGS84/UTM Zone 32N reference system by manually collimating peculiar features (e.g., bastion corners) visually recognisable both in the historical and in the UAV point cloud (Figure 19).

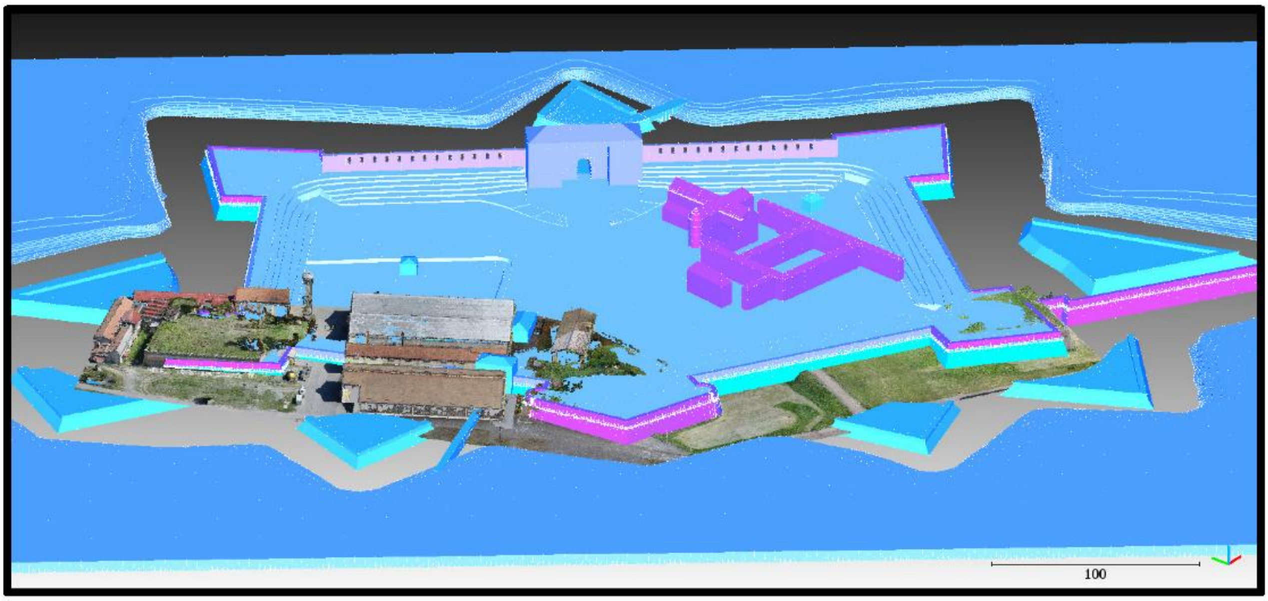


*Figure 19. Historical 3D reconstruction of the Farnese Castle inserted in the same reference system of the survey point clouds after the georeferencing in WGS84/UTM Zone 32N (from Gaspari et al., 2024a).*

The external areas of the three bastions, San Giacomo, San Giovanni, and San Benedetto, were reconstructed by integrating UAV and terrestrial images into a cohesive photogrammetric block, processed using Agisoft Metashape. The accuracy of the photogrammetric block was evaluated based on nine CPs not used in the bundle adjustment, yielding an RMSE of 3.5 cm (Table 4). The resulting photogrammetric point cloud comprised 85 million points.

*Table 4. Statistics on the residuals computed on 24 GCP and 9 CP coordinates after photogrammetric processing (from Gaspari et al., 2024).*

| | GCPs | | | CPs | | |
|---|---|---|---|---|---|---|
| | **East** | **North** | $h_{ell}$ | **East** | **North** | $h_{ell}$ |
| **Average (m)** | -0.001 | 0.005 | 0.002 | 0.003 | -0.001 | 0.002 |
| **σ (m)** | 0.008 | 0.01 | 0.013 | 0.01 | 0.028 | 0.018 |
| **RMSE (m)** | 0.008 | 0.011 | 0.013 | 0.011 | 0.028 | 0.018 |

The TLS survey consisted of 14 scans of the San Giacomo Bastion interior corridors and a portion of the outer wall. The resulting point cloud, consisting of approximately 145 million points, included RGB colours derived from the TLS camera and laser return intensity for each point. The co-registration of TLS scans, based on the ICP algorithm and aided by four targets measured with sub-centimetric accuracy with the multi-station MS60, resulted in a Root Mean Squared Error (RMSE) of 1.2 cm in overlapping areas.

The coherence between the photogrammetric and TLS point clouds was evaluated in an overlapping portion of the outer San Giacomo Bastion wall by a cloud-to-cloud comparison using CloudCompare. This analysis yielded an RMS of distances between the point clouds of 1.8 cm, which is comparable to the accuracy of the photogrammetric models and the TLS registration error. The final unified and subsampled point cloud of Farnese Castle comprised 32 million points, with an average point spacing of 2 cm and centimetric accuracy.

The following transition to web-ready format started with the conversion of the georeferenced point cloud resulting from the in situ survey in the Potree-supported octree format through the dedicated

PotreeConverter tool. Hence, a basic HTML index page was configured in order to include in the web page the Potree render area for the visualisation of 3D objects, as well as its sidebar that contains native tools for making measurements, extracting cross-section and volumes from a point cloud.

### 5.1.3 Interface and viewer structure

The viewer interface was designed to offer an accessible and interactive environment for both technical users and non-specialists. It utilises a layered navigation approach that accommodates both casual and professional users through distinct interaction paradigms. The general public is provided with simple and intuitive georeferenced storytelling, while cultural heritage professionals from various disciplines are equipped with essential quantitative tools for information extraction and evaluation of 3D products within a shared environment. The main principles for the adopted dual-audience design are summarised in Figure 20.

Target users and platform functionalities

| | General public | Professionals |
|---|---|---|
| **Navigation** | Guided hotspots navigation | Autonomous 3D exploration |
| **Spatial understanding** | Pre-defined camera animations | Dual-scene architecture (indoor and outdoor) |
| **Temporal understanding** | Fixed-shortcuts to distinct epochs | Multi-modal data integration custom menu |
| **Graphic features** | Static multimedia pop-up panels and carousels | Oriented images projected on the 3D products |

*Figure 20. Detailed description of the viewer features best aligned with the target user groups, supporting their friendly exploration of the cultural heritage site.*

For general public, the system features dedicated hotspots guided navigation, relying on a streamlined control interface that presents predetermined viewpoints of significant heritage portions (Bastione San Giovanni, San Benedetto, San Giacomo). Users traverse these designated locations through directional controls or via drop-down menu selection. Automated camera trajectories provide predetermined walk paths through interior spaces, circumventing requirements for manual three-dimensional navigation proficiency and spatial understanding. Regarding the temporal dimension, a diachronic visualisation functionality enables exploration through a dedicated interface element that sequences nine distinct construction epochs (spanning "Before 1547" through "May 1553"), facilitating observation of the structure's architectural evolution. Finally, minimal graphic overlays deliver multimedia content panels containing archival imagery and contextualised historical information. Interactive markers activate these overlays; for instance, orbital icons reveal period engravings accompanied by descriptive annotations.

Professional users interested in evaluating the site in a critical and quantitative way, instead, can use the platform as a tool that facilitates heterogeneous data synthesis, integrating multi-source datasets, and historically informed reconstruction geometries within a unified visualisation environment. Dual scene configuration employs distinct exterior and interior environments optimised for their respective survey methodologies (UAV-based versus TLS-based acquisition), incorporating fluid transitional mechanisms between spatial contexts. With the standard WebGL controls, unrestricted spatial exploration preserves complete viewer native functionality for specialists requiring autonomous navigation capabilities, with operational documentation accessible through contextual help interfaces. Finally, georeferenced imagery provides UAV-survey photographs with embedded spatial metadata, enabling professionals to correlate three-dimensional datasets with source documentation, accessible through dedicated toggle controls directly in the 3D context.

As a consequence of the target users' needed functionalities, three main components were identified for the following implementation of the platform. Figure 21 illustrates a 3-step architectural framework for the standalone-viewer customisation, structured around three complementary yet functionally distinct layers:

1. The visualisation engine layer establishes the foundational rendering infrastructure, concerning scene management protocols for differentiated spatial contexts, geometric asset configuration, and the implementation of interaction functionalities. This layer represents the technical substrate upon which user-facing features are constructed.
2. The interpretive interface layer addresses the challenge of knowledge dissemination through spatio-temporal narrative strategies. This component bridges the gap between raw three-dimensional data and meaningful cultural content by integrating curated navigation pathways, accessibility-oriented interaction shortcuts, and enriched multimedia resources. The approach reflects a user-centred design philosophy that offer comprehension over technical complexity also to casual visitors of the platform.
3. The sustainability and transferability layer demonstrates a commitment to open science principles and long-term viewer viability. By emphasising code transparency and comprehensive technical documentation, this component facilitates both methodological reproducibility and adaptation to alternative heritage contexts, which represent critical considerations for research infrastructure in the digital humanities, giving additional higher-level tools for interested professionals.

This architecture enables simultaneous service to diverse stakeholder communities (public audiences versus specialist researchers) while maintaining system coherence, a design principle increasingly recognised as essential for sustainable digital heritage platforms.

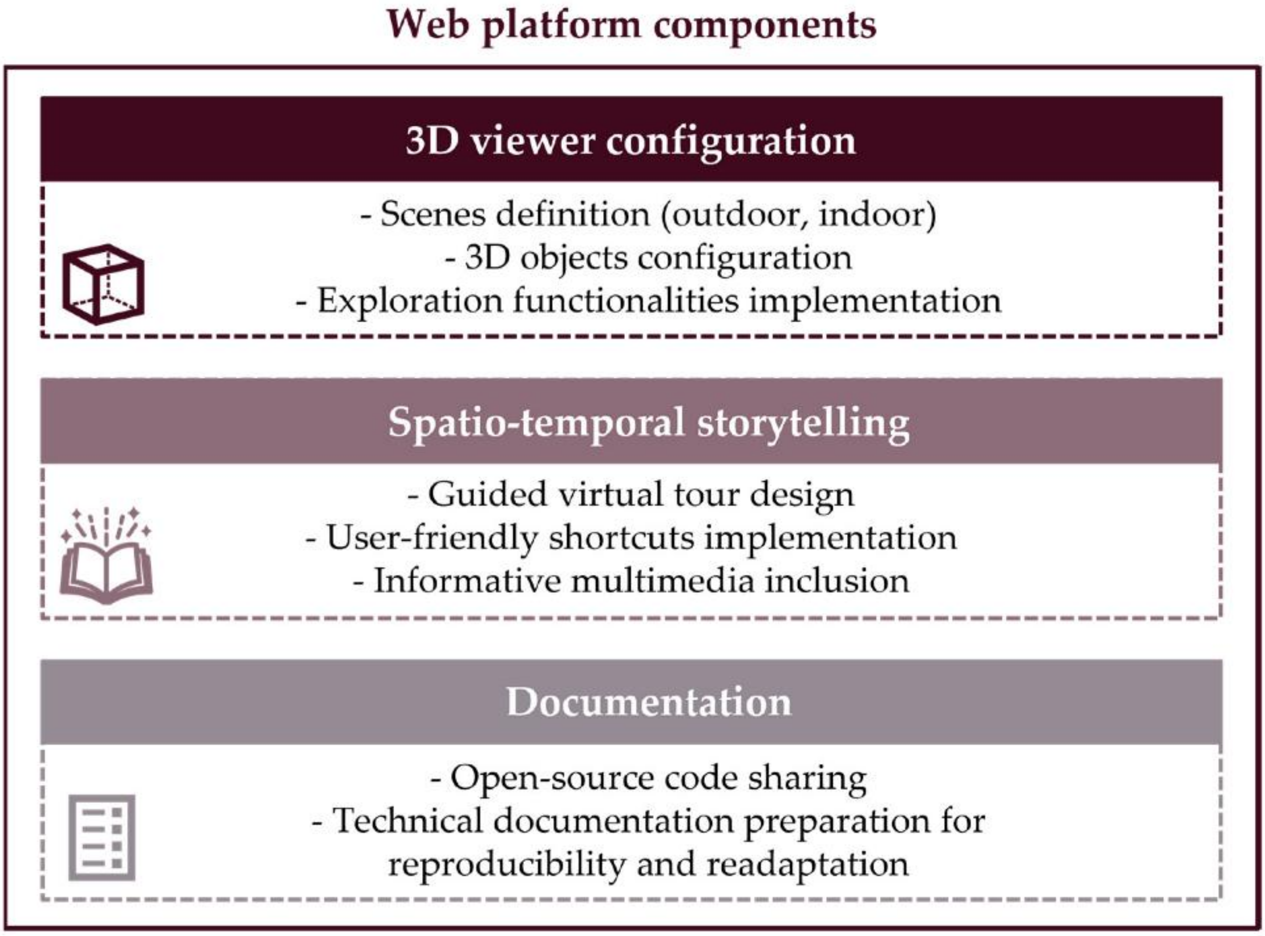


*Figure 21. Schema of the different components of the castle implementation. Each of them is responsible for the implementation, usability, and reproducibility of the project (from Gaspari et al., 2024a).*

The first essential step in implementing the web viewer is to configure the lightweight web space that enables 3D object exploration. In the framework defined in Chapter 4, the tool adopted for this purpose is the open-source WebGL Potree, optimised for the web-based rendering of dense point clouds like the ones resulting from the castle survey. In this environment, the point cloud is added to the main scene in the render area, already enabling the native functionalities of the viewer, such as pan, zoom and rotation.

In order to include other georeferenced multimedia and informative objects in the viewer, two distinct scenes are then considered (Figure 22): the outdoor one to exploit the visualisation potential at the entire cultural heritage site scale, and the indoor one for the exploration of the more detailed environment inside the surveyed castle rampart. This choice is motivated by the need to subsequently define specific storytelling strategies at different scales, as well as to ensure optimised computation and rendering of 3D objects by efficiently regulating their visibility on the screen.

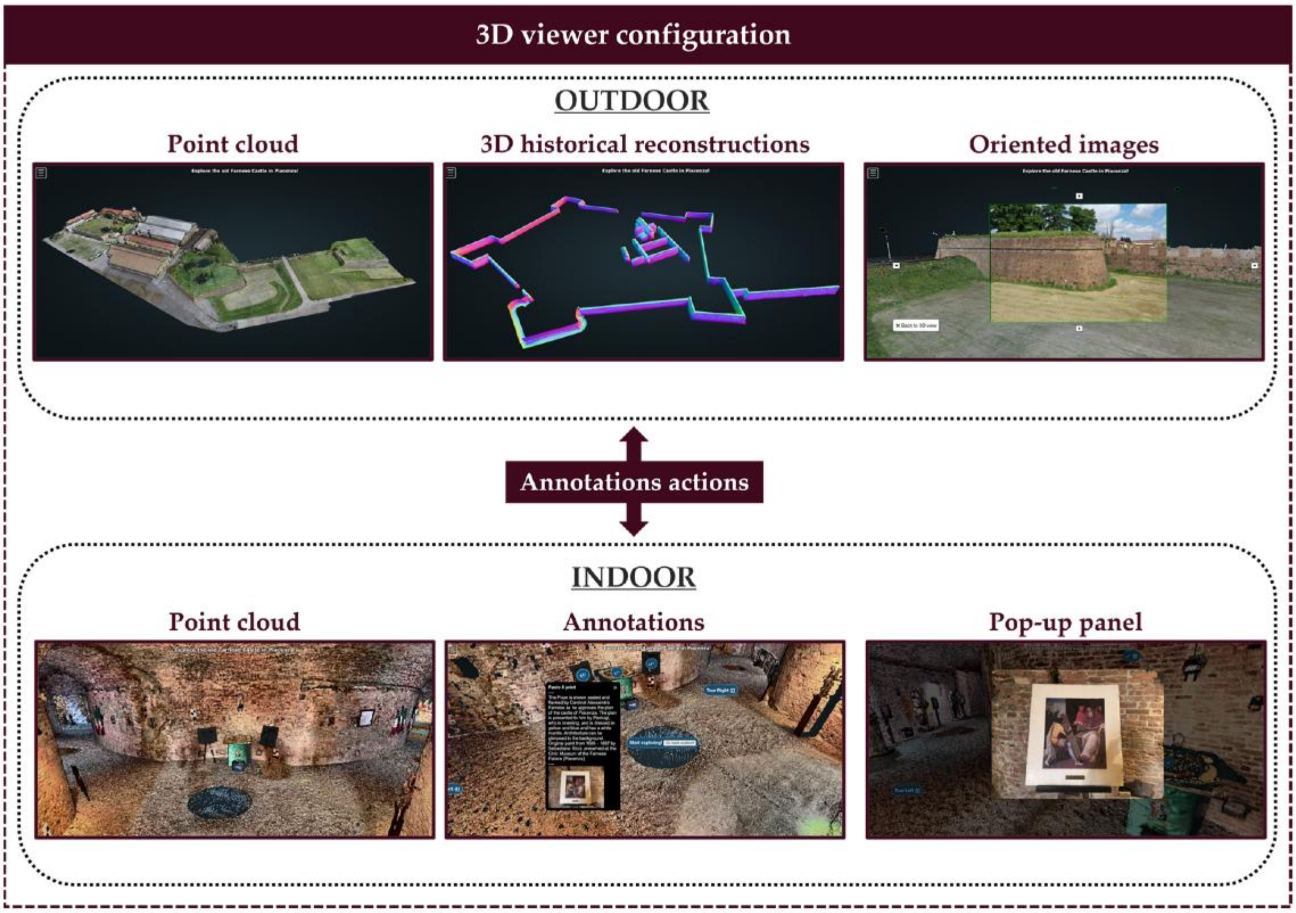


*Figure 22. Configuration structure of the 3D viewer in the platform, composed of objects inserted in two different scenes for the outdoor and indoor environments, interacting with each other through dedicated actions (from Gaspari et al., 2024a).*

Different types of objects are included in the two scenes. In particular, in the outdoor scene the point cloud of the current state of the site (the remaining visible three ramparts) is loaded and set as visible alongside the 3D historic reconstruction models of the entire castle. Also, the same scene includes oriented images, e.g., photos taken by drones or ground cameras and used for the 3D reconstruction process, obtaining their orientation parameters (projection centre, camera position and angles at the time of each shot). The result of such an operation is the ability to click on a given oriented image positioned in the outdoor scene and evaluate it in detail in a 2D view, also making measurements on it that are coherently projected onto the 3D point cloud.

The indoor scene contains a point cloud set as visible representing the 3D interior environment of the inspected rampart. Such a georeferenced product serves as the starting point for inserting annotations in the scene to support user navigation. Properties of such annotations are pre-defined statically in the code, defining through JSON structure their position coordinates, the content of their pop-up panels in HTML and eventually an "effect" that can be triggered when they are clicked. For example, when clicking on some of the indoor annotations, users can start the exploration with guided camera views of objects or artefacts of interest in the indoor environment. Moreover, each annotation is associated with a descriptive multimedia panel that contains additional information on the historical or cultural context of the linked element. Alternatively, a dedicated fixed pop-up appearing on the scene can be associated with chosen annotations, highlighting particular elements.

Finally, the spatial interaction between the indoor and the outdoor scenes is managed by inserting special annotations with actions, i.e., icons that, when clicked, activate a camera transition from the outdoor to the indoor environment or vice versa. Depending on the scene that is the target of the actions, the visibility of specific objects and entities on the viewer is then automatically changed based on pre-defined coded settings. The possibility to autonomously change the visibility of given objects is always given to the users through the native Potree sidebar for advanced functionalities.

The simple setup of the Potree environment with both the viewer and the sidebar provides essential exploration tools for those who are already familiar with the library. However, the non-technical audience still lacks user-friendly shortcuts and facilities that make the point cloud format more understandable or allow easy interaction with each scene. For this purpose, the basic Potree interface has been updated with custom Graphic User Interface (GUI) features, like buttons, sliders, dropdown menus, and interactive texts (Figure 23).

In particular, six main buttons are included in the main GUI, providing the users with easy access to interactive functionalities. Some of them allow users to enter full-screen mode, make the navigation instructions panel visible or reload the page. Other custom buttons make it possible to show a small OpenStreetMap (OSM) map highlighting the position of the bounding box of the loaded scene and to change the visibility of the oriented images in the outdoor scene. A special storytelling function is provided by the "rewind" button, which, through successive clicks, changes the visibility of the 3D objects—either point clouds or meshes—showing the evolution of the Farnese Castle complex from 1547 to the present day. To make it easier to understand this functionality, each click is associated with the appearance of a dynamic text on the right-hand side of the screen with the name of the historical phase represented by the model being displayed. Then, in order to facilitate the spatial exploration of the cultural heritage site, a navigation bar is configured to allow navigation through predefined hotspots of interest by clicking left and right arrows. Additionally, a dropdown menu accessible by clicking on the navigation bar is available, making it possible to switch the camera view to the desired hotspot on the scene.

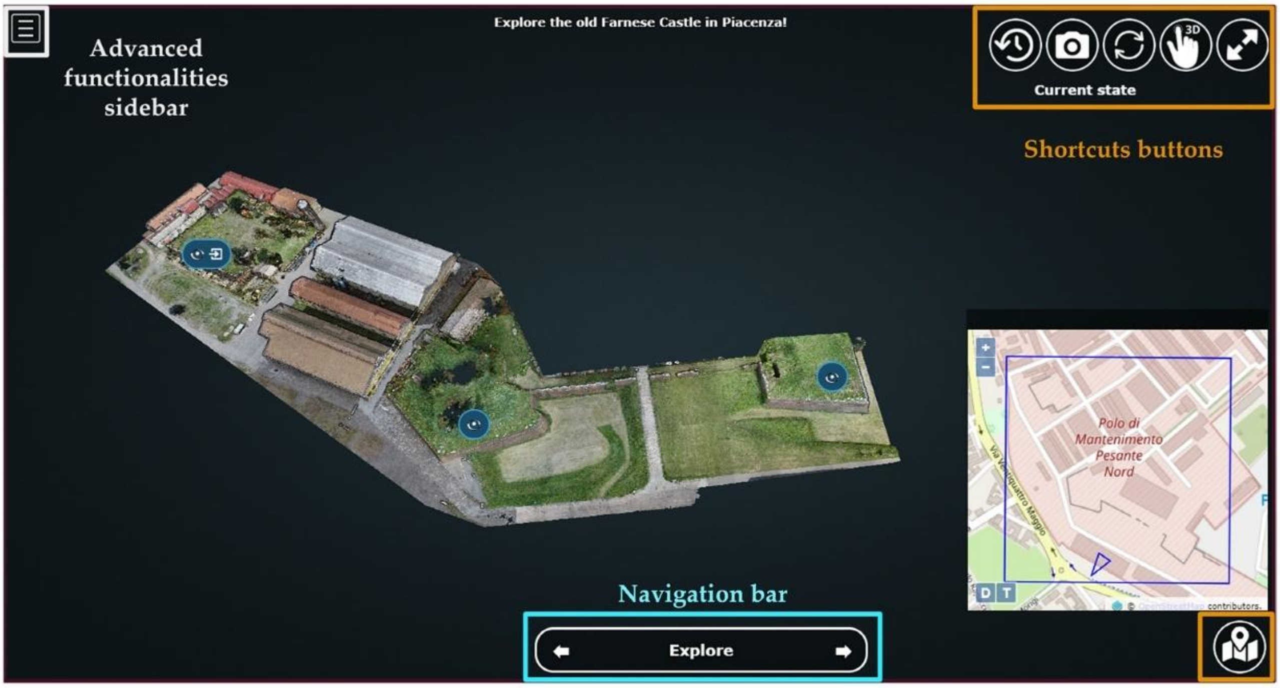


*Figure 23. Homepage of the web platform with the integrations of shortcut buttons and navigation facilities in support of a user-friendly spatiotemporal storytelling experience (from Gaspari et al., 2024a).*

Indoor space exploration is designed along pre-fixed paths, simulating a first-person movement along corridors. Custom annotations are inserted at the entrance of the two wings of the indoor rampart. They include annotations that, if clicked, trigger a camera animation, launching a virtual tour of both interior corridors and activating along the path the visibility of annotations linked to artworks and exhibition features. Such animations are implemented through the interpolation of a set of triplets of coordinate values of camera positions as well as their orientation parameters.

The implemented 3D web viewer, currently hosted on the LabMGF server, serves as the main platform where users can retrieve both historical and metrical information (https://labmgf.dica.polimi.it/pujob/potree-template/, accessed on March 25$^{th}$, 2026). It provides simplified access to accurate 3D georeferenced data and makes it possible to explore it with simple mouse clicks. In particular, it supports the navigation and multi-level evaluation of the cultural heritage site. By integrating different formats of 3D data, it allows the exploration of their functionalities for different types of audiences. For example, oriented images of the outdoor scene help users unfamiliar with 3D products, such as point clouds, to navigate through the current state of the site. At the same time, they provide a georeferenced visual record of the condition of the site at the time of the survey, giving experts in the field valuable insight into the structural health assessment of the castle. Experts can easily identify defects or damages with a virtual visual inspection and then annotate them, extracting their coordinates, and measure their extension on the structure, obtaining quantitative observations on their level of severity. Such operations are made possible by the fact that the orientation parameters associated with the images allow a clicked point on the 2D object (single picture) to be automatically associated with a specific triplet of coordinates in the 3D scene in which the point cloud is located (Figure 24).


*Figure 24. The distances measured on features visible on the oriented images are connected to the point clouds of the site inserted in the 3D scene. This is possible thanks to the Potree native functionalities position the drone images using their camera calibration information as well as the orientation parameters computed during the photogrammetric reconstruction and point cloud generation (from Gaspari et al., 2024a).*

Additionally, the viewer gives users the choice of freely exploring the 3D scene or following predefined virtual tour routes. This flexible approach is, again, particularly useful for providing custom experiences suitable to a wide variety of users with different backgrounds and interests. From the historical storytelling point of view, for instance, new users can gradually evaluate the progress in the construction of the cultural heritage site by simply clicking a dedicated button in sequence. However, more familiar users of similar Potree-based platforms can directly access a specific historical reconstruction from the lateral sidebar, activating the visibility of the desired 3D object on the structure tree of the scene (Figure 25). Similarly, users may decide to take advantage of the presence of the hotspot bar for navigating through the prefixed point of view or ignore it and directly jump to the desired point of interest inside the scene, using hidden annotations from the sidebar or exploring with laptop mouse controls. Ultimately, regardless of the exploration choices and modes chosen by the user, the public can interactively reconstruct the history of the cultural heritage site, raising awareness of how the Castle has changed drastically over time and what remains in the current state of the complex.

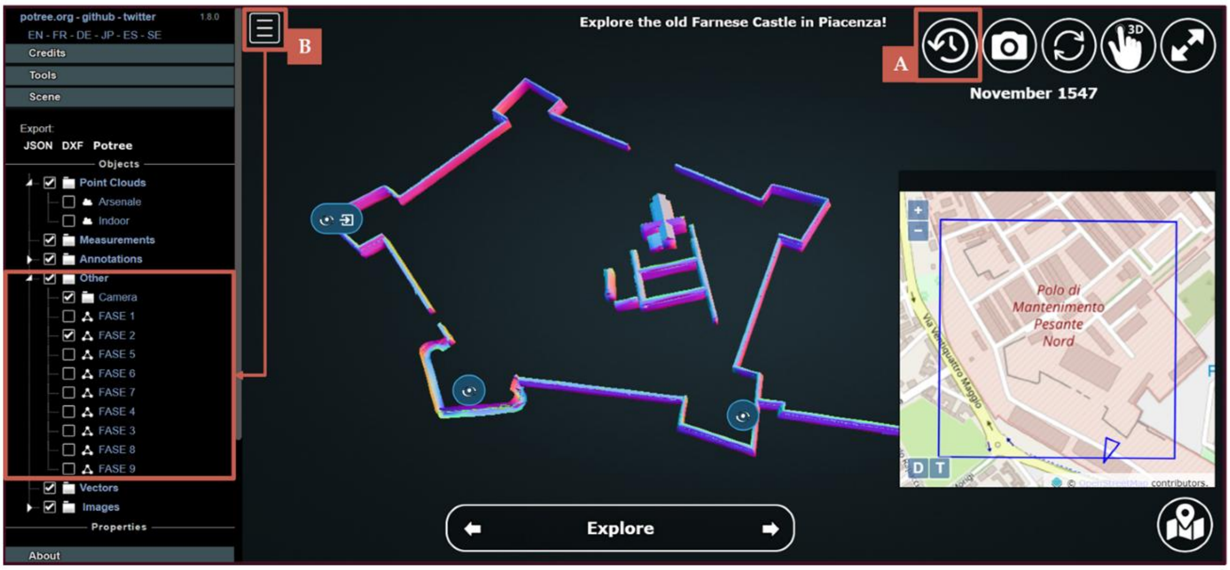


*Figure 25. An example of how users could either choose to adopt guided shortcut (button A) for switching in temporal order the visualisation of different construction phases or to activate advanced features in the technical sidebar (button B), autonomously selecting the phase of interest from the object tree in the scene (from Gaspari et al., 2024a).*

In addition, native Potree annotations provide a double functionality in support of a user-friendly and enjoyable 3D scene exploration. First, they enrich the storytelling of the site, giving users additional historical and cultural context with custom pop-ups containing images, texts, slideshows, and external links for in-depth studies of objects inside the scene (Figure 26). Second, annotations provide reliable anchor points for users who, if lost in free navigation of the scene, can click on one of them to return to pre-established virtual tours (Figure 27). The inclusion of actions to activate camera animations and toggle the visibility of objects in the scene also encourages users to explore the site more interactively, defining a treasure hunt-like experience to discover all the hidden elements in the Castle.

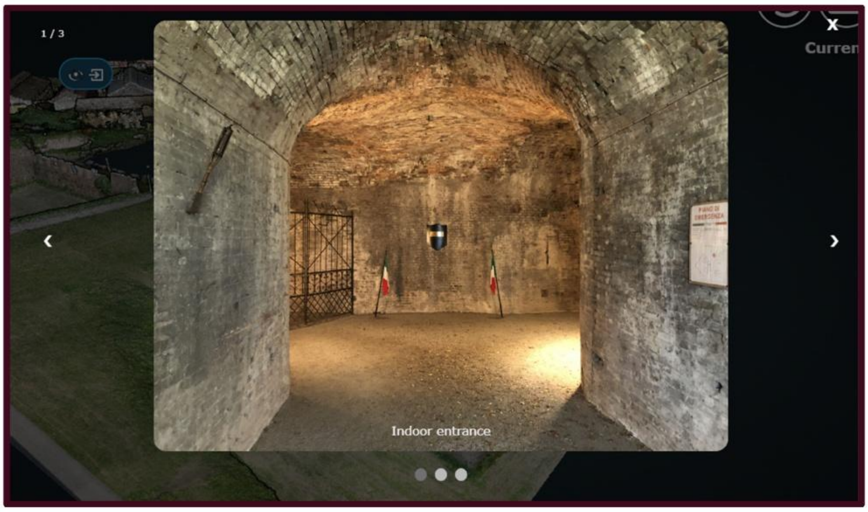


*Figure 26. Example of a custom pop-up panel associated with the San Giovanni bastion annotation. The indoor corridors of the rampart were not surveyed with TLS, but this functionality allows users to explore anyway the interior with an image slideshow and a text (from Gaspari et al., 2024a).*

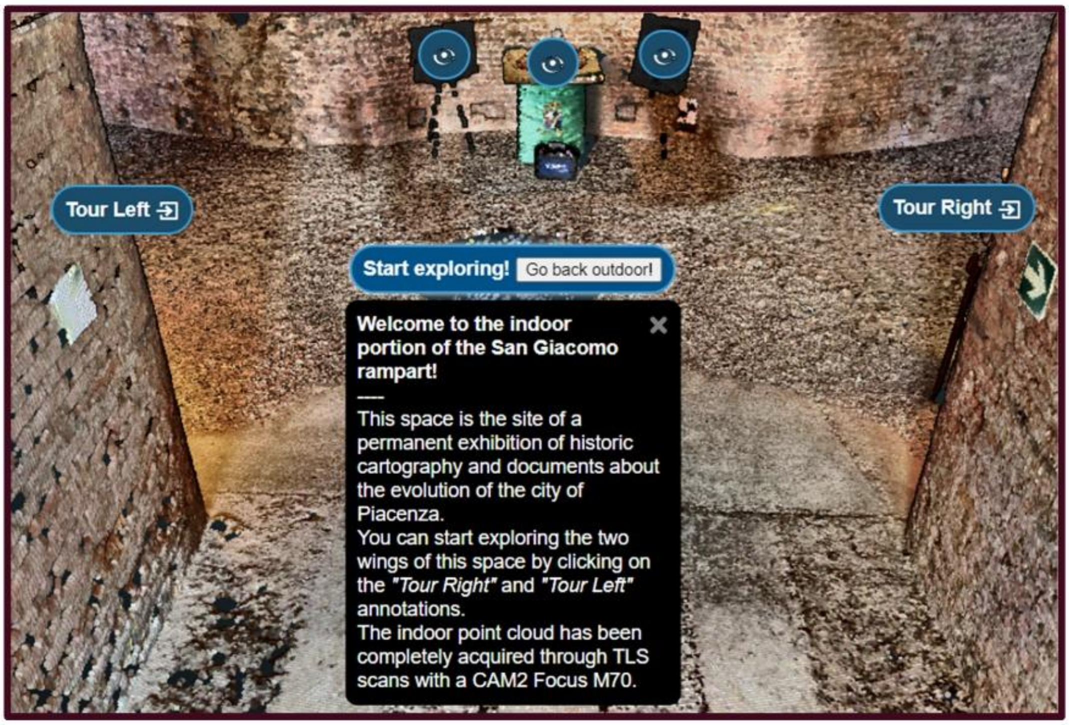


*Figure 27. Example of annotations inside the San Giacomo bastion helping users to orientate themselves inside the dense point cloud and starting dedicated virtual tour with simple clicks that activate pre-defined camera animations on the lateral corridors (from Gaspari et al., 2024a).*

The template code, written in HTML, CSS and JavaScript, along with images and icon assets is available on a dedicated GitHub repository (https://github.com/Tars4815/potree-chtemplate) (accessed on March 27th, 2026).

In addition to the implementation of the web platform, technical documentation of the entire procedure adopted for the case study was prepared to promote the future adoption of the proposed FOSS architecture for other cultural heritage sites. This included detailed instructions on how to define 3D scenes and place objects within them, as well as tutorials on how to incorporate specific GUI commands, shortcuts, and exploration features. This information was formatted into reStructuredText (.rst) files using the Python Sphynx library and then posted on a dedicated webspace instance of ReadTheDocs, an open-source technical documentation hosting platform. Additionally, the code (HTML, CSS and JS language) for the 3D web viewer application has been openly made available online in a dedicated open-source GitHub repository. This way, future researchers or developers interested in the project could modify and adapt the code structure to other case studies and applications, fostering collaboration and reproducibility (Figure 28).

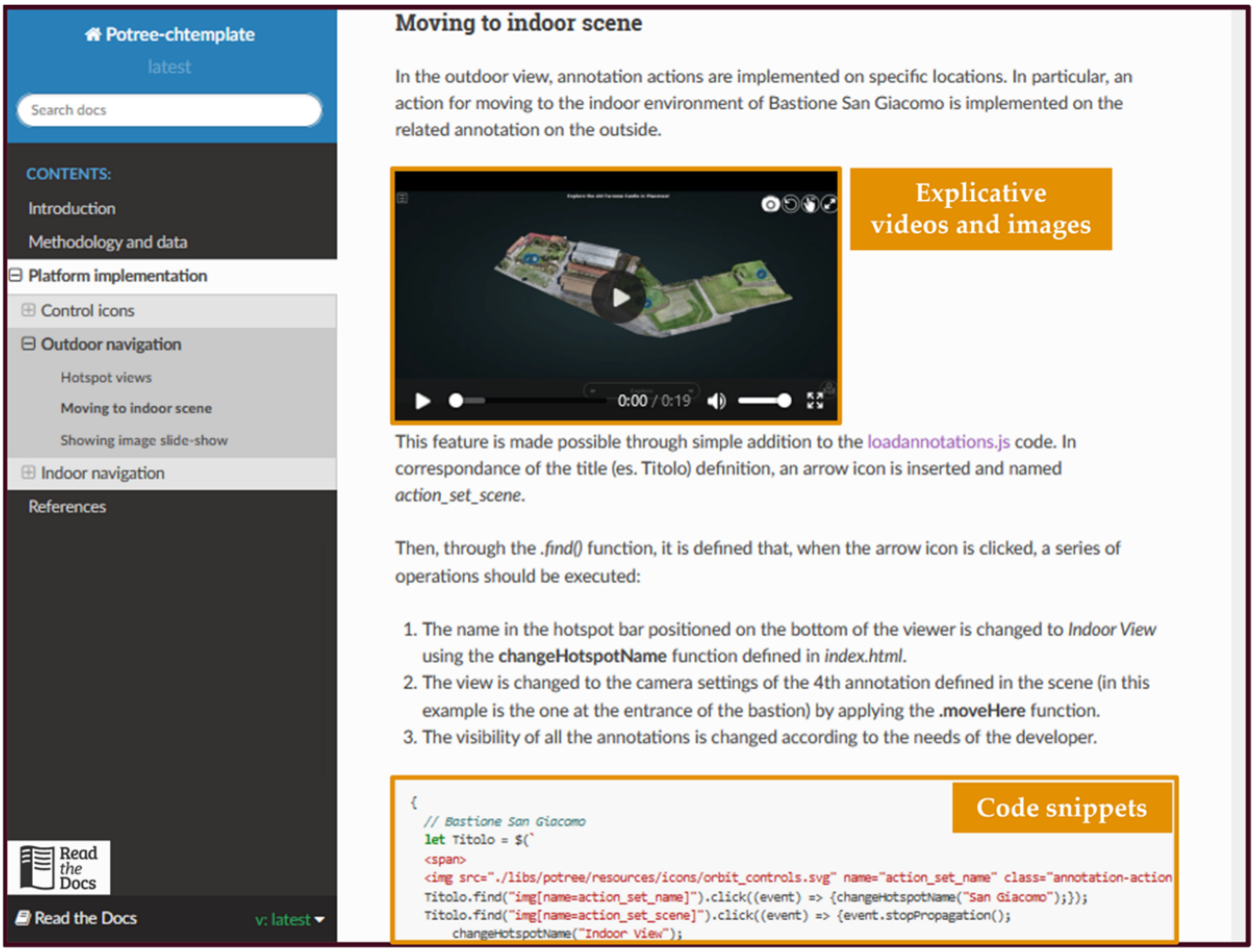


*Figure 28. Screenshot of the ReadTheDocs documentation in support of the implementation of the web-based 3D platform. Each functionality is documented in a dedicated section with explanatory multimedia and comments linked to the code shared in a GitHub template repository (from Gaspari et al., 2024a).*

### 5.1.4 Implementation outcomes

The case study implementation presented in this section identifies a foundation for the visualisation and reproducibility components of the framework and a common ground for digital documentation and storytelling, implementing simple visualisation and elaboration instruments with simplified and accessible exploration functionalities for CH dissemination and promotion to non-expert audiences. The ability of a WebGL-enabled environment based on the JS library of Potree allows us to easily integrate different formats of 3D and 2D data in a single platform, giving users the possibility to interact with it in multiple ways depending on their needs, becoming familiar with the environment and the objects themselves. The inclusion of photogrammetry and TLS-derived products also supports a more realistic virtual experience on the web platform, providing a better understanding of the conditions of the surveyed site.

The design and the implementation of the viewer are intended to be low-cost and easy to replicate. In practice, interested researchers or CH experts can create their own version of the viewer for another site by simply forking the code from GitHub. They can then load converted point clouds into the corresponding subfolder and define custom settings for annotations and pop-ups in the associated JavaScript file. Using the code as the basis for their own custom viewer allows pre-defined static elements to be easily recompiled and gives scope to expand the viewer's functionality for other interaction purposes.

## 5.2 Natural environment implementation

### 5.2.1 Objectives and customisation logic

Building upon the foundational dissemination strategies explored for the Farnese Castle case study, the customisation for the natural environment domain extends the application of the proposed framework with capabilities in support of quantitative monitoring and multi-temporal visualisation. In particular, in this case study the tested viewer module has been encapsulated into a broader project website (https://thebelvedereglacier.it/, accessed on March 27th, 2026), which acts as a central hub for users' onboarding and redirection of diverse user groups to dedicated services for users involved from the data collection to the data interrogation and download (Figure 29).

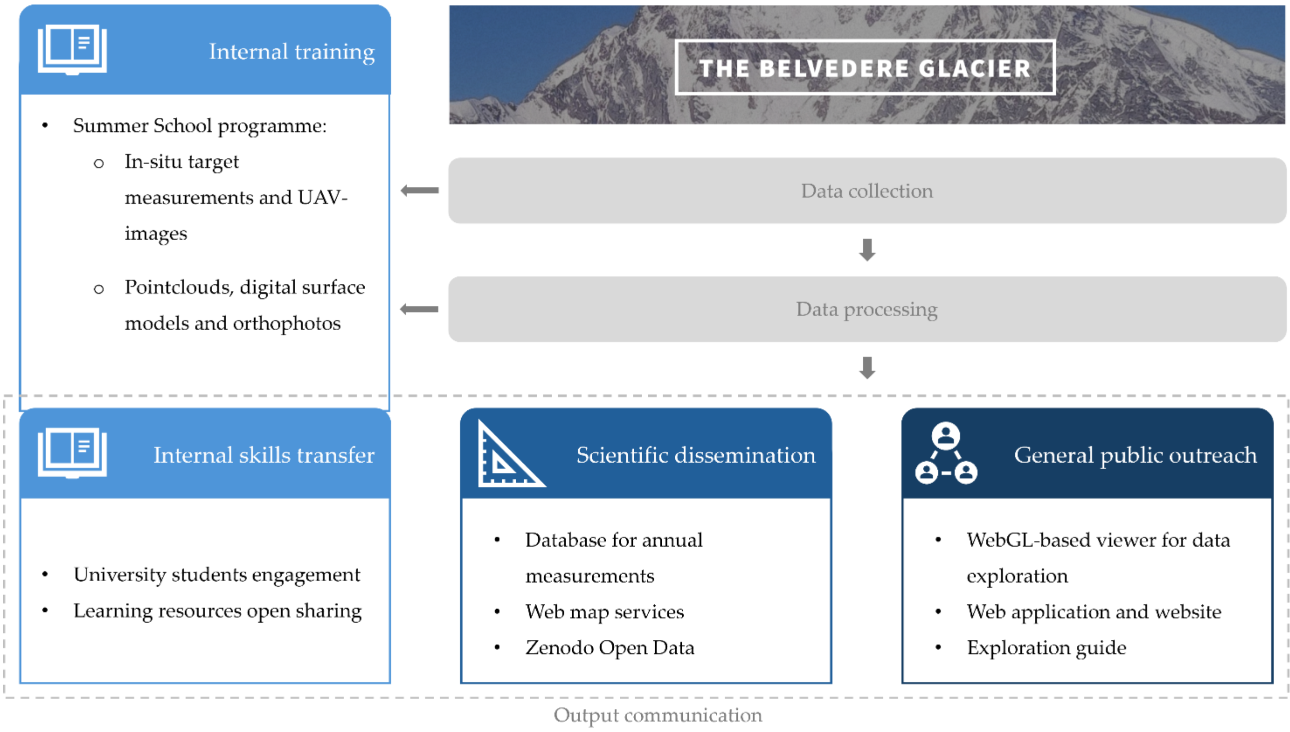


*Figure 29. Components of the Belvedere Glacier project engaging different target audiences in the research communication of collected and processed products (from Gaspari et al., 2025a).*

The focus shifts to the Belvedere Glacier monitoring project, which serves as the primary testing ground for implementing other modules of the system, connecting the 3D viewer to a structured system. Indeed, while the previous case study prioritised stateless 3D exploration for heritage outreach, the environmental monitoring of a dynamic alpine site necessitates a transition towards state-aware data management. This configuration introduces the Data Storage tier – comprising the Data storage and the Data sharing components - as a central memory for the system, employing an open-source database technology to archive multi-epoch GNSS measurements, survey metadata, and derived glacier velocities, maintaining their geospatial dimension. The Data Sharing is activated through a geospatial open-source server, enabling the streaming of high-resolution orthomosaics and Digital Surface Models (DSMs) via the WMS protocol. The customisation of the Visualisation component allows for a bi-directional, read-only connection between the 2D map, the 3D viewer and the relational backend. This also enables the functionality of querying temporal data directly within the 3D scene. This deployment validates the framework's capacity to transform fragmented survey products into a searchable contextual repository, providing a robust tool for scientific dissemination and public awareness in the context of climate change, supporting scientific objectives and broader societal engagement.

The case study's three target audience components include:

- Internal Training and Skill Transfer component: designed for students, not only for educational purposes but also to offer hands-on experience of data collection and processing techniques. During a dedicated summer school, students engage in practical exercises, such as in situ target measurements and UAV image acquisition, which feed into the data processing pipeline. This integration ensures that students gain real-world skills in data acquisition and analysis, forming a bridge between theoretical learning and applied geomatics skills. This dual focus explains the division within the internal training and skill transfer components in Figure 29. The internal training aspect emphasizes capacity building through structured programs like the summer school, while the skill transfer highlights the dissemination of these skills within the academic environment, ensuring that university students can engage beyond their initial training.
- Scientific Dissemination component: geared towards a technical audience already familiar with geomatics and cartography, this module facilitates access to 2D and 3D geo-data collected and processed during annual in situ surveys. By making this high-quality digital documentation of the glacier openly available, the platform aims to support multidisciplinary research and technical studies on a rapidly changing natural heritage site.
- General Public Outreach component: targeted at the general public, this module centres around the main website, which provides an accessible entry point to the project. Through a user-friendly interface, citizens can navigate georeferenced 2D and 3D data, visualise quantitative information on glacier evolution, and access a range of multimedia resources that illustrate changes over time.

### 5.2.2 Training and skill-transfer branch

The Belvedere Glacier project heavily relies on the interface between research and higher education. Since 2016, the Department of Civil and Environmental Engineering of the Politecnico di Milano has been organizing the summer school "Design and Implementation of Topographic Surveys for Territorial Monitoring in Mountain Environments". The program targets undergraduate, graduate, and doctoral students in civil and environmental engineering, geoinformatics, and architecture (Gaspari et al., 2024b). The author of this thesis participated first as a student in 2021 and, since 2022, as a tutor. The annual program aims to immerse participants in a hands-on experience of topographic land surveying in mountainous regions, while actively contributing to an ongoing long-term research project. This area of study is often covered only in lectures, with few opportunities for in situ practice, which is often confined to controlled learning environments. Over the course of a full week, hosted in a traditional mountain hut, students turn knowledge into skills through a two-phase programme. Preparatory theory classes and seminars are followed by practical activities in photogrammetry, GNSS positioning, and Geographic Information System (GIS) processing and analysis, under the guidance of a Professor and the young researchers of the organising team (Figure 30).

*Figure 30. Images of a student group with tutors during the 2024 Belvedere Glacier summer school activities (from Gaspari et al., 2025a).*

The summer school learning resources are organised into six modules, beginning with a brief overview of the history of monitoring activities on the Belvedere Glacier over recent decades. Each module serves as a foundation for transferring key theoretical concepts related to photogrammetry, drone surveying, GNSS positioning, GIS and database design, stereo camera processing, and 3D web geovisualisation (see Figure 31). With targeted explanations and guided tutorials, students will grasp the theoretical aspects and have the opportunity to apply their knowledge using widely used software such as Agisoft Metashape 2.2.0, CloudCompare 2.13.1, QGIS 3.34.4, PostgreSQL 17, PostGIS 3.5.2, and Potree 1.8.

The material is made available online through a website developed with MkDocs and GitHub Pages, utilising open-source code and linked as a learning documentation on the Belvedere Glacier main website, enriching the re-adaptability module potential of the overall learning component of the framework. It can be directly accessed via the following URL: https://tars4815.github.io/belvedere-summer-school/ (accessed on March 30th, 2026). This adaptable approach not only facilitates ongoing updates and modifications to resources but also encourages online collaboration with other educators keen on creating similar educational experiences (Senger et al., 2021a; Senger et al., 2021b, Potůčková et al., 2023). The website content is provided to students ahead of their fieldwork, serving as a key component of the preparatory phase. Additionally, the 3D viewer customisation implemented for this case study and described in section 5.3.4 enables a virtual interactive exploration of the site beforehand. This advanced exposure helps participants gain a solid understanding of both the theoretical and practical aspects they will engage with during the summer school, fostering a sense of awareness and responsibility.

Students actively generate and analyse data as they transition from passive learners to active contributors, which increases their sense of ownership and engagement with actual glacier monitoring initiatives. Since many undergraduate and graduate students have continued to work on various project components as part of their thesis work over the past ten years, as well as creating specialised plugins for processing and extracting additional information from the data, the impact of this aspect goes beyond the summer school experience.

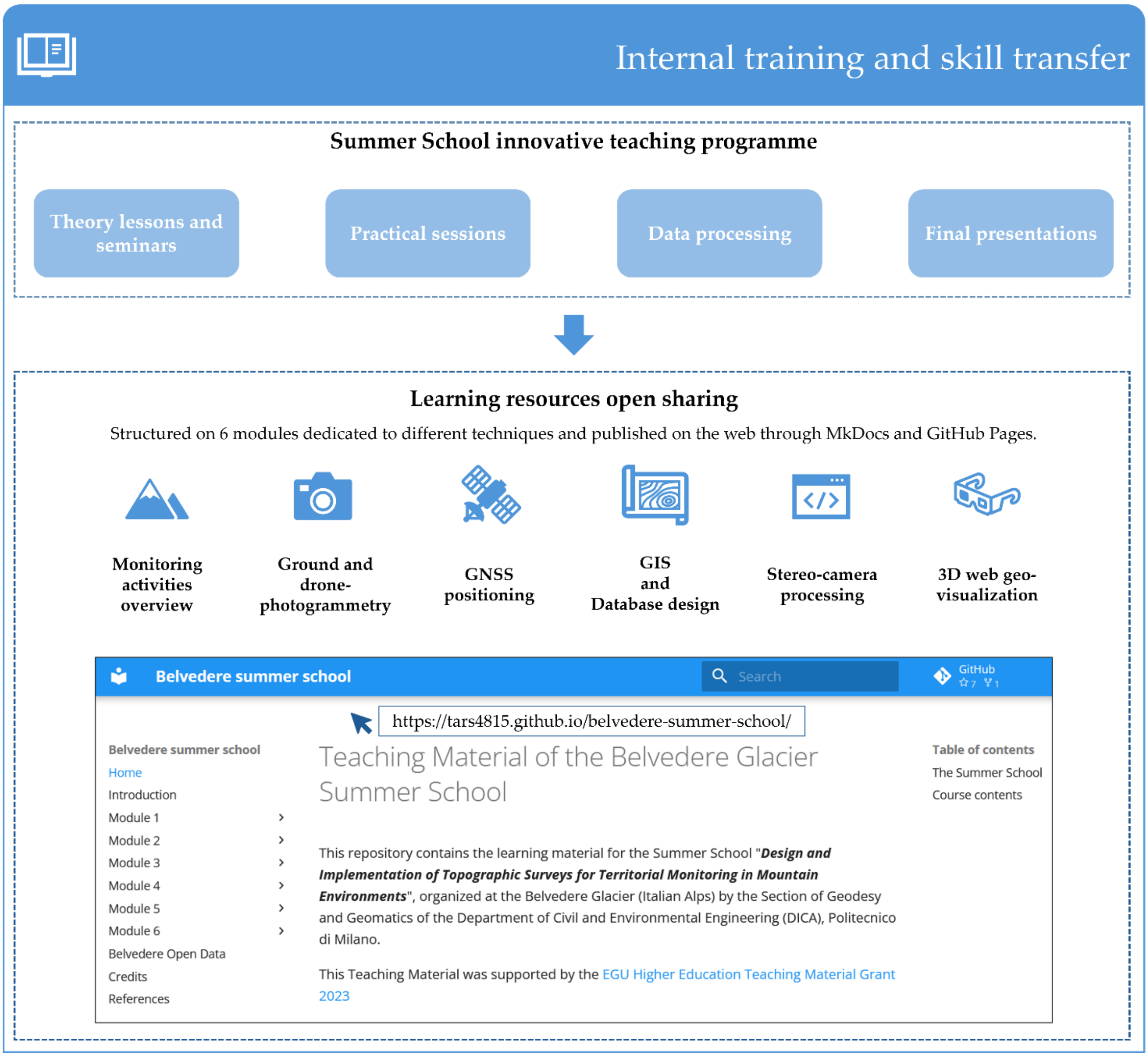


*Figure 31. Overview of the Internal Training and Skill Transfer component, showcasing the innovative summer school teaching programme and the structured open sharing of learning resources across six technical modules, accessible through MkDocs and GitHub Pages (from Gaspari et al., 2025a).*

This program equips participants with essential skills and hands-on experience using cutting-edge equipment and software for fieldwork, while also fostering critical thinking abilities necessary to recognise the advantages and constraints of geomatics in challenging terrains. This educational approach is vital, given that commercial drones and surveying tools have become more readily available recently; however, access to comprehensive training on their proper use remains limited outside of academic institutions (Balletti et al., 2023). Moreover, staying in a historic alpine hut built in the 1920s immerses both students and instructors in the mountain setting, offering a genuine glimpse into the culture and daily life of the local community. Thus, the summer school not only helps participants reconnect with the landscape and its inhabitants but also fosters connections among the participants themselves and with local residents, all while tackling the challenges posed by a rapidly changing natural heritage site in the context of climate change (Achille & Fiorillo, 2022; Achille et al., 2017). At the conclusion of the summer school, students collaborate in groups to present their findings to an audience of researchers from the Department of Civil and Environmental Engineering at Politecnico di Milano. This occasion enhances their communication and public speaking skills as they showcase the results obtained from their field data, illustrating glacier movement and volume changes through quantitative analyses derived from point clouds and digital elevation models. After undergoing a validation process by the summer school tutors, these results are subsequently shared with a broader audience in an updated version of the Belvedere glacier Open Data available on Zenodo.

### 5.2.3 Scientific dissemination branch

The Scientific Dissemination section serves as a well-organised repository of data and tools tailored for technical users and is based on the activation of the data storage and sharing components of the framework component. Indeed, it provides access to comprehensive measurements and geospatial outputs derived from the Belvedere Glacier monitoring campaigns. This section outlines the key resources required to upgrade the framework, which was first tested with its viewer in the case study of Farnese Castle (see Figure 32):

- The adoption of a centralised PostGIS database is used to store annual GNSS measurements, survey dates, instrument specifications, and displacement and velocity data. This system enables researchers to monitor glacier changes over time with high precision (Data storage)
- The publication of the long-term archival of raster and three-dimensional data, including point clouds, orthophotos, and digital surface models, through a Zenodo repository. This open access strategy enhances data transparency and facilitates reusability for future studies and interdisciplinary research (Data storage).
- The hosting of web map services on GeoServer offers WMS links for orthophotomosaics and digital surface models. These resources enable technical users to incorporate the provided layers into GIS projects (Data sharing).
- An interactive two-dimensional web map developed using Leaflet displays key measurement points extracted from the database. This visualisation provides a dedicated service interface for users with a comprehensive overview of GNSS measurements and spatial changes observed on the glacier surface (Visualisation – 2D map).

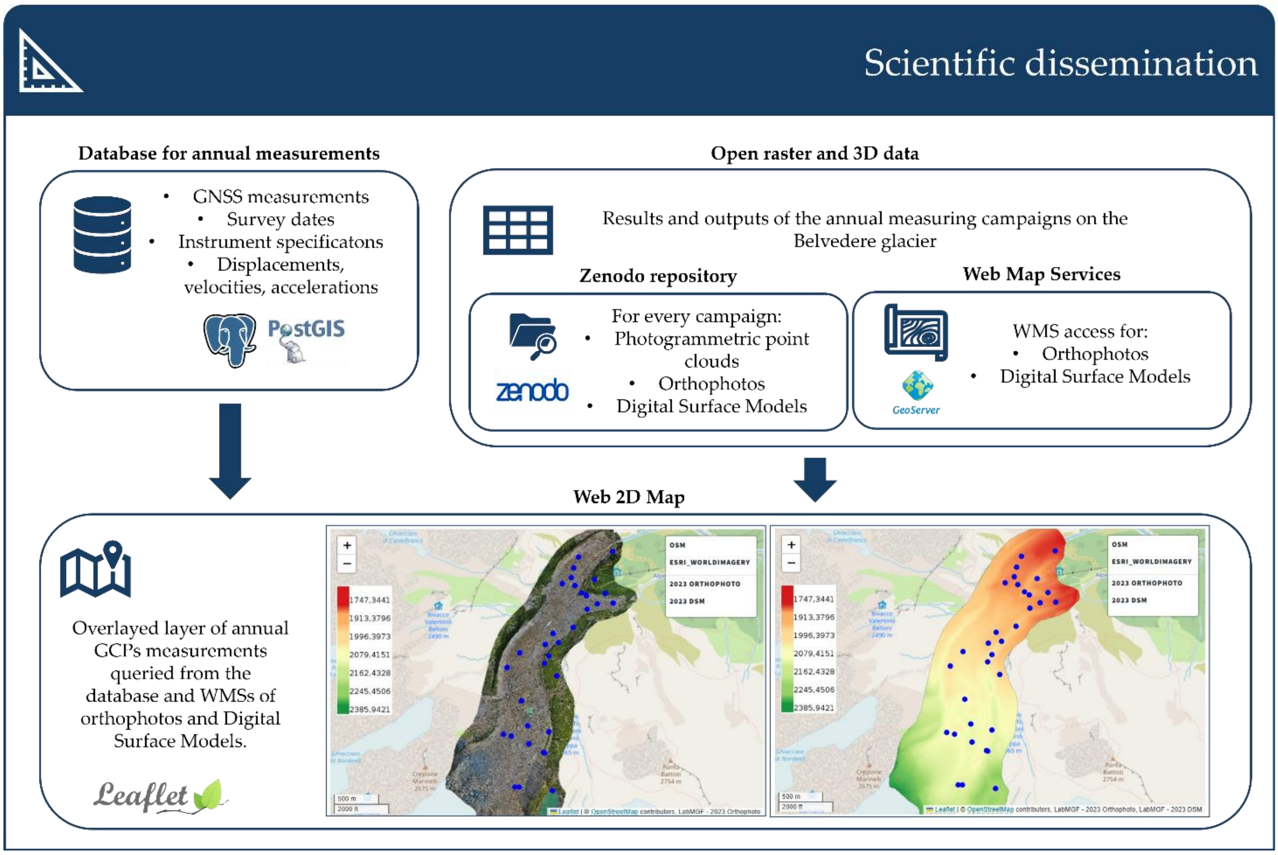


*Figure 32. Design component of web resources for accessing and visualising annual glacier monitoring data from the Belvedere Glacier, including GNSS measurements, photogrammetry, and derived products for a scientific audience (from Gaspari et al., 2025a).*

Prior to 2024, access to monitoring products was limited to researchers directly involved in data collection and processing or to external scientists who formally requested the data. Furthermore, most measured target analytics were stored in an unstructured format (e.g. Excel tables or PDF reports), which hindered efficient editing and querying. To address these limitations, a relational database was developed as the primary repository for data generated by annual in situ campaigns and related research activities associated with the Belvedere Glacier project. The database aims to support efficient storage, accessibility, and data sharing among users with varying roles. PostgreSQL 17 (Stonebreaker & Rowe, 1986) was selected with PostGIS 3.5.2 (McKenna, 2021) as the extension for managing geospatial data and formats. Customising user permissions through defined roles enables direct integration with GIS environments for both routine operations and remote public access. The scientific and technical outreach section details the first use case, while the 3D viewer interface implementation addresses read-only database connections.

In accordance with relational database principles, data is organised across multiple tables. Access is enabled through established relationships, using primary and foreign keys. The database Entity Relationship Diagram (ERD) shown in Figure 33, illustrates the main entities and their relationships.

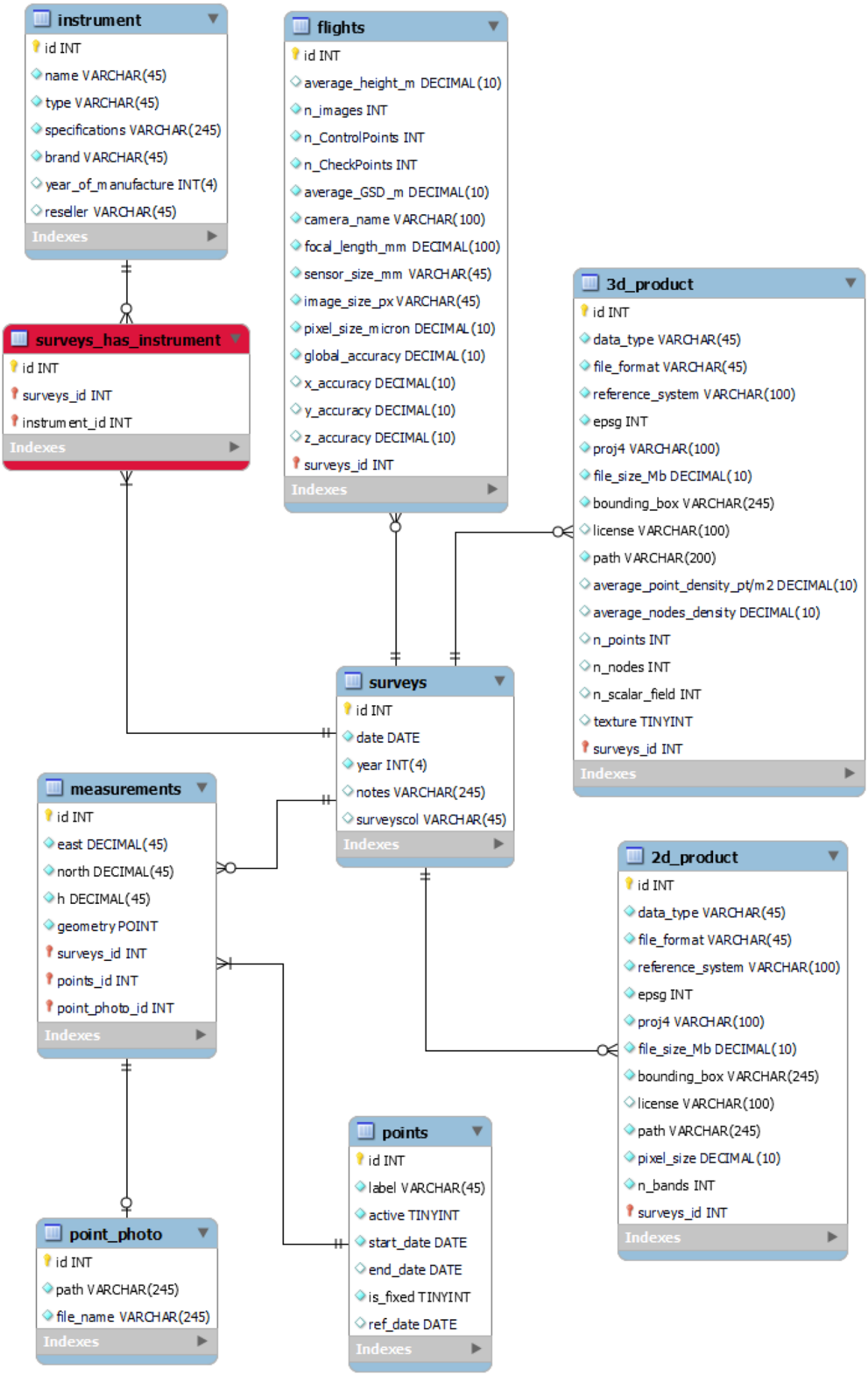


*Figure 33. Relational database model for the Belvedere Glacier monitoring project, organizing data on instruments, surveys, points, measurements, and derived products (from Gaspari et al., 2025a).*

The core database schema comprises three tables. The Surveys table records details of the in-situ activities, such as date and organising year. The Points table registers all glacier points periodically surveyed via GNSS. The Measurements table stores the measured coordinates of every point acquired during each annual monitoring campaign. The ERD illustrates how these tables relate to one another, making it possible to get survey and point data for every measurement record. The execution of a Structured Query Language (SQL) query, such as extracting all data from a specific survey year or the time series of measurements for a chosen point, is therefore made possible by this structure. Furthermore, supplementary information pertaining to each survey can be accessed through the associations with the entities Instrument (e.g., specifications of employed equipment), Flight (e.g., camera affixed to the drone, quantity of images captured, average ground sampling distance), and Product (which encompasses all data regarding the outputs of the photogrammetric processes, such as DSMs, orthophotos, point clouds, and meshes).

A generalisation with a downward collapse is used to solve this final entity, accounting for the unique characteristics of the 2D and 3D visualisations. The database's core is represented by the schema in Figure 33, which is only editable by the team members in charge of maintaining and updating the records. Read-only views were created in a separate public schema using a combination of practical regular queries to enable external access to the quantitative data gathered and processed during the project. Access to data, such the measured points for each year, is made easier with such a solution.

Additionally, they automatically calculate time series data for displacements, velocities, and accelerations for each point by differentiating successive observations, and they identify active points (i.e., targets that are still on the glacier and have not been lost) by supplying their most recent measurements. The automatic conversion of GNSS coordinates between the projected RDN2008/UTM Zone 32N reference system and the WGS84 geographic reference system is one of the additional features. Furthermore, utilizing bilinear interpolation based on the Italian geoid model ITALGEO05, the database enables the computation of orthometric heights for every measurement (Barzaghi et al., 2007).

All point clouds, DSMs, and orthophotos of the glacier are made freely available under the Creative Commons Attribution 4.0 International on a Zenodo repository in order to foster cooperation and open science (Ioli et al., 2024) (Figure 34). This dataset facilitates interdisciplinary study by providing researchers with a structured JSON file that contains necessary metadata. In addition to offering a basis for researching other geomorphological phenomena, such as moraine collapse, or acquiring fresh perspectives on glacier dynamics, these materials facilitate the replication of analyses carried out as part of the glacier monitoring project, such as estimates of glacier velocity and volume change. In separately downloaded zip folders called belvedere_YYYY.zip, the data is arranged by year. All of the data for that particular year, including photogrammetric point clouds, orthophotos, and DEMs, are included in each folder along with the relevant information. A JSON file with metadata provides the necessary details for data utilization. The compressed LAZ format is used to store point clouds. Georeferenced Tagged Image File Format (TIFF) pictures make up orthophotos and DSMs. The data for huge point clouds are separated into regular tiles and numbered row by row starting from the bottom-left corner of the enclosing box.

Furthermore, GeoServer (Aime et al., 2024) makes the DSMs and orthophotos from the glacier monitoring campaign available as WMS. Wide compatibility with GIS applications is ensured by GeoServer's support for a variety of data formats and standards, including OGC services like Web Feature Service (WFS) and WMS. By storing the data on GeoServer, users can view the rasters immediately in GIS programs without having to download big files, facilitating interactive exploration and effective remote access. This method allows glacier monitoring data to be instantly integrated into a variety of analytical procedures, improving accessibility and facilitating multidisciplinary study.


*Figure 34. Record entry description of the Zenodo repository containing the point clouds, DSMs and orthophotos of the Belvedere Glacier starting from epoch 1977.*

The annual target measurements stored in the database are generally accessible to external users via the 2D web map. It is based on Leaflet.js and offers users an interactive platform to see and retrieve measurement data for a particular campaign that is carried out every year along the glacier. Every data point can be clicked to display exact coordinates and make data retrieval simple. Additionally, the map incorporates overlays of multiple WMS, including DSM and orthophotos from various years, which improve spatial analysis by providing a visual context of the glacier topography. To filter the data available for a given time period, users can choose a year from the dropdown menu. They can then download the data in Comma Separated Values (CSV) format for additional analysis or retrieve the data for on-screen display. Users can examine changes over time and perform comparison studies with the most recent datasets, including the 2023 DSM and orthophoto layers (Figure 35), thanks to the map's combination of base layers from sources like OpenStreetMap and EsriWorld Imagery.

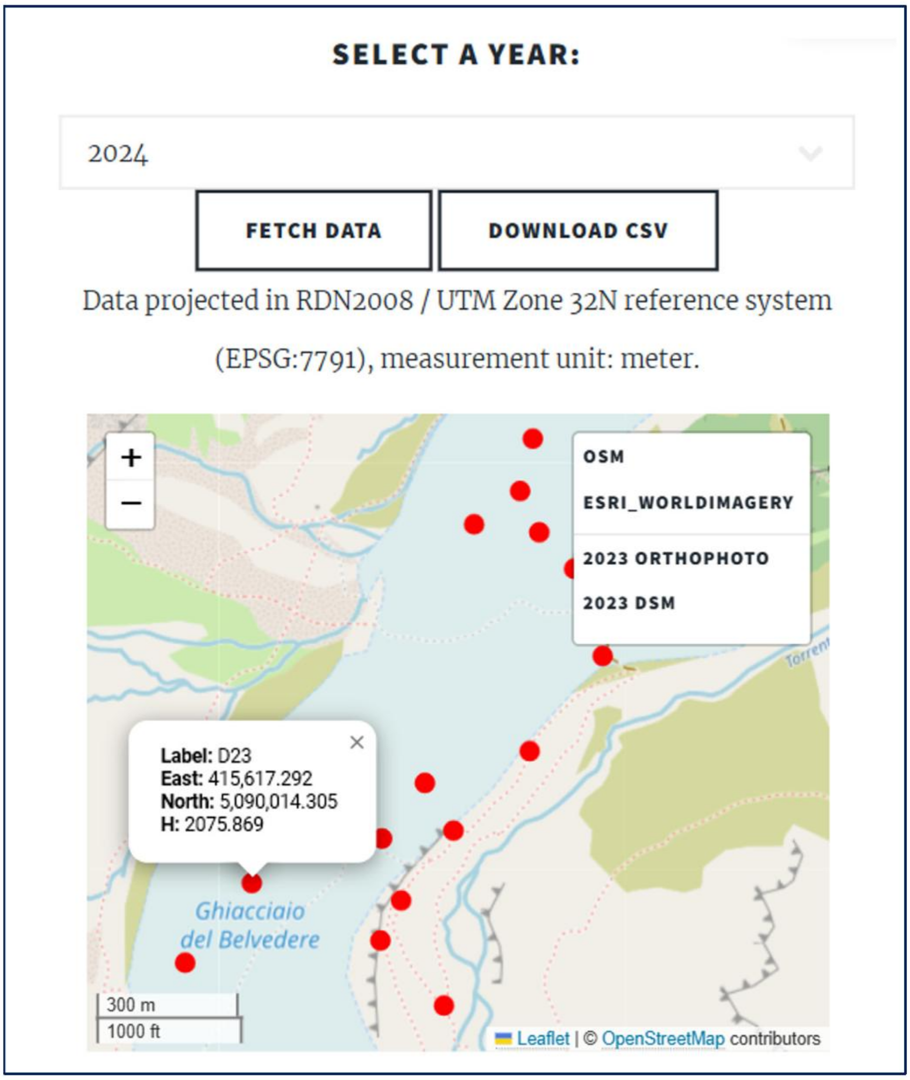


*Figure 35. User-friendly web interface for visualising and downloading annual glacier monitoring data on the Belvedere Glacier, allowing users to select years and download data in CSV format (from Gaspari et al., 2025a).*

### 5.2.4 Public outreach branch

An extensive data library detailing the glacier's evolution has been created with ten years of in situ surveys and monitoring operations on the Belvedere Glacier. Changes in displacement, velocity, and acceleration, assessed annually, are captured in these data, which include point clouds, digital surface models, and GNSS measurements of target sites. To make such outputs accessible to a broader audience, levelling up the experience of the CH visualisation module of the previous case study, a 4D viewer was created in response to the pressing need to document a disappearing natural heritage site and raise awareness of the direct effects of climate change. With the use of this approach, the general public learn about the most recent activities taking place on the glacier and view over time the 3D products created by continuous monitoring that were previously only accessible to a limited number of informed users.

To achieve these outreach goals, the Visualisation – 3D viewer component (Figure 36) was designed with the following logic:

- Data Storage connection: described in the previous section, the integration of the database offers a well-structured and often updated repository of the gathered data, facilitating precise management and preservation inside the Belvedere Glacier project.
- 3D Viewer User Interface customisation: the viewer provides an interactive digital navigation area where users can examine the outcomes of monitoring campaigns both qualitatively and numerically.
- User Exploration Guide: this documentation, which was developed as a digital manual, offers instructions for examining the platform's capabilities, describes data characteristics, and assists users in navigating the web application. Built with GitHub pages, it supports the possibility for more experienced users to open pull requests to fix issue they detected or suggest improvements for a better navigation.
- The complete website codebase is made available on GitHub to facilitate openness and reproducibility, encouraging teamwork and allowing anyone to duplicate or add to the project. By defining services like the Apache web server with environmental variables for database connectivity, the repository's Docker configuration simplifies deployment and scalability. DigitalOcean is used to host the application online, guaranteeing dependable performance and access. Developer deployment is made easier with this configuration, which also promotes smooth project evolution contributions.

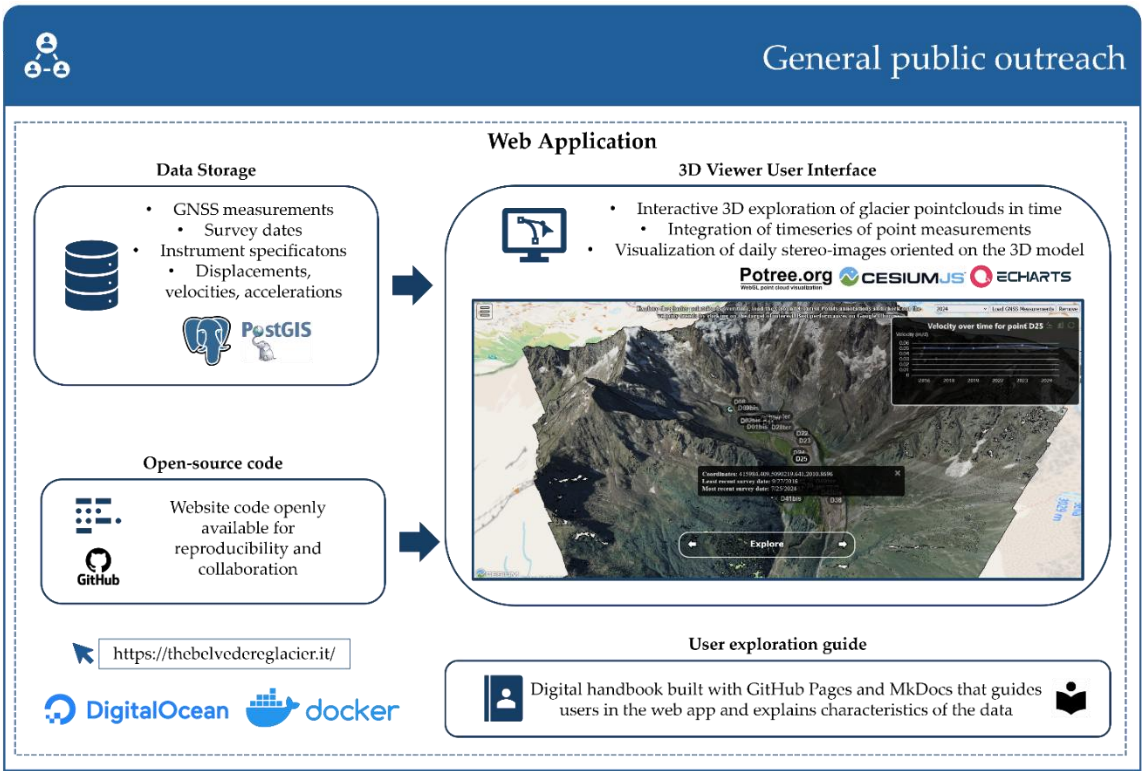


*Figure 36. Design of the web application for public outreach and interactive exploration of the Belvedere Glacier monitoring project. Users can visualise 3D point clouds, time series data, and daily stereo images oriented on the 3D model. The application is built using open-source technologies and is hosted on DigitalOcean (from Gaspari et al., 2025a).*

The customised web-based 3D viewer makes the results of the yearly glacier survey campaigns available to the general public. Its foundation is a combination of the Potree, and Cesium JS libraries, both of which offer high-performance 3D geospatial visualisation on the web (Campiani et al., 2023). When combined, all that is needed for a seamless interaction with big datasets is a reliable internet connection. Custom features, like the ability to sequentially explore point clouds from various epochs and the connection to the database, are implemented in addition to the Potree library's native functionalities readapting custom elements of the interface already developed for the Castello Farnese. For instance, the hotspot navigation bar previously used to easily switch between fixed point of view is now used as 4D spatio-temporal enabler, allowing users to select the epoch of interest from a list, triggering specific visibility and loading settings that results in the exclusive rendering of the point clouds associated to the selected year. Enriching the monitoring capabilities with time selection, specifically for this case study, the 3D viewer also enables a straightforward drop-down menu to query observations in the database year by year (Figure 37). Once a specific year is selected, the targets measured in the chosen campaign are then loaded in the scene along the glacier in the 3D environment. The related time series of velocities, computed over all the measurements of that point recorded in the database, can then be seen by clicking on one of them, made possible by the integration of the Echarts.js library with a pop-up.

An online practical guide is provided to enhance the general public's experience on the platform (https://labmgf-polimi.github.io/thebelvedereglacier-handbook/) (accessed on March 27th, 2026)) as a space that can be continuously updated (Figure 38). Using the same technologies as the open publication of the summer school learning resources, the Belvedere Glacier handbook is a digital platform that offers end users tutorials and advice on how to improve their interactive experience with the various tools created as part of the monitoring project, with a particular emphasis on the online 3D viewer. For instance, it offers tutorials on how to zoom in on various objects, rotate the 3D scene, and measure distances. It also explains how to extract cross-sections from various point clouds and compare them qualitatively or quantitatively. Particular focus is placed on the Belvedere viewer's unique characteristics, namely the temporal investigation of the point clouds of glacier surfaces in several epochs and the synchronized connection to the targeted measurement database. Visual instructions and real-world exploration examples are provided to help the user navigate the many application functions.

The source code for the 3D viewer used in this project is publicly accessible on GitHub (https://github.com/Tars4815/thebelvedereglacier (accessed on March 27th, 2026)) in an effort to foster openness and facilitate community development. This method promotes repeatability and enables researchers and developers to modify or expand the viewer's features to suit their requirements. The goal is to enable collaborative enhancements by making the underlying code accessible, especially for bespoke features like integrating with the target’s measurement database and comparing temporal point clouds. This dedication to open-source ideals strengthens the project's alignment with science that is accessible and collaborative.

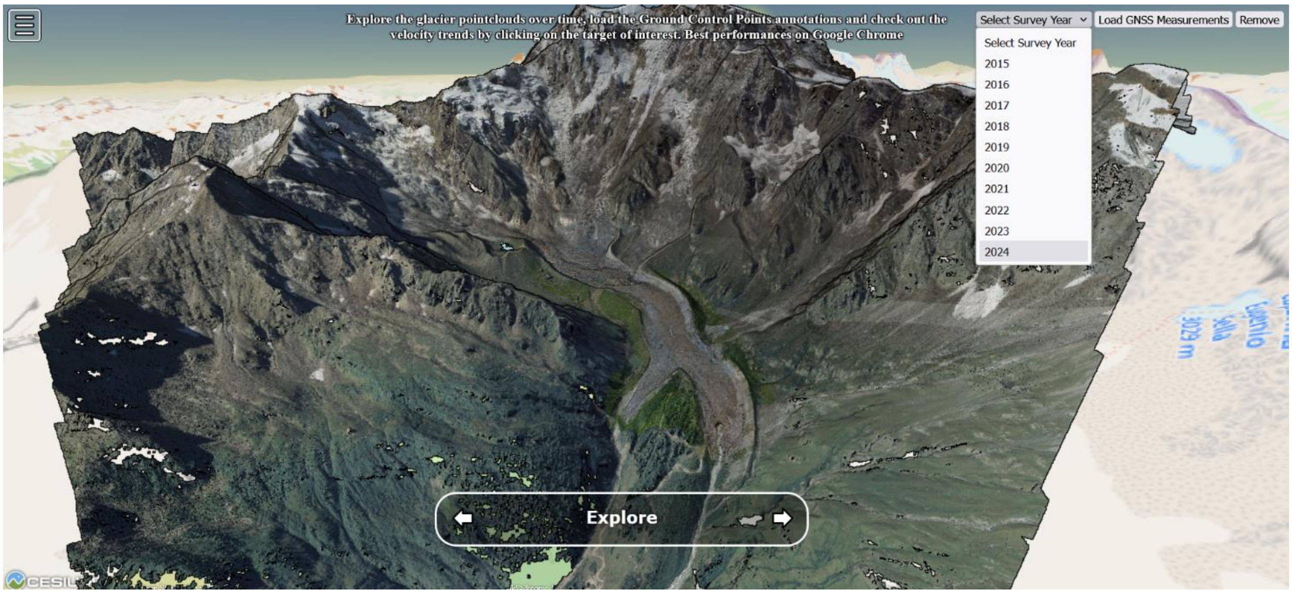


*Figure 37. Potree-based interactive 3D viewer for exploring glacier monitoring data on the Belvedere Glacier. Background context is provided by the integration of the Cesium JS library (from Gaspari et al., 2025a).*

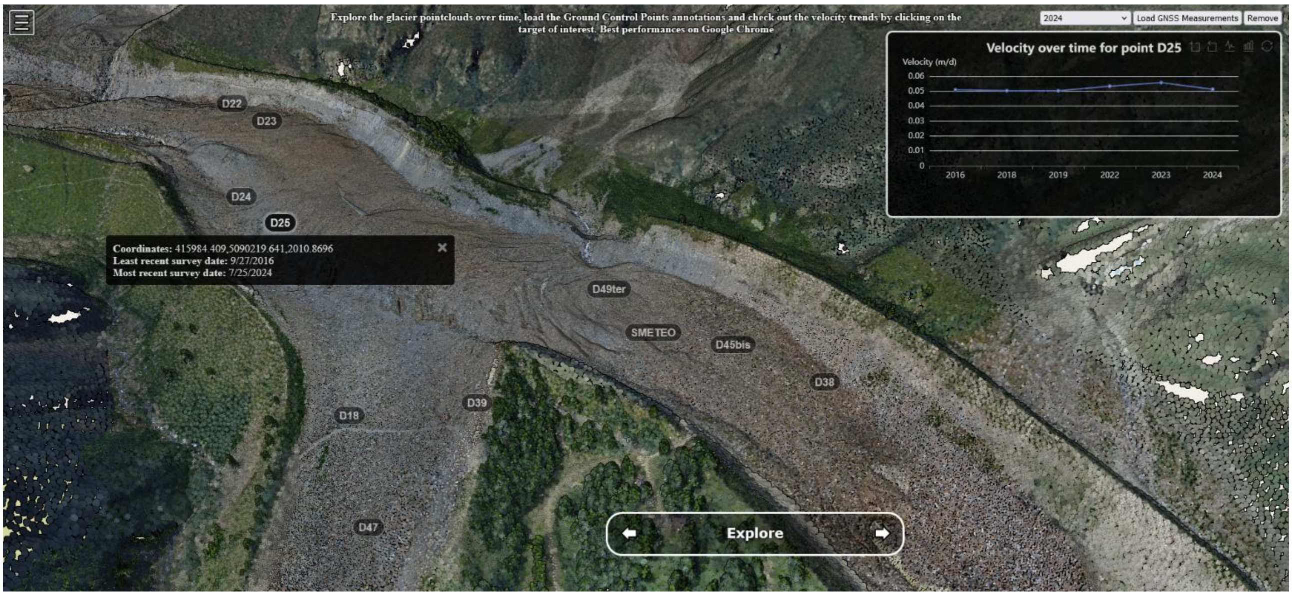


*Figure 38. Example of a graphical visualisation of the velocity time series of a user-selected target measured along the glacier. The real-time connection to the geodatabase allows the query of targets measured on a given survey. The pop-up windows show additional details on each point as well as their calculated velocity trends (from Gaspari et al., 2025a).*

By offering extremely user-friendly and accessible tools for non-specialists, the public component aims to raise awareness and promote accessibility. Without the need for locally installed specialist software or technical know-how, anyone with an internet connection can interactively explore 3D glacier reconstructions using the web-based 3D viewer. A broad audience, irrespective of technical expertise, can interact with and comprehend the consequences of climate change on the glacier thanks to the proposed open access strategy. The platform's user-friendly interface, streamlined navigation, and extra user guides improve its usability and make it appropriate for individuals who have no prior background in geomatics or geospatial analysis. By offering a visual and interactive experience that simplifies difficult scientific facts into a graphical style that is understandable to non-experts, the design promotes exploration. In particular, the straightforward measurement tool offered natively by Potree to extract distances and cross-sections makes point clouds—which are typically thought of as difficult objects to comprehend—accessible and familiar to users. Users can also download the derived point clouds in different formats from the platform to utilise in other software programs for additional analysis (Figure 39 andFigure 40).


*Figure 39. Example of a procedure for cross-sections extraction from the interactive 3D web viewer used for public outreach, with the section command available on the lateral sidebar and its interactive definition in the 3D scene (from Gaspari et al., 2025a).*

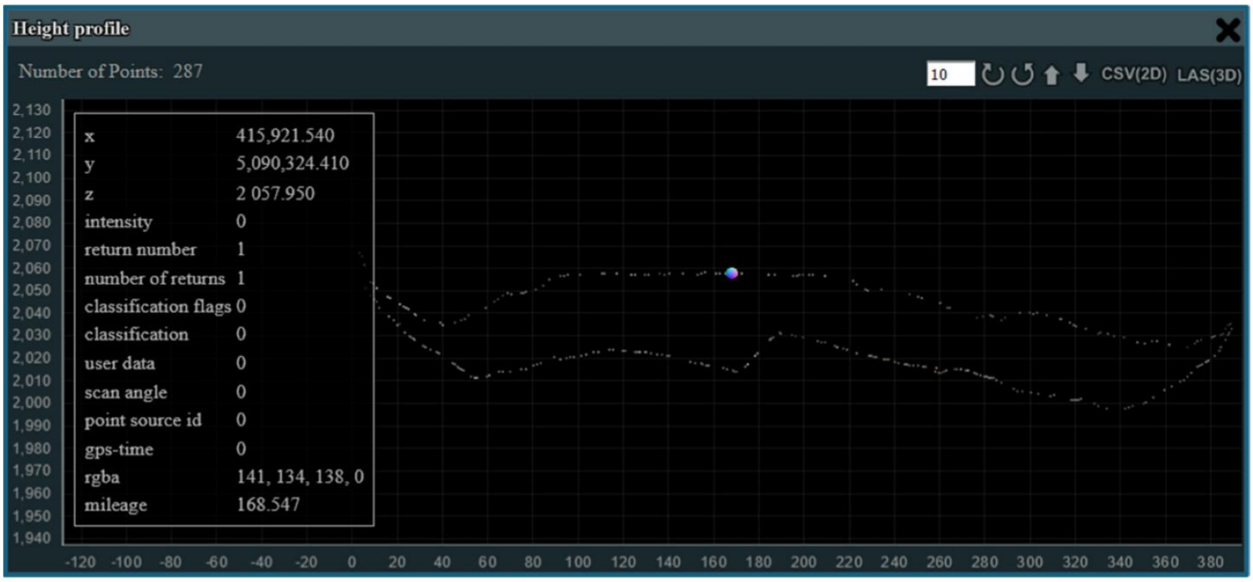


*Figure 40. Dedicated window for the defined cross-section. By activating multiple point clouds, it is possible to quantitatively compare the changes between distinct epochs (from Gaspari et al., 2025a).*

Users essentially assume the role of readers in this system, consuming and interacting with pre-processed data and graph visualisations. Their involvement with the platform encourages more engagement in the dissemination of glacier monitoring efforts and climate research, even though they do not participate in data collection or processing. The component supports more general educational and awareness-raising objectives by bridging the gap between science and the general population.

### 5.2.5 Implementation outcomes

Students, researchers and technicians, and the general public are the three primary groups that the digital interface created for the Belvedere Glacier project is intended to reach in order to satisfy these varied demands. Customised tools and features that strike a balance between usability, accessibility, and content depth are advantageous to each audience.

The features of these solutions are compiled in Table 5, which also highlights the differences in terms of:

- Accessibility: level of effort or requirements to access the corresponding tools (e.g., logins, hardware, software, licenses, etc.).
- User friendliness: how intuitive and simple the tools and their GUIs are.
- Data access level: whether the audience can access raw data, pre-processed products, or only visualizations.
- Required prior knowledge: the level of expertise needed to use the tools effectively.
- User role: whether users are simply passive recipients (readers) or active participants (producers) of the research output through the developed platform.

*Table 5. Comparison of the different experiences of the target users according to the characteristics of the platform. The qualitative evaluation presented is based on the author's laboratory group estimate (from Gaspari et al., 2025a).*

| **Audience component** | Educational | Scientific | General Public |
|---|---|---|---|
| **Accessibility** | Moderate | Low | High |
| **User friendliness** | Moderate | Low | High |
| **Data access level** | High | High* | Low |
| **Required prior knowledge** | Moderate | High | Low |
| **User role** | Producer and Reader | Reader | Reader |

The Belvedere Glacier's educational component offers a cutting-edge framework for learning that blends academic understanding with practical experience in data processing and glacier monitoring. This strategy directly supports SDG targets 13.3 (building knowledge and capacity for climate action) and 4.7 (promoting education for sustainable development and empowering students as global citizens capable of addressing environmental challenges) (Biermann et al. 2022). Since the project includes freely accessible tutorials and learning materials posted on a MkDocs website, the educational component is moderately accessible, as seen in Table 5. This means that any interested student can easily access the project's key components. By offering tools and materials for the creation of particular exercises and examples from real-world problems and current research to practical sessions and seminars within the university curriculum, this strategy guarantees a lasting influence that extends beyond the fieldwork experience. However, because it necessitates involvement in structured programs like summer school, access to the experience's full potential is more restricted. Only a small number of students may attend each year due to practical and logistical limitations, despite the fact that the summer school offers a thorough and immersive study environment. Significant obstacles are presented, in particular, by limitations like the mountain hut's limited capacity for accommodations, limitations that can impact students with impairments, and the current registration policy, which mostly applies to Politecnico di Milano students. These restrictions draw attention to the necessity of possible modifications to increase inclusivity and broaden the educational experience's reach without sacrificing the quality of the hands-on instruction given during the field trips.

The technical component, which offers high accessibility to data and tools designed for sophisticated analysis and monitoring, is primarily targeted at researchers and technicians. This component consists of publicly accessible pre-processed datasets, including digital surface models, orthophotos, and photogrammetric point clouds, which are made accessible via a dedicated Zenodo repository and WMS services. Free and open-source geospatial software (FOSS4G), such QGIS and CloudCompare, makes it simple to access the data due to its open format. Even if they don't directly access the raw UAV-collected image dataset or unfiltered point clouds, researchers can still develop analyses and conduct studies, bearing in mind the data collection and processing approaches documented in the metadata. Consequently, even in interdisciplinary settings, these resources enable users to do sophisticated research and independently examine the datasets. By analysing pre-processed data, the target users indirectly contribute to the research's broader impact by formulating their own research questions and putting their own unique instruments to use in solving them, even though their primary role is that of simple readers. This technical component aligns strongly with target 11.4 of the SDGs which emphasises the importance of protecting natural heritage. In addition to monitoring environmental change, the platform serves to preserve the cultural and natural significance of the Belvedere glacial as an essential component of the Alpine landscape by facilitating in-depth documenting and analysis of glacial dynamics. This dual function emphasises the value of long-term data management and the necessity of open science and teamwork to tackle upcoming obstacles.

The creation of an extensive, computerised, and easily available 3D record of the glacier is a key development of this endeavour. In contrast to conventional 2D imaging techniques, this offers a more engaging and educational depiction of this quickly evolving natural setting, made possible by the creation of specialized solutions that connect users who are accustomed to geographical data with the general public. For academics, educators, and the general public, this digital platform will be a priceless tool that will help them better comprehend the effects of climate change and the significance of glacial ecosystems.

Nevertheless, there are a number of difficulties in creating an open access web platform for geospatial communication and visualisation. Evaluating the balance between performance and usability is necessary to support the effective processing and presentation of huge datasets while preserving accessibility for the various user objectives. Another important factor to take into account for guaranteeing the project's long-term viability is interoperability with changing geospatial standards and data formats for online distribution and publication. Maintaining an open access platform also necessitates regular updates to stay up to speed with technology developments and handle any possible problems with infrastructure expenses, data licensing, and privacy. Notwithstanding these difficulties, this approach's open-source nature encourages cooperation, transparency, and reproducibility among scientists. In addition to promoting a positive cycle of knowledge sharing and awareness for local communities and society at large, the research team's goal in making data publicly available is to add to the mounting body of evidence demonstrating the urgent need for climate change action.

Current work on the project addresses the limitations of distinct platform modules and the need for long-term maintenance procedures for different geovisualisation technologies. To keep the platform aligned with the latest web-based data sharing standards and trends, the 3D viewer is being updated to convert point clouds to the most recent OGC standards for 3D tile data and cloud transmission. Moreover, the submission of GlacioTools to the QGIS official repository for approval is under evaluation (Fajardo Turner et al., 2025). This plugin was developed as part of the summer school initiative and simplifies the execution of routine operations in the processing of fieldwork data. It facilitates the interpolation of displacements, velocities, and acceleration along the glacier surface, as well as the reporting of custom fieldwork atlases, which are essential for documenting GNSS targets and their timeline in monitoring activities. At the same time, an upgrade to the 2D web map for downloading survey data to a Django-based interface with Cesium JS as the main JavaScript rendering library is underway (Bianchi et al., 2025; Pines, 2025).

## 5.3 Civil infrastructure implementation

### 5.3.1 Objectives and customisation logic

Concluding the testing of the framework, this section addresses the Civil Infrastructure domain, focusing on the management of road bridge networks. While the previous sections demonstrated the framework's capacity for dissemination and scientific monitoring, the structural maintenance of critical assets requires a shift from analytical observation to active operational agency. The implementation for the Potree-based platfOrm for iNfrasTructure Inspection (P.O.N.T.I.) prototype fully activates the user as a writer, transforming the platform into a persistent environment where user interactions are no longer transient. Hence, the system moves beyond read-only database connections to support full CRUD operations, establishing a bi-directional link between the visualisation and data storage module. The proposed system is designed to meet the following goals: modularity, user-centric design, and re-adaptability.

User-centric interface design is another guiding principle throughout the development process. The interface shaped through iterative consultations with small or medium-size local administrators has to be aligned with the practical workflows of different user groups, especially simplifying the access to UAV-derived products and GIS-based services (Hognogi et al., 2021). This approach results in a platform that adapts to the context of use, offering tailored visualisation presets for inspectors and planners, as well as streamlined access to advanced tools only when required (Zejdlik and Vozenilek, 2024), prioritising clarity and usability. This ensures that data stewards, engineers, and public stakeholders interact with the platform according to their specific responsibilities, thereby supporting secure and efficient collaboration as well as operations tracking and versioning (Rowland et al., 2020).

### 5.3.2 Prototype architecture and data structure

Based on the specific users' requirements and case studies customisation, a minimal prototype of P.O.N.T.I. has been developed and tested, implementing the designed modules and essential interaction components for bridge inspection data management. Starting from the general framework structure, key customisation to the visualisation component and the underlying interconnected data storage have been implemented to answer the needs of the target users.

#### *5.3.2.1 Data inventory and relational schema*

Similarly to the case of the glacier, the inventory module serves as the system's memory, managing the logical relationships between historical records and multi-epoch inspection data. The core of this module is a relational database built with PostgreSQL and PostGIS, designed to handle the heterogeneity of bridge documentation, from 3D geometries to PDF reports.

This component deals with the inventory of the historical information on the asset as well as data collected during inspections, continuous monitoring, and special field operations. The database, which acts as the system's memory, needs to preserve the logical relationship between different bridge-related entities and manage various data types, including descriptions, quantitative measurements, and multimedia attachments. However, it is particularly important to manage geospatial data, as this is necessary for understanding the geographical and geometric context of a given structure and its components at different scales. Indeed, the underlying database has to organise a wide range of data associated with each structure, including general information such as geometry, type and ownership, as well as details about structural elements and their materials. The system records inspection campaigns carried out over time, documenting any defects observed, their severity, and their spatial location. In this way, when interacting with a connected viewer, users can also annotate and save georeferenced defect recognised on the images or 3D products from specific inspections. Such edits can then be flexibly retrieved with SQL queries thanks to the proposed database structure, whose ERD is provided in Figure 41. As the common practice for relational database design, the ERD is used here to explicitly define the relationships between the spatial, temporal, and descriptive components of the system. The schema is centred on the Structures table, which acts as the main asset inventory. This table stores descriptive information (e.g., name, road_code), key temporal data (e.g., prj_year), and its primary spatial location (the geom field) as a 2D point. This table has one-to-many relationships with its child tables. Regarding the Inspections entity, it captures the main temporal component of the data, with each record representing a single survey event defined by its date. Sub-elements, instead, define the individual components of a structure (e.g., a specific pile or beam), each with its own geometry, described as a 3D polygon, and descriptive attributes (material). Finally, the Attachments table allows for linking any number of non-spatial documents (like PDF reports or historical drawings) directly to the main asset.

In this way, the Inspections table acts as a key observation hub. Each inspection record is the parent for the data collected during that event, including multiple 3D products (paths to point clouds or models), Images, with their camera poses saved as 3D points and linked to a Cameras table storing their parameters, and Defects, archiving as 3D points.

The chosen essential schema consequently ensures that all data, from defects to imagery, can be traced back to the corresponding structure and inspection event. This architecture facilitates comprehensive condition assessments, supports digital documentation workflows, and enables integration with geospatial and photogrammetric data sources.

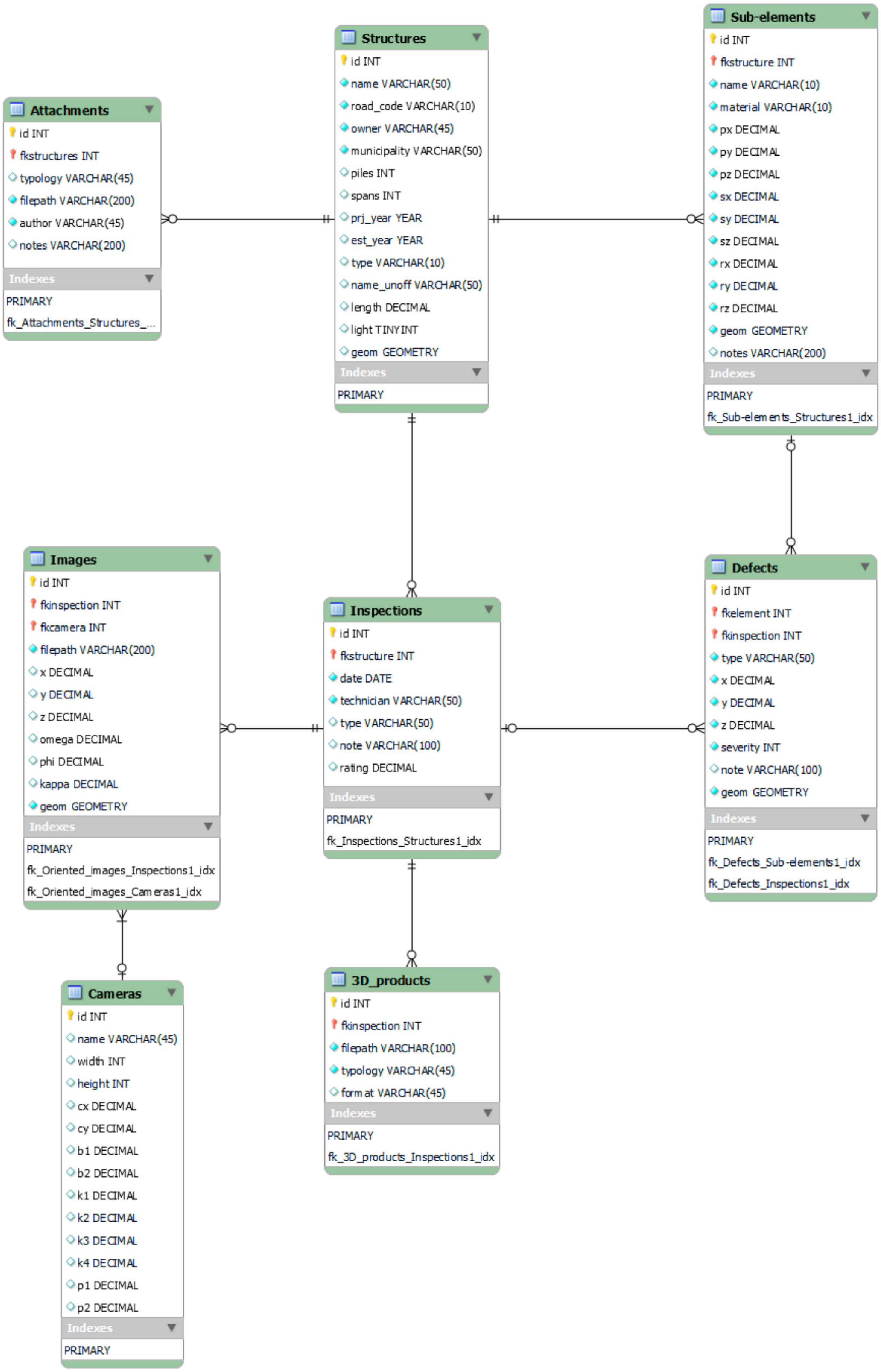


*Figure 41 Entity Relationship Diagram (ERD) for the platform made with MySQL Workbench (from Gaspari et al., 2025b).*

### *5.3.2.2 Bi-directional connection and role-based user agency*

A defining technical characteristic of the P.O.N.T.I. prototype is the transition from the read-only scientific monitoring used in the Belvedere Glacier case study to a fully bidirectional data flow. While the previous implementations primarily focused on data retrieval and visualisation, this infrastructure-specific instantiation upgrades the connection between the web interface and the PostGIS database to support a persistent system memory.

This peculiarity of the system complements the viewing capabilities of the visualisation module by providing full support for CRUD operations, as well as enabling memory storage for user interaction. In addition, it facilitates the upload and export of inspection reports, supporting documents, and survey outputs, thereby streamlining the documentation process and ensuring that all relevant materials are centrally archived and easily retrievable. The annotation tools directly available in the viewer allow users to tag defects directly on the 3D model or associated imagery, enhancing the precision of condition assessments and enabling the integration of photographic evidence through image annotation features. All editing and annotation functionalities are managed through a role-based access control system, which ensures that only authorised users can modify or approve critical data, thus maintaining data integrity and supporting collaborative workflows among inspectors, engineers, and administrators (Table 6). Specifically, this system is designed around three main user groups, defined internally by the public administration. The System Administrator (e.g., IT Technician) role holds full privileged access for system maintenance, user management, and configuration. The editor role (e.g., GIS Specialist) holds full CRUD permissions for the platform's content, responsible for uploading and managing the core asset inventory and inspection data. The user role (e.g., Inspector/Engineer) has comprehensive read access to all data but limited specific writing permission focused on contributing technical assessments, such as creating and updating defect annotations on structural digital replicas.

*Table 6. Definition of the three internal user role groups and their corresponding platform permissions (from Gaspari et al., 2025b).*

| User Role | Primary Responsibility | Key Permissions |
|---|---|---|
| IT Technician(s) (System Administrator) | System maintenance and integrity | Full administrative control. Manage user accounts and permissions (Create, read, update, delete users). Configure DB connections and system settings. |
| GIS Specialist(s) (Data Manager) | Management of the asset inventory and inspection data | Upload, manage and delete inspection data. Create, edit and delete asset inventory records. Manage 2D additional map layers. |
| Bridge engineer(s) (Inspector/Engineers) | Technical assessment and condition monitoring | View and query all assets and inspection data. Create, read and update defect annotations. Use 3D viewer tools (measurement, clipping, sectioning) Generate PDF reports. |

Consequently, the visualisation module is designed to help different users of the system plot and query data from the underlying inventory module. This requires efficient, dedicated tools and libraries to create interactive, user-friendly GUIs for filtering relevant data at different spatial and semantic scales. When using this module, it is important to consider data exploration and filtering at the level of individual structural elements (e.g., beams and piles) and entire structures. This must take into account their interaction with their immediate surroundings or their position within the road network. Such an approach requires lightweight 2D maps with spatial filtering, overview dynamic dashboards for single bridge inspection history, and 3D web-based viewers for detailed product virtual exploration. The query interface leverages this relational structure to execute powerful, cross-table queries. For example, the Home map interface runs a spatial query to fetch all Structures within the current map view's bounding box. When a user selects a bridge, the Inspection history dashboard performs a query using the structure's ID to retrieve all associated Inspections records, ordered by date. The 3D viewer then executes more complex joins, such as retrieving all Defects (and their geom columns) linked to a specific Inspection ID to visualise them in 3D space. The tools responsible for each database-reading functionality must be able to interact with each other in a collaborative web space supporting different platforms, whether desktop or mobile, without the need to install additional software locally.

Taking into account all the specific peculiarities of the P.O.N.T.I. implementation, the resulting framework customisation consists in a 3D WebGIS prototype whose system modules are summarised in Figure 42.

Regarding the server architecture, the current proposed prototype is deployed locally using XAMPP (Apache Friends, 2026), which provides an Apache-based environment. In its current testing phase, the communication between the user interfaces (built in HTML/JavaScript) and the PostgreSQL/PostGIS database is not managed by a formal Representational State Transfer (REST) Application Programming Interface) API or a dedicated GeoServer. Instead, it employs a classic server-side scripting model using PHP scripts. When the frontend client requires data (e.g., to populate the web-map interface or retrieve inspection details), it sends a request to a specific PHP script. This script then directly connects to the database, executes the necessary SQL query, formats and results and return them to the client. This lightweight approach was sufficient for the prototype, while the potential implementation of a more scalable REST API architecture using frameworks like Node.js or Flask is identified as a future enhancement.

To clarify the 3D data workflow, it is important to distinguish the main 3D reconstruction process (which is outside the scope of this platform) from the 3D data processing pipeline, which is fundamental to the system. The platform is designed to accept the products of 3D surveys, such as dense point clouds (e.g., in LAS/LAZ format), as well as BIM models (e.g., in IFC format (ISO 16739)) when available. These raw files, which are often massive, cannot be loaded directly into a web browser. First, they must undergo preprocessing and tiling, which constitutes the abstraction layer mentioned in Section 3.2 of the design principles. Therefore, raw LAS/LAZ files are converted into a web-optimised, multi-resolution octree data structure using PotreeConverter. The GIS specialist responsible for updating the data uses the converter's user-friendly desktop interface. This hierarchical structure is essential for managing levels of detail and ensuring high performance. Similarly, IFC or CAD models are processed into web-streamable formats, such as OGC 3D Tiles, which are natively supported for visualization by CesiumJS and can be generated from PostGIS. These compressed formats are also required by XEOKIT (.xkt). The system then ingests these processed, web-ready outputs. Their file paths and metadata are stored in the database's 3D products table, which links them to the correct inspection. The server serves these as static assets. When a user enters the 3D viewer explorer, the front-end application is given the path to these optimised assets. The respective libraries then handle efficient streaming and rendering. This standard-oriented approach is adopted also for the 2D map interface, which is built to be compliant with OGC WMS and WFS, enabling the integration of external data layers when needed by the users (e.g., regional risk maps). Furthermore, all front-end components are built with HTML5, CSS and JavaScript, following World Wide Web Consortium (W3C) standards to promote cross-browser compatibility.

For the case study of the Province of Piacenza, the chosen reference system for the input inspection data is ETRS89/UTM Zone 32N (EPSG: 25832). This is the system officially adopted for geodata exchange by Emilia-Romagna, the Italian region in which the case study is located. Transformations from other EPSG, particularly EPSG: 4326, are handled through the open-source PROJ.4 library to facilitate globe-based representation.

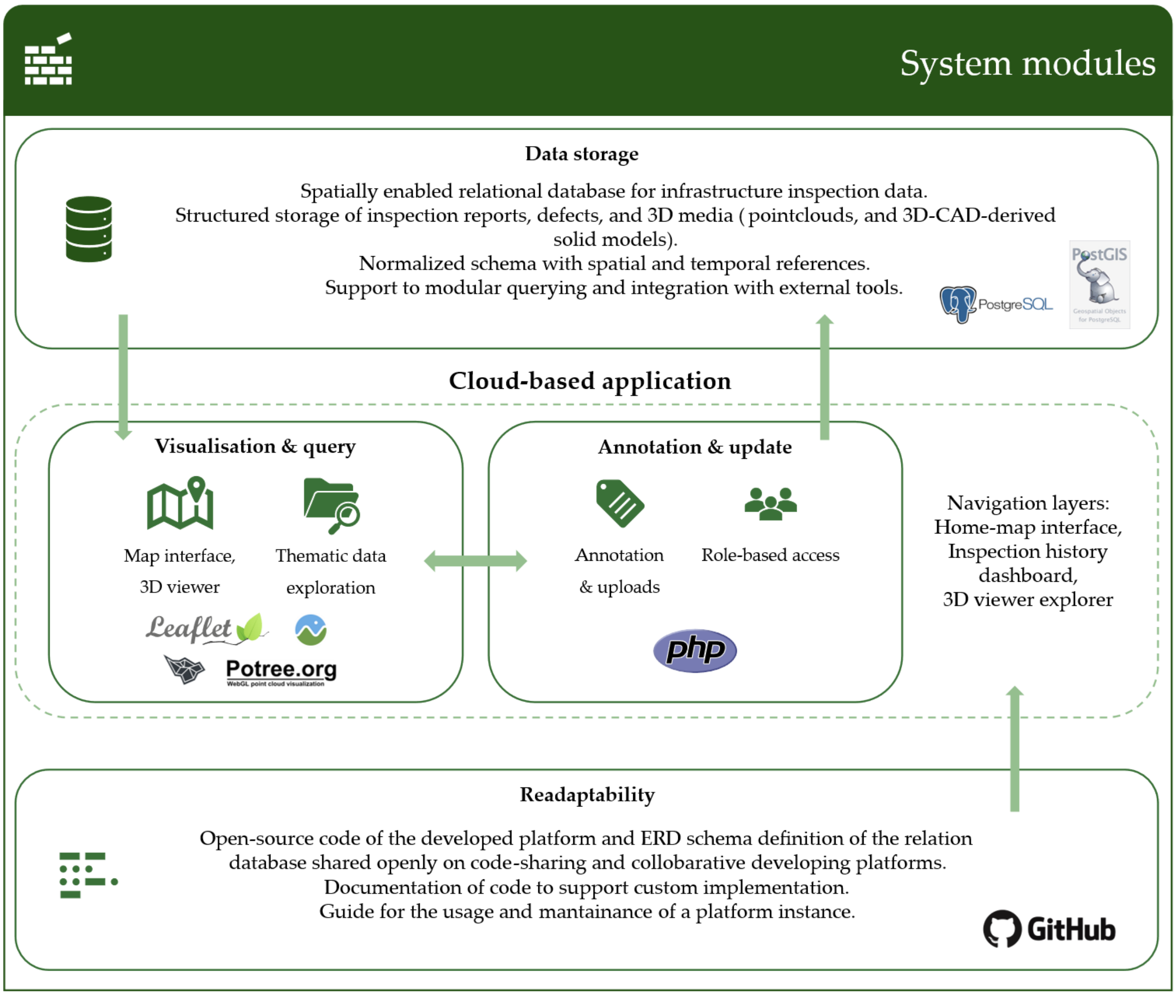


*Figure 42. System modules and architecture of the P.O.N.T.I. platform prototype. The architecture integrates a spatially enabled data storage backend, a WebGIS-based application for visualization, querying, annotation, and updates, and a re-adaptability module to support reuse and customization. Key technologies include PostgreSQL/PostGIS, Leaflet, Potree, PHP scripting, and open-source resources shared via GitHub (from Gaspari et al., 2025b).*

### 5.3.3 Interface layers and interaction workflow

Aligning to the design principles, the customised visualisation interface of the P.O.N.T.I. prototype consists of 3 layers, supporting asset exploration at different scales while allowing flexible rendering of 2D and 3D objects in an interactive scene. Figure 43 summarises the roles and functions of each layer.

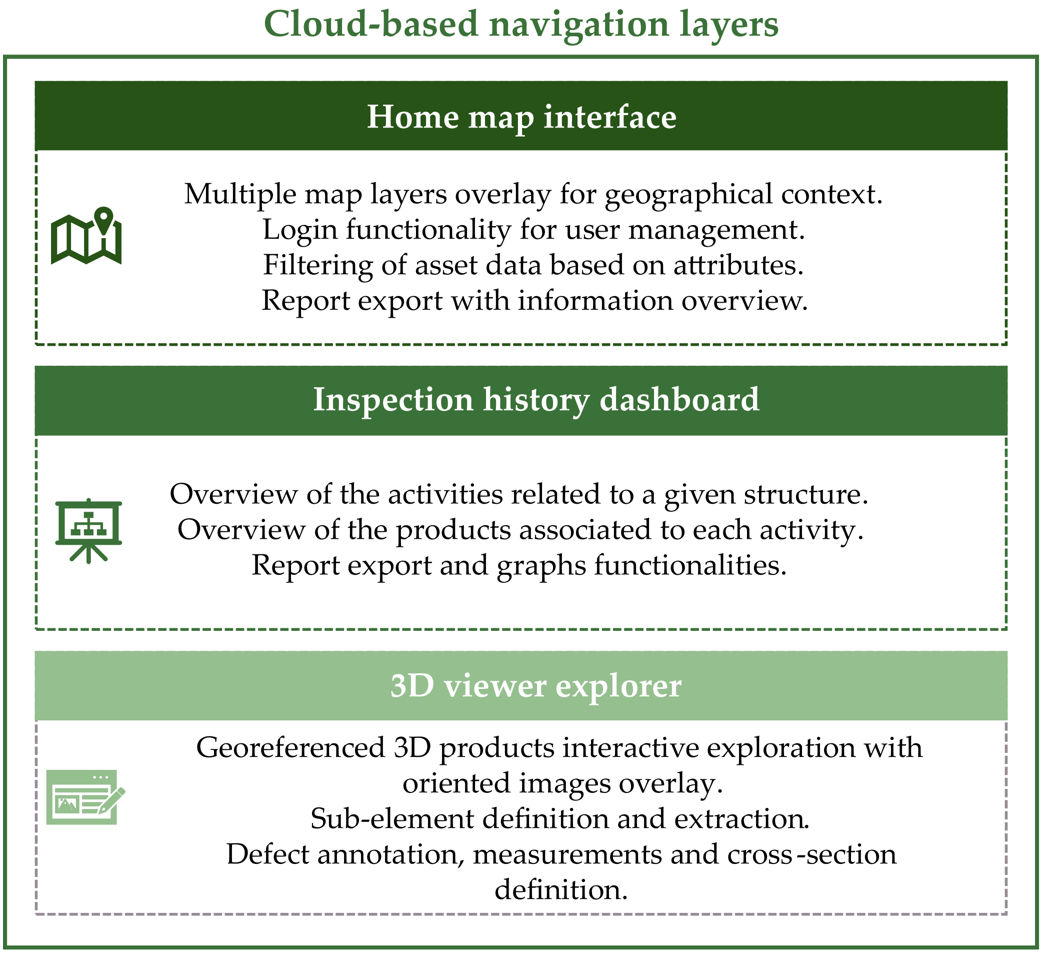


*Figure 43. Application navigation layers of the P.O.N.T.I. platform. The interface offers progressive access through a home map, an inspection history dashboard, and a 3D viewer explorer, supporting spatial browsing, inspection data retrieval, and immersive survey product visualisation (from Gaspari et al., 2025b).*

#### *5.3.3.1 Home map interface*

The landing page of the developed prototype features a Leaflet-based web map within a GUI designed for simplicity using Bootstrap (Figure 44). The choice of the Leaflet library was made after considering alternatives such as OpenLayers. While OpenLayers offers a comprehensive feature set, Leaflet was selected for its lightweight nature, simplicity, and ease of integration (Balla and Gede, 2025). Unlike the previous case studies, this 2D web map layer plays an important role in the interface. Its main function is to provide asset managers with an overview of the managed network and its structure and distribution across the territory. It also allows users to quickly filter elements of interest using toggle buttons and export informative reports on the history of the bridges before exploring more complex products.

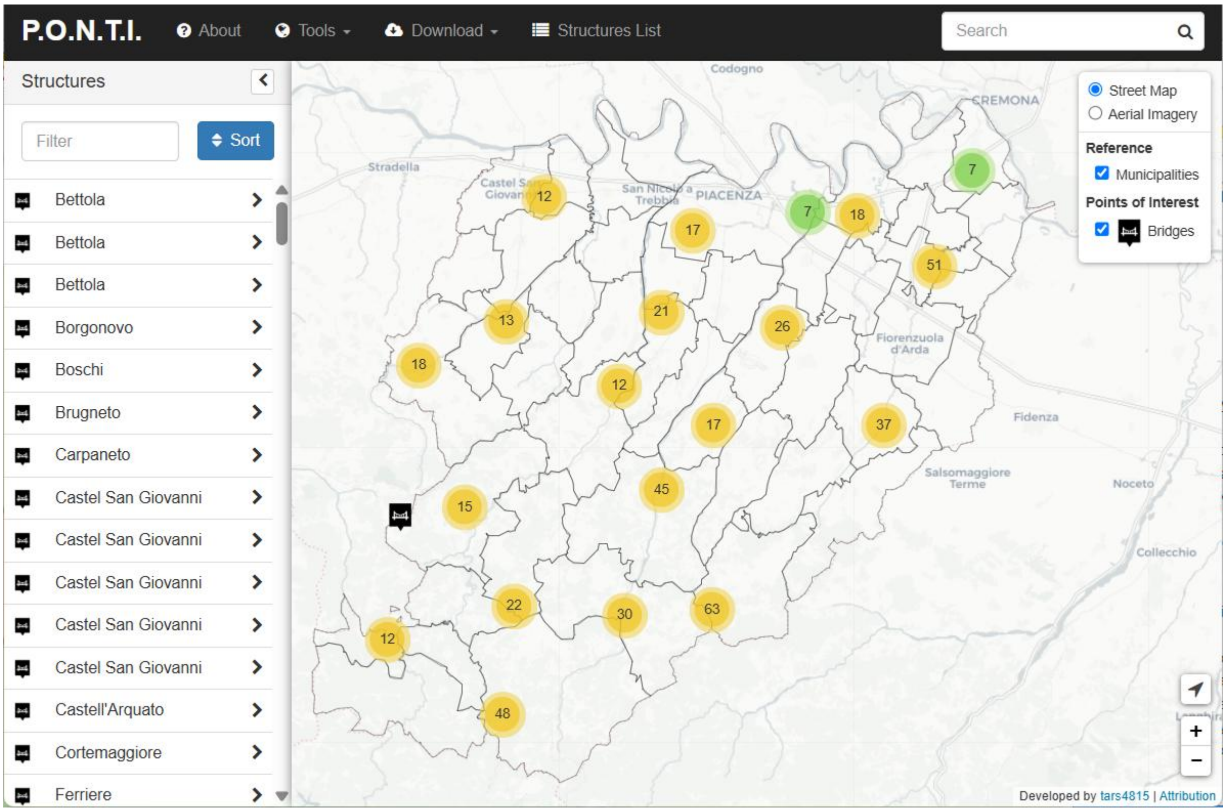


*Figure 44. Home page of the prototype with bridge asset overview in the interactive Leaflet-based map. The sidebar on the left allows users to filter structures based on attributes (e.g., official name, municipality). Based on the scale of visualization, point map features are clustered thanks to the Leaflet.markerCluster plugin, with varying colors based on numerosity of clusters (from Gaspari et al., 2025b).*

To take advantage of updating and writing permissions, users need to log in via the 'Tools' option in the top navigation bar. Here, it is also possible to implement other custom functionalities, such as downloading visualised data, measuring distance and calculating routes. The Leaflet map implements native core features such as zoom and user geolocation. The latter is particularly useful if the user is accessing the application from a mobile device in the field. In its current state, P.O.N.T.I. does not deploy its own GeoServer instance for publishing its internal data. As the architecture in Figure 44 suggests, the Leaflet map accesses the bridge data stored in the database through a more direct, lightweight method. The backend executes a spatial query against the PostgreSQL/PostGIS database, retrieves the Structures data, and serves it to the Leaflet client as a GeoJSON object, which is then rendered as map features. The platform's interaction with OGC services is limited to acting as a consumer. Customisation with connection to services of interest for the managers will allows users to overlay external data layers (e.g., WMS/WFS from a regional geoportal) for added context. Indeed, by layering multiple thematic information onto the asset dataset, it is possible to qualitatively evaluate other variables characterising the territorial context, such as hydraulic risk, catalogued gravitational phenomena or seismic zonation. Moreover, the rendering legend of the asset can be customised according to the end users' preferences. Structures can be symbolised differently according to the most recent inspections, live operability and rated conditions. If a rating system is needed in compliance with regional regulations on the matter, calculations can be implemented at the database level. This approach helps bridge management units to quickly identify structures requiring an up-to-date visual inspection for the planning of future maintenance activities.

Once a bridge of interest is identified on the map, clicking its icon provides the logged user with an overview of the main information associated to the bridge with a pop-up panel that includes both the report generation functionality and the inspection history access point, explained in detail in the next section. If a simplified report for a given bridge is needed, the user can click on the "Generate PDF" button (Figure 45). This action triggers the automatic generation of PDF file, thanks to the JSPDF library. The output document is created starting from a pre-defined template filled with information on the structure retrieved from the underlying database. This functionality can be useful and time-saving when country-specific regulations – like the Italian one – ask asset managers to fill standard PDF tables.

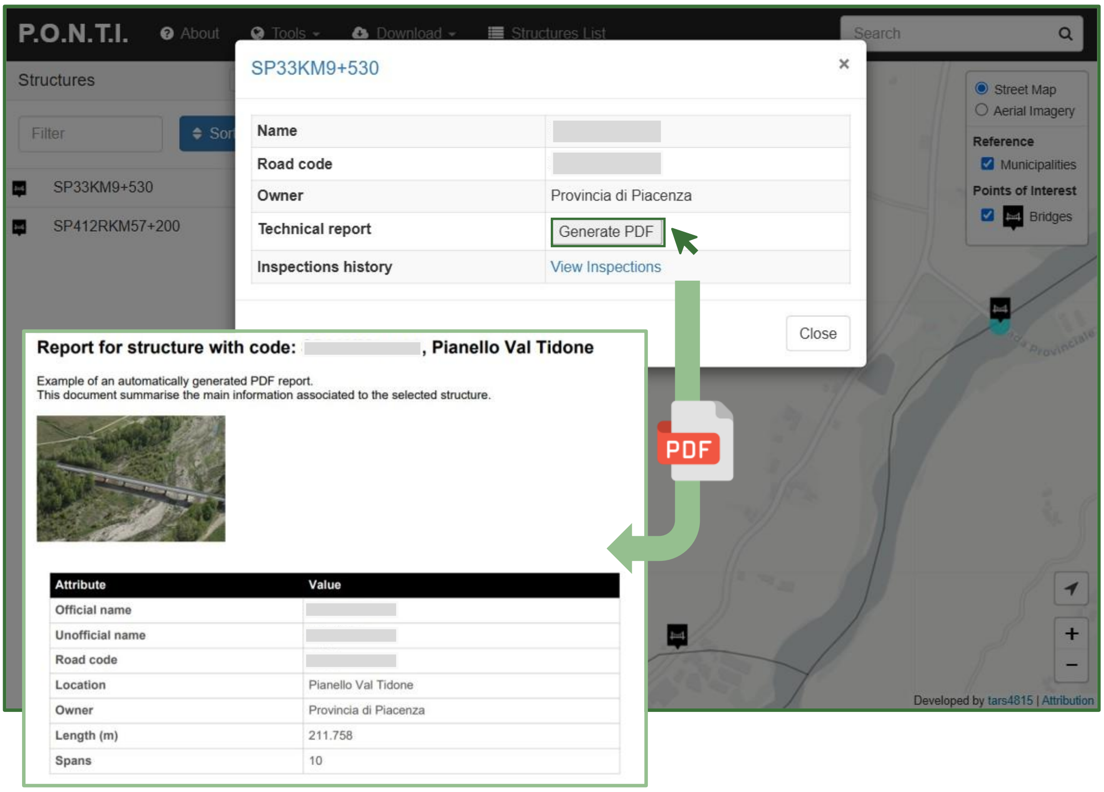


*Figure 45. Example of the export mode from the home page that leverages the functionalities of JSPDF for the automatic generation of PDF report files with bridge information that could be accessed offline (from Gaspari et al., 2025b).*

### *5.3.3.2 Inspection history dashboard*

After exploring the network-scale viewer and selecting a bridge of interest, users can access the structure-level menu, which provides an overview of the bridge's inspection history. This consists of a list of all surveying activities retrieved from the database by filtering by the bridge identifier (see Figure 46). It represents a custom feature with respect to the implementation of previous case studies, as it supports the systematic exploration of inspection reporting activities via a dedicated interface. Users can implement filters in this window according to their specific needs to simplify the search for activities within a specific time range or that produced specific products (e.g. point clouds and/or oriented images).

When a single inspection entry is selected, an informative panel is made visible, summarising the quantity and variety of products (e.g. the number of images, the presence of point clouds or BIM models) and the defects identified during the inspection (both in situ and a posteriori through the viewer). If the annotated defects have been assigned a severity level and a grading formula has been implemented in the code, an overall structure assessment rating is displayed. This custom functionality must be defined and implemented differently according to the case study, as most bridge grading systems are country- or region-specific. Finally, a small 3D viewer embedded in the inspection info panel shows a 3D viewer preview of the associated point cloud, if available for the given inspection.

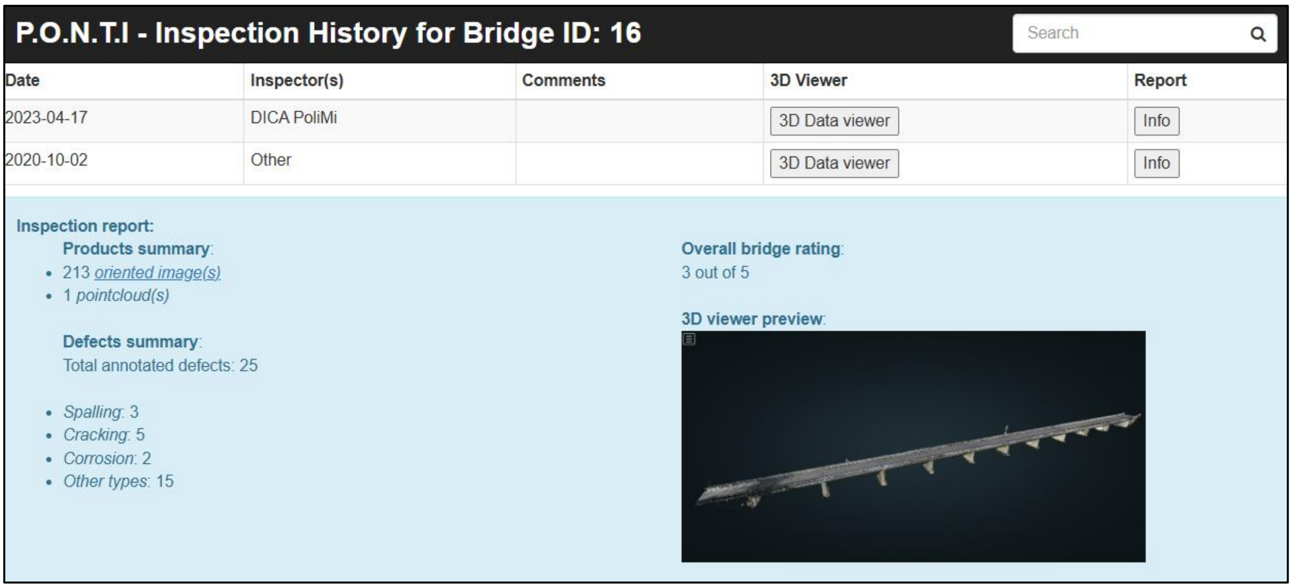


*Figure 46. Inspection dashboard for a selected structure. This page summarises the timeline of the bridge inspections, providing a simple interface for exploring the available survey products, computed bridge assessment rating and preview of the viewer (from Gaspari et al.. 2025b).*

#### *5.3.3.3 Three-dimensional viewer explorer*

Expanding the functionalities seen in the previous case study implementations, the 3D viewer module enables advanced interaction with bridge inspection data, supporting the interactive exploration of georeferenced point clouds and BIM models directly within the browser environment. To ensure high performance across these heterogeneous data types, the prototype adopts a modular architectural approach. In its current implementation, the system provides specialised viewing environments rather than a single fused scene; users are redirected from the main dashboard to the appropriate specialized viewer based on the specific 3D product (point cloud or BIM) attached to the inspection record (Figure 47Figure 48 Figure 49).

For point cloud datasets, the interface integrates PotreeJS, which is powered up by CesiumJS to provide a global geospatial context, including standard OpenStreetMap basemaps and terrain data. Within this environment, users can leverage polygon clipping and filtering tools to extract specific sub-elements, such as beams or decks, facilitating the isolated analysis of structural components (Figure 48). For instances requiring enhanced geospatial contextualization and completeness, a prospective customization involves pre-processing IFC models into OGC 3D Tiles. This would allow for the simultaneous visualisation of BIM data alongside point clouds within the Potree-Cesium viewer, using the native 3D Tiles loader from the CesiumJS engine.

Conversely, BIM-specific visualisation is handled via the XEOKIT library, chosen for its high-performance capabilities in parsing and visualising semantic IFC models. This module enables detailed component-level inspection, including hierarchical model navigation, object selection, sectioning, and the consultation of semantic metadata (Figure 49). The strategic selection of CesiumJS for global georeferencing and XEOKIT for architectural semantics reflects a robust technology choice for integrated GIS-BIM functionalities, aligning with validated trends in recent open-source bridge documentation research (Gao et al., 2024).


*Figure 47. The interface allows users to inspect a textured 3D model of the bridge and record defect annotations by selecting a point directly on the geometry. Each annotation captures spatial coordinates, defect type (e.g., spalling), severity level, and optional textual descriptions. This integration facilitates consistent documentation and streamlined condition assessment in a spatially aware environment (from Gaspari et al., 2025b).*


*Figure 48. Example of a user-input procedure for defining a structural element directly within the 3D viewer. This approach allows users to define a bounding box to quickly filter the point cloud view and hide irrelevant parts. The OpenStreetMap basemap on the background is visualised through CesiumJS functionalities (from Gaspari et al., 2025b).*

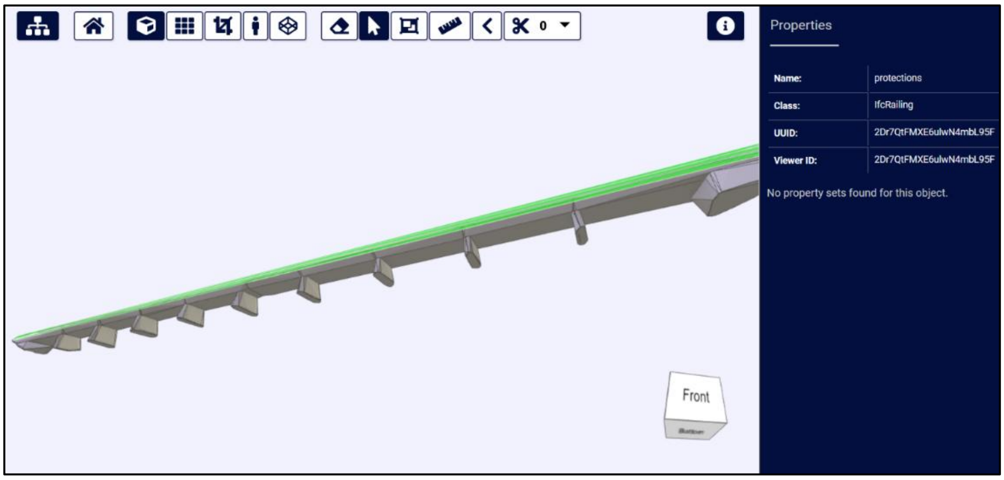


*Figure 49. Screenshot of user interface for the 3D viewer component based on XEOKIT library for visualising BIM models and inspecting their properties (from Gaspari et al., 2025b).*

Point clouds are overlaid with images captured during surveys and oriented in the correct direction (Figure 47). Clicking on a given image in the 3D space overlays it in that space. The camera parameters stored in the database are used to link the 2D image pixels to the 3D point cloud geometry via dedicated native Potree functionality. This enables users to compare textures and locate defects by clicking on the photo to generate a 3D annotation. Indeed, a key feature of the P.O.N.T.I. implementation is the capability to annotate defects directly on 3D models, attaching severity grades and notes linked to the database for effective reporting. The severity grade option implements a single defect severity according to an arbitrary grading scale chosen by the asset management administration. This allows for a country-specific defect grading system to be chosen for custom implementation. Once defects are entered into the database for a given inspection, a structure-level grading formula calculates an overall bridge rating (see the example in Figure 46). In this case, too, the formula must be chosen by the administration, as the resulting indicator could be derived using different approaches depending on the country's regulations—either averaged, worst-conditioned, or other (Iacovino et al., 2021). These modifications can be made at the database level by implementing custom trigger formulas for the relevant field in the inspection entity. Measurement tools for distances, surface areas, and volumes are integrated, along with the ability to define custom cross-sections to inspect internal structural features. These functionalities are critical for detailed, compliant bridge inspections and maintenance planning.

This integrated 3D viewer thus enhances remote inspection and collaborative assessment by combining spatially accurate visualization, analytic tools, and interactive defect management. In accordance with the design including a re-adaptability component, the prototyped code, written in HTML, CSS and JavaScript languages, is available on a GitHub repository (https://github.com/Tars4815/ponti) (accessed on March 29th, 2026).

### 5.3.4 Implementation outcomes

The customisation of the P.O.N.T.I. prototype demonstrates the feasibility of an open-source, state-aware framework for infrastructure management. By integrating structured database storage with interactive 3D geovisualisation, the prototype provides a robust response to the data fragmentation identified in the initial requirement analysis together with the officers from the Province of Piacenza.

The prototype achieved the successful centralisation of heterogeneous inspection products ranging from raw UAV-derived point clouds and BIM/IFC models to 2D records into a single Common Data

Environment (CDE). This integration effectively resolves the data silo problem common in provincial administrations, where relevant information is often dispersed across inconsistent local folders. By adhering to common standards and utilising FOSS components, the system ensures that bridge data remains interoperable and accessible without the constraints of proprietary licensing, thereby supporting the long-term digital sovereignty of the managing public administration.

A key technical outcome is the transition from passive visualisation to active management. The prototype's interactive digital 3D annotation feature allows inspectors to georeference structural defects directly onto the point cloud from in-situ surveys. Unlike traditional 2D reporting, this spatialised approach ensures:

- Traceability, as every defect is linked to a specific coordinate in the PostGIS database.
- Accountability through role-based access which ensures that only authorised engineers can validate or update the status of an inspection.
- Clarity, with the system providing a robust alternative to textual documentation by guiding the user through oriented photos and 3D geometric filters, significantly improving the coherence of the structural health record.

The implementation confirms that a modular, micro-services-based architecture is highly suitable for administrations with limited financial and technical resources. The use of a free and open-source stack (PostgreSQL/PostGIS, Potree, XEOKIT) allowed the Province of Piacenza to deploy a customised management tool without the burden of expensive software suites. Furthermore, the ability to generate automated reports and exports directly from the database reduces administrative overhead, allowing technicians to focus on safety assessments rather than data retrieval.

## 5.4 Summary of case studies implementations

The three case studies presented in this chapter demonstrate the practical scalability of the proposed framework, successfully traversing the first three stages of the digital maturity roadmap. By instantiating the same core architecture across diverse domains, the research validates the framework's role as a common ground for geospatial data management.

The primary architectural takeaway from these implementations is the strategic, incremental activation of functional modules tailored to the specific level of user agency required by each domain. The framework proves that the transition from a narrative-focused tool to an operational management system does not require a complete redesign of the engine but rather a calibrated configuration of its modular components. This scalability is rooted in the state-aware evolution of the system's memory, which moved from the stateless, memoryless visualisation environment of the Farnese Castle towards the complex, persistent relational databases required for infrastructure management in the P.O.N.T.I. prototype. In the cultural heritage case, the architecture was optimised for a realistic virtual accessibility of a complex site, leveraging out-of-core 3D streaming to break physical barriers for public storytelling without the need for a persistent backend. This baseline was significantly expanded in the Belvedere Glacier implementation, which introduced new functionalities by integrating a read-only spatial database for 4D monitoring. This adaptation demonstrated the framework's ability to manage longitudinal scientific records and time-series data, effectively transforming the 3D scene from a static model into a searchable scientific repository aligned to persistent external archives like Zenodo. The progression culminated in the P.O.N.T.I. prototype, where the architecture was further upgraded by enabling full bidirectional CRUD operations. This final stage transitioned the platform into an active operational workspace, where the integration of semantic BIM/IFC models through XEOKIT and the implementation of role-based access control allowed professional inspectors to take direct agency by updating structural records within a georeferenced environment.

# 6

# Cross-domain analysis and validation

*Evaluating framework flexibility across built and natural environments*

The previous chapter presented the practical application of the framework across three distinct and heterogeneous domains: cultural heritage, the natural environment, and civil infrastructure. While each case study addressed site-specific challenges ranging from the interactive storytelling of the Castello Farnese to the 4D monitoring of the Belvedere Glacier and the structural management of the P.O.N.T.I. prototype, they collectively provide the empirical evidence required to validate the modular architecture described in Chapter 4. This chapter serves to discuss the results, moving beyond the specificities of the individual sites to identify the technical and functional commonalities that characterise the framework's overall performance.

The inductive logic of this research suggests that despite the varying scales and data types involved, the core requirements for geospatial data management remain consistent. The framework enables increasing levels of customization by progressively unlocking its internal modules as the user's needs evolve. In the following sections, this chapter synthesises the results of these experiments through a three-fold validation strategy: an external validation against the current state-of-the-art (Section 6.1), a quantitative benchmark of maturity performance (Section 6.2), and a critical discussion of the technical trade-offs and re-adaptability of the open-source stack (Sections 6.3).

## 6.1 Validation against State-of-the-Art

In order to assess the effectiveness of the custom implementations of the framework in each domain, a dedicated validation of the implemented case studies against similar state-of-the-art approaches and applications documented in literature has been conducted. Given the multidisciplinary nature of this research, the validation follows two distinct pathways. For the natural environment domain, a direct comparative analysis is conducted against a well-established project for web-based geoscientific data integration. For the cultural heritage and civil infrastructure domains, where the landscape is characterised by fragmented specialised tools rather than unified platforms, a requirement fulfilment analysis is employed. In these cases, the framework is validated against a synthesis of best practice requirements derived from recent literature, demonstrating how the modular architecture fulfils the functional, technical, and governance goals identified by the research community.

### 6.1.1 Cultural Heritage

The implementation of the Farnese Castle platform serves as the practical realisation of the paradigm shift currently discussed in digital heritage literature. While the study by Jin and Liu (2022) provides the theoretical recommendations for the “fluid space" of digital heritage, and the research conducted by Potenziani et al. (2025) outlines the technical best practices for interactive deployment and data reuse (Table 7), the framework developed in this research provides a concrete, open-source workflow that bridges the gap between high-end scientific documentation and public accessibility in interactive viewers.

*Table 7. A comparison of the main topics and related recommendations for digital platforms in the field of cultural heritage, as well as the solutions implemented in the Castello Farnese viewer.*

| Key element | Recommendation | Implemented solution |
|---|---|---|
| Accessibility | Overcome physical site restrictions and barriers with an intuitive GUI | Web-native viewer that allows to explore dynamically a restricted area (Potree + GUI buttons moving between predefined hotspots) |
| Temporal state | Show past and present conditions of the site along a timeline | Definition of temporal rewind icons and slider showing different historical phases in a single scene |
| Sustainability | Adopt reusable technologies and FOSS stacks | Adoption of open-source solutions with their reproducible code freely accessible on GitHub |

A core contribution of this implementation is indeed its ability to create what Jin and Liu (2022) define as a "fluid space". This concept is particularly relevant for the Castello Farnese, a site characterised by restricted accessibility due to its location within an active military zone. By adopting a web-native architecture, the framework moves the heritage experience away from a fixed physical location into a globally accessible digital environment. Furthermore, the implementation of the temporal rewind feature, allowing users to toggle between the 1547 reconstruction and the current structural state, directly addresses Jin and Liu’s call for digital experiences to reflect the "living state of history" by integrating past, present, and future temporal dimensions.

The validation further confirms the framework’s alignment with the recent technical recommendations defined by Potenziani et al. (2025). A primary challenge in heritage digitisation is the high cost of creating 3D content exclusively for dissemination purposes. This framework addresses these limitations by reusing scientific documentation data (TLS and UAV photogrammetry) originally generated for structural health assessment and historical research, serving two purposes (Figure 50). By direct-streaming these accurate products through the Potree-based viewer, the framework proves that high-fidelity geomatics data can serve a dual purpose: expert analysis and public storytelling.

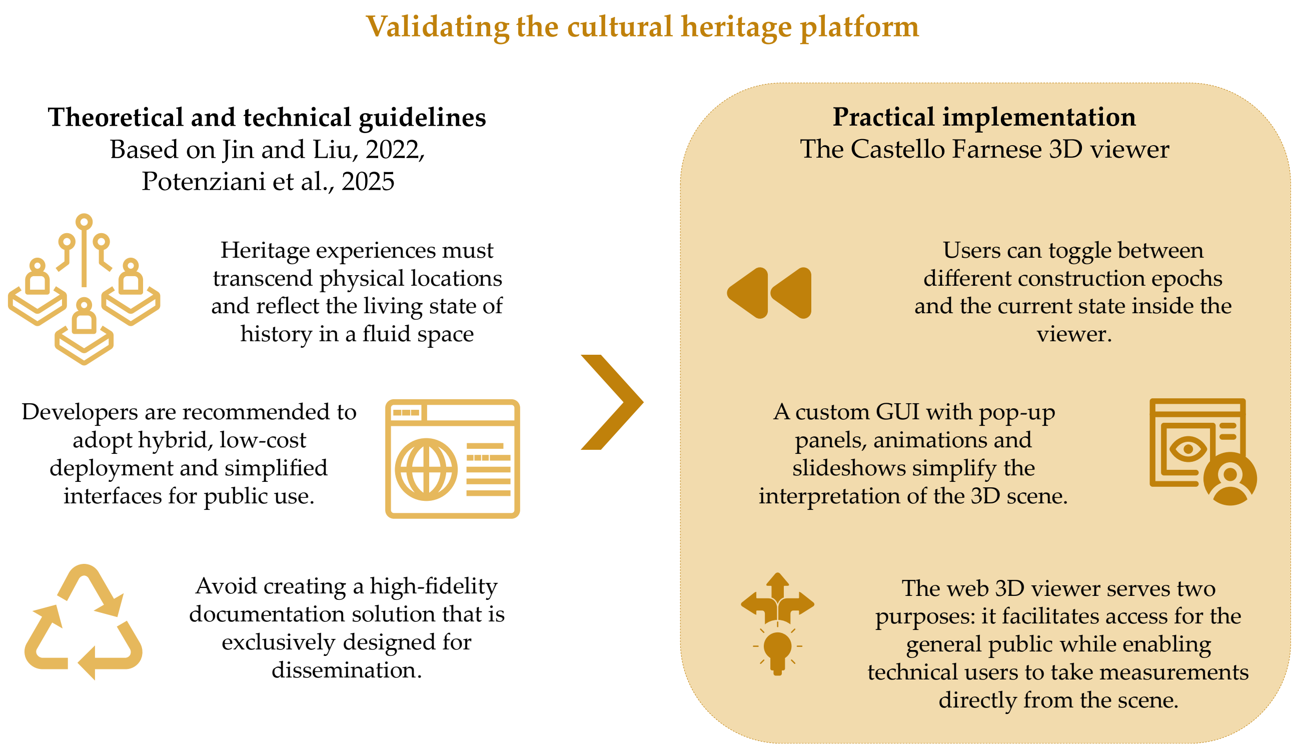


*Figure 50. Summary of the main challenges and guidelines from literature on digital heritage visualisation and dissemination compared to how they were addressed in the Castello Farnese case study.*

Another critical point is the framework's response to the User Experience (UX) issues highlighted by Potenziani et al. (2025). While tools like Potree are excellent for rendering massive point clouds, their native interfaces are often too technically oriented for general public use or installation in interactive kiosks on site. The Farnese Castle implementation solves this specific problem by developing a customised set of layers for the GUI. By stripping away expert-level menus and replacing them with simplified navigation hotspots, guided virtual tours, and intuitive storytelling widgets, the framework transforms a solution with highly specialised tools for Geomatics practitioners into a user-centric dissemination platform.

Finally, the platform validates the transition towards hybrid, low-cost dissemination strategies. Recent literature emphasises that the modern trend in heritage management is the use of WebGL-based technologies that can be deployed simultaneously online and on physical, in-situ interactive kiosks. By building on an entirely FOSS stack and realising the underlying source code, this case study provides a viable, reproducible alternative to expensive, proprietary black-box solutions. This approach ensures that small and medium-sized institutions can maintain digital sovereignty over their assets, providing a foundational baseline for the more advanced monitoring and management levels.

### 6.1.2 Natural Environment

The Belvedere Glacier project's implementation has a direct counterpart in the Svalbox project, a leading web-based portal for integrating geoscientific data in the high arctic (Senger et al., 2021a). While Svalbox engages a larger consortium of academic institutions and covers a broader geographic area (Svalbox, 2026), both platforms share the fundamental objective of democratising access to high-resolution field documentation. Specifically, both initiatives propose modular frameworks for geospatial data management and provide robust dissemination strategies for scientific research and pedagogical applications. Comparing these two approaches allows to evaluate the methodology designed for the Belvedere Glacier as an accessible alternative for localised environmental monitoring.

The Svalbox project is a comprehensive geoscientific platform designed to integrate multi-scale geological data from the Norwegian Arctic archipelago of Svalbard, developed at the University Centre in Svalbard (UNIS) since 2017 (Senger et al., 2021b). Acting as both a research database and an educational tool, the project aims to digitally document Svalbard's unique geological history and make this information accessible to the wider global geoscience community. Unlike many long-term monitoring projects, the Svalbox Digital Model Database publishes complete data packages on repositories such as Zenodo and the Norwegian National Infrastructure for Research Data. These packages include input data (e.g. raw imagery and GNSS logs), processing metadata (e.g. software reports and project files) and outputs (e.g. digital outcrop models and orthomosaics) (Betlem et al., 2023).

Rather than a standalone application, the operating system developed for Svalbox creates a digital ecosystem of software (Table 8). Metadata is managed via a PostgreSQL database with PostGIS extensions and fed into a public web portal. It also integrates with external 2D and 3D visualisation tools and platforms, such as ArcGIS StoryMaps, SketchFab and V3Geo. As of the 2023 release, the database contained 135 Digital Outcrop Models, covering around 114 km² of stratigraphy and establishing the system as a valuable regional resource for geological analysis and digital twin generation. Svalbox is actively used to bridge the gap between traditional fieldwork and digital analysis. It supports virtual field trips and course modules, in which students and researchers use the data to solve real-world problems, such as reservoir characterisation and licence claim simulations (Senger et al., 2021a).

*Table 8. Summary of the tools adopted for the implementation of the Svalbox project, classified according to their corresponding module and primary responsibility.*

| Module | Primary Responsibility | SVALBOX | Belvedere |
|---|---|---|---|
| Data storage | Long-term preservation following FAIR principles for both raw and processed data. | UNIS Windows File Server, PostgreSQL | PostgreSQL, PostGIS |
| Data sharing | Public access of 2D and 3D models for scientific collaborations and educational initiatives. | Zenodo, ArcGIS REST API, SketchFab, V3Geo | GeoServer, Zenodo |
| Visualisation | Rendering of interactive 2D and 3D virtual field trips and mapping experiences. | Svalbox portal (Wordpress+ArcGIS), ArcGIS StoryMaps, | Website, Potree, Cesium, Leaflet, Echarts |

Regarding data integration, Svalbox operates as a distributed ecosystem, leveraging a network of external platforms to handle heterogeneous data types. In this model, 2D data and borehole records are hosted on an ArcGIS-based portal, while 3D digital outcrop models are offloaded to specialized external repositories. This allows Svalbox to excel in multi-scale geological characterization, particularly in the integration of surface outcrops with subsurface seismic data. Conversely, the Belvedere project adopts a centralized approach, integrating 2D GNSS data, WMS layers, and 3D morphology within a single, unified custom interface. By layering these datasets within a synchronised environment, the framework prioritises the immediate spatial correlation between surface morphology and point-based observations. This divergence extends to the technical architecture and accessibility strategies. Svalbox relies on established commercial and community infrastructures to ensure high availability through third-party viewer capabilities. In contrast, the Belvedere framework is built upon a fully custom, self-hosted open-source stack deployed via Docker. By utilizing foundational libraries like Potree, CesiumJS, and Echarts.js directly, the framework avoids dependency on third-party hosting constraints. Furthermore, the publication of the full source code on GitHub reinforces a commitment to scientific reproducibility and adaptability, allowing other researchers to fork and modify the stack for localized monitoring needs.

However, the most significant distinction lies in the conceptualisation of analytical agency and temporal data. Within the Svalbox environment, the 4D component is largely interpreted through the lens of geological deep time and stratigraphy, with the web viewer serving primarily as a tool for static visualisation and virtual field trips. While temporal analysis of surface changes is possible, it generally requires downloading the datasets for traditional desktop analysis. The Belvedere framework, however, shifts the focus towards dynamic physical monitoring. It treats time as a near-real-time variable, featuring specific tools for the sequential navigation of multi-epoch point clouds and interactive pop-up graphs. These tools visualise velocity time-series derived directly from the connected PostGIS database, transforming the platform from a static repository into a proactive scientific monitoring system.

While the Svalbox project represents an efficient example for large-scale geoscientific dissemination as a data-centric geological atlas, the Belvedere Glacier customisation distinguishes itself by prioritising multi-audience agency over broad-scale exploration (Figure 51). Unlike portals that focus on the visualisation of static geological outcrops, this framework's integration of persistent database queries and interactive time-series analysis fulfils the requirements for a tool designed specifically for active environmental monitoring. This comparison confirms that the proposed architecture is a specialised customisation optimised for the high-frequency temporal analysis necessary for modern glaciological research that is able to support dissemination strategies targeting a larger audience.

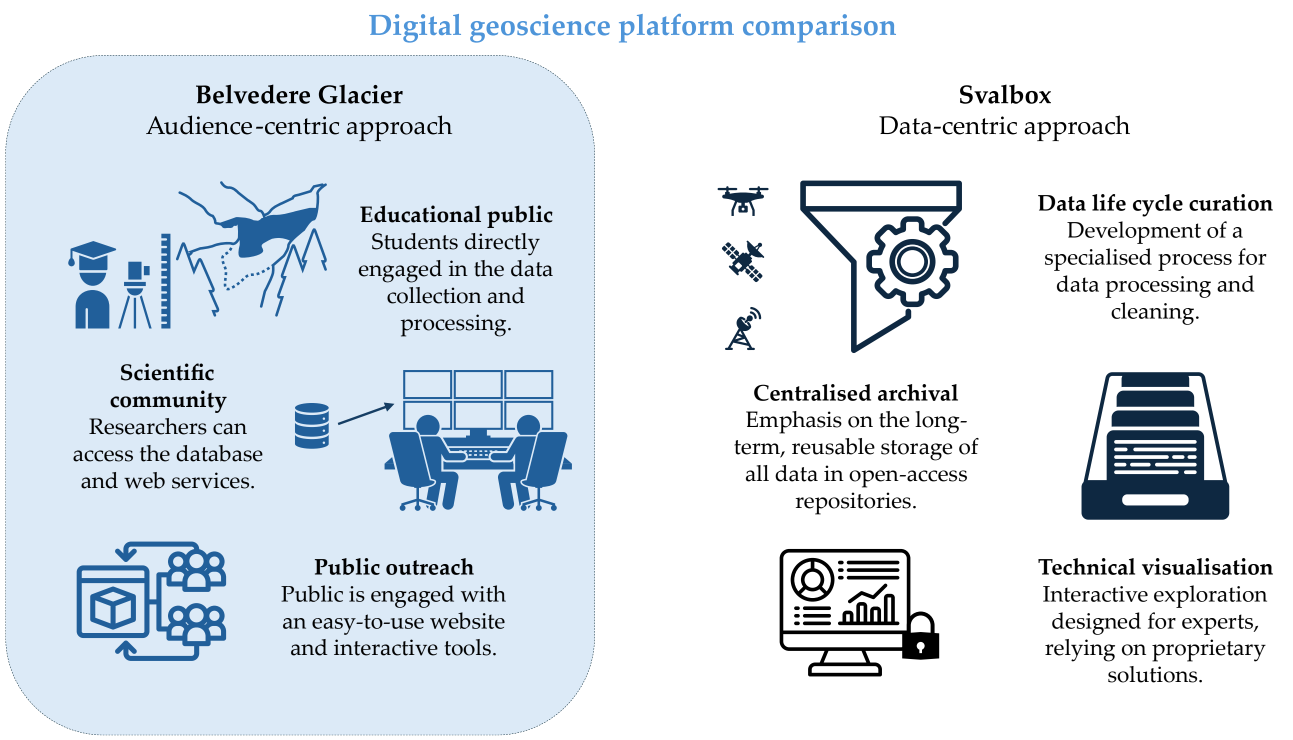


*Figure 51. Synthesis of the comparison between the different approaches developed for the Belvedere Glacier platform and the Svalbox larger-scale initiative maintained by the University Centre in Svalbard.*

### 6.1.3 Civil Infrastructure

The validation of the P.O.N.T.I. prototype is conducted by measuring its functional capabilities against the theoretical frameworks and industry trends identified in recent comprehensive reviews by Mohammed et al. (2026) and Nhamage et al. (2025). While these review papers act as a theoretical blueprint for the future of the sector, identifying systemic gaps in data fragmentation and budget constraints, the implementation presented serves as an empirical validation of how these gaps can be bridged using an open-source, modular approach (Figure 52).

A primary alignment is found in the role of Web-GIS as a centralized information hub. Mohammed et al. identify the lack of a unified organising platform as a core reason for obscured risk in infrastructure management. The P.O.N.T.I. prototype directly operationalises this requirement by transitioning from fragmented, local file-based workflows (spreadsheets and local folders) to a centralised Web-GIS environment. This architecture fulfils the organising platform role by ensuring that spatial data, analytical queries, and decision-making processes are co-located within a single, accessible interface.

Furthermore, the framework addresses the critical need for multi-scale data integration (BIM, GIS, and point clouds). The prototype validates this trend by integrating specialised libraries, such as Potree for massive point clouds and XEOKIT for BIM/IFC models, within a unified access where users can access both type of output. This allows for the management of "as-is" structural conditions derived from laser scanning and photogrammetry, directly responding to the call for semantically enriched spatial inventories.

A significant contribution of P.O.N.T.I., noted as a recurring challenge in literature, is the mitigation of cost barriers and accessibility gaps. Both references cite budget constraints and software maintenance costs as primary obstacles to the adoption of bridge Digital Twins. By developing the framework entirely on a FOSS stack, the presented implementation provides a scalable solution specifically tailored for small and medium-sized public administrations, as an alternative open and feasible approach to complete data-driven approaches in proprietary ecosystems (Pallante et al., 2024). This approach ensures that the digital transformation of infrastructure remains economically sustainable and supports the digital sovereignty of public institutions.

Finally, the P.O.N.T.I. implementation allows for a clear distinction between a Management System and a full Digital Twin. While Nhamage et al. define the Digital Twin through real-time IoT integration and predictive simulation, the P.O.N.T.I. prototype focuses on the robust management of static, high-resolution inspection records. However, by designing the platform with an extensible, modular architecture, it aligns with the future directions suggested by the state-of-the-art. The current implementation provides the necessary foundational core, the transit hub for geospatial data, to which public administration needs to first align in an accessible way upon which future real-time monitoring and AI-driven predictive tools can be integrated, as discussed in Chapter 8.

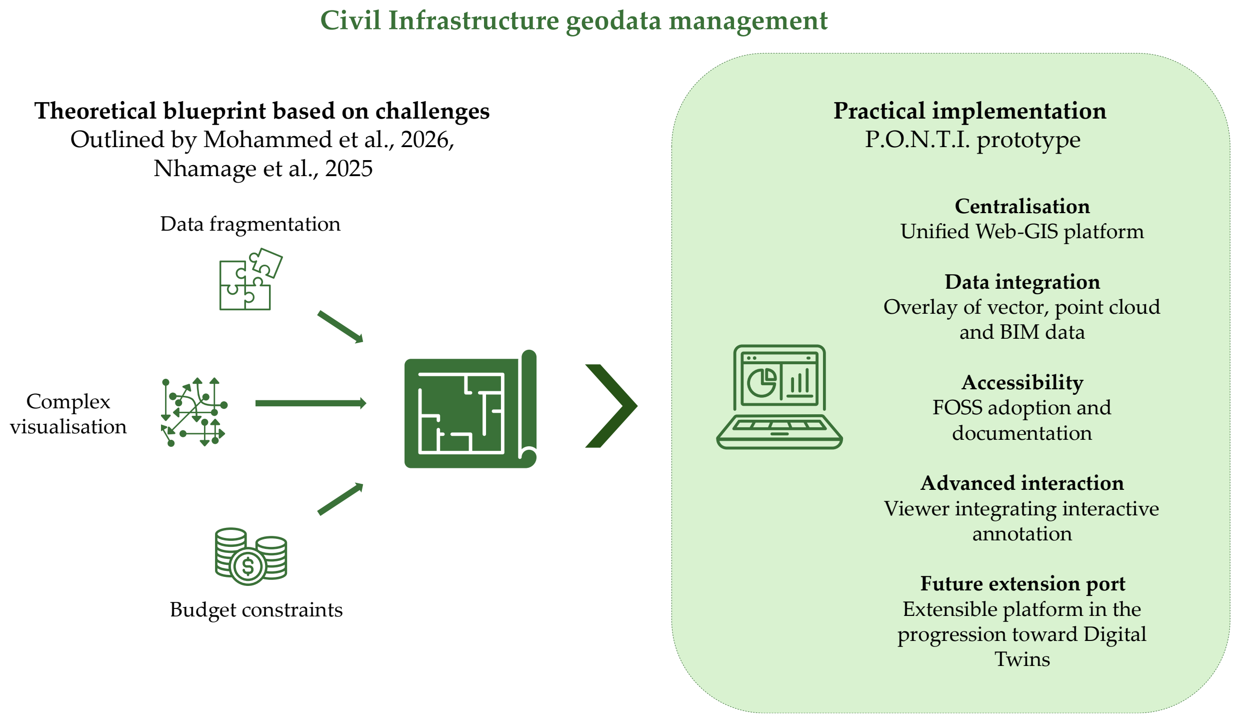


*Figure 52. Summary of the main recommendations from the literature on road infrastructure management and visualisation and compared to how they were implemented in the P.O.N.T.I. prototype.*

## 6.2 Benchmark maturity evaluation

This section performs a cross-domain analysis of the three framework customisations detailed in Chapter 5. To move beyond qualitative descriptions, the research employs the User Engagement Maturity Model introduced in Section 3.3.1 with four distinct dimensions, providing a structured system to evaluate the platform's ability across different domains. To assign a specific implementation to a given maturity level, the model evaluates a set of benchmark dimensions capturing how the platform supports verification, traceability, and operational use. The four benchmarks' dimensions are defined as user agency, system memory, data handling and operational goal.

Of these, the user agency dimension measures the extent to which users are granted control and responsibility within the digital environment, as well as their capacity to take intentional actions based on their own goals and desires (You et al., 2024; McGivney, 2025). At an initial passive level, users can only visualise precomputed 2D and 3D content and cannot influence the underlying data. As the system evolves to the analytical level, users are granted greater agency by being allowed to interrogate the data through spatial queries and attribute inspection.

System memory evaluates the mechanisms through which the platform stores, recalls and maintains knowledge over time, essentially defining its level of state awareness. At the initial stateless level, the viewer renders static data without a persistent back-end state, meaning that interactions do not survive the session. Maturity increases at the second level, which is defined by a read-only state. At this level, the system can retrieve structured information from a database for display, but it cannot modify the source records. The model reaches its highest level with a persistent bi-directional state, which supports full transactional read and write access to a relational database.

The data handling dimension measures the complexity and semantic richness of the information processed by the platform, tracking the transition from simple geometric visualisation to integrated, multi-dimensional information systems. This metric serves as a proxy for the system's capacity to support scientific reasoning and decision-making, rather than just aesthetic rendering. At the static geometry level, the platform handles points, meshes, or raster layers that lack a broader temporal or semantic structure. As the system moves towards spatio-temporal data, it begins to integrate time-series information, 4D datasets, and evolving measurements, allowing for the analysis of dynamic phenomena. The highest level of maturity is achieved when the platform acts as a unified hub for inspection reports, semantic classifications, administrative records, and complex management workflows.

The operational goal dimension identifies the primary purpose for which the platform is designed and validated, effectively linking technical capabilities to real-world use contexts. This dimension makes system maturity explicitly use-oriented, ensuring that higher levels correspond to environments capable of sustaining institutional responsibility, reliability, and routine workflows. At the dissemination level, the platform's objective is focused solely on communication, public outreach, and exploratory visualisation. As the system matures towards scientific monitoring, the goal shifts to the rigorous measurement, comparison, and interpretation of dynamic spatio-temporal phenomena. Improving complexity in the set of needed operations, asset management systems support instead critical operational functions such as inspection, maintenance, regulatory compliance, and long-term governance. Higher level of operations implies instead prediction capabilities for generating simulation scenarios in digital twins and autonomous update through interconnected network of physical and crowdsourced systems.

The results of this comparative analysis are summarised in Table 9, which classifies the maturity reached by the Farnese Castle, Belvedere Glacier, and P.O.N.T.I. implementations.

*Table 9. Comparative benchmarking of the three case studies against the maturity model dimensions.*

| Dimension | Farnese Castle | Belvedere Glacier | P.O.N.T.I. |
|---|---|---|---|
| User agency | Passive, restricted to curated navigation paths and pre-defined visual toggles. | Analytical, with users performing on-demand spatial queries to extract quantitative attributes (velocity). | Productive, as users perform full CRUD operations (create/edit defects) directly within the interface. |
| System memory | Stateless, as no persistent backend connection is implements, resulting in the | Read-only, unidirectional connection from Server to Client for retrieving time-series data. | Persistent, transactional connection: user inputs are permanently stored in the DB. |

| | | | |
|---|---|---|---|
| | reset of interactions after each session. | | |
| Data handling | Static geometry with high-resolution point clouds and meshes representing fixed historical epochs. | Spatio-temporal with the integration of 4D time-series, multi-epoch surveys, and displacement vectors. | Operational ecosystem, with the integration of BIM models, oriented imagery and inspection reports. |
| Operational goal | Dissemination, aiming at public engagement and interactive storytelling. | Scientific monitoring, implying quantitative documentation of environmental dynamics. | Asset management, supporting decision-making, maintenance planning and accountability. |
| **Level** | Digital exhibition (Level 1) | Scientific monitor (Level 2) | Management system (Level 3) |

The comparative analysis of the implemented prototypes, as synthesised in Table 9, demonstrates the framework's capacity to scale its functional maturity across distinct operational requirements through a progressive improvement of technical complexity and user agency. Starting with the Farnese Castle implementation, the framework validates a Level 1 for digital exhibition capability: the system prioritises immediate, browser-based accessibility through a stateless configuration that delivers high-resolution photogrammetric and historical narratives in a memoryless architecture, intentionally restricting the user to a passive yet guided storytelling role to ensure intuitive navigation for non-expert audiences. Moving towards the Belvedere Glacier case study, the architecture matures into a Level 2 for scientific monitor, introducing state-awareness via a read-only relational database that elevates the user to an analytical role. This transition effectively transforms the 3D scene into a searchable 4D repository, where stakeholders can interrogate multi-temporal scientific measurements over decadal scales without modifying the source records, thus maintaining the metric integrity required for environmental documentation. Finally, the P.O.N.T.I. prototype achieves Level 3 for management system status, marking the definitive shift to productive agency where inspectors perform bidirectional CRUD operations directly within the 3D environment. This persistent system state ensures that every structural annotation and element segmentation is permanently archived, fulfilling the requirements for a legally auditable infrastructure governance tool that integrates BIM models and qualitative inspection reports into a unified operational ecosystem.

Collectively, these implementations validate the framework as a robust digital shadow (Kritzinger et al., 2018; Fuller et al., 2020), a high-fidelity replica updated through structured human interaction, establishing the necessary readiness roadmap to bridge the current gap towards predictive Level IV Digital Twins. This gradualist progression ensures that the modular architecture serves as an extensible foundation, empowering stakeholders as skilled agents in their own digital sovereignty rather than merely deploying a "black-box" autonomous system from scratch. By proving that a single open-source engine can satisfy the diverse needs of heritage dissemination, environmental monitoring, and civil infrastructure governance, the research confirms that the path towards a unified common ground for geomatics lies in the modular scalability of user agency and system memory.

## 6.3 Framework re-adaptability

As established in the design phase, a critical requirement for overcoming the data silo problem was ensuring that the developed solutions were not restricted to a single project but could serve as a versatile template for diverse built and natural environmental contexts.

### 6.3.1 Cross-domain readaptation

A fundamental achievement of the proposed framework is the high degree of portability exhibited by its architectural layers. Rather than developing isolated silos for each domain, the research followed a common ground philosophy where the core components, specifically the geospatially enabled database schema and the 3D viewer modules, were designed for transversal application. In particular, the full re-adaptability of the management system logic across domains was tested through the implementation of the Church of the Benedictines case study documented in Gaspari et al., 2025c.

The goal was to test the re-adaptability of the P.O.N.T.I. framework while providing digital documentation and condition assessment tools for a 17th century Roman Catholic complex in Piacenza, Italy. Having remained closed and abandoned for decades, the church suffered significant structural degradation resulting from neglect and varied historical misuse until 2000s. As the local municipality was seeking a modern approach to documenting these complex pathologies, the framework's relational database schema was adapted from one initially designed for tracking bridge defects to track masonry decay. In this case, the need for defect annotations extended beyond structural deficiencies, encompassing damage to artworks such as statues and frescoes located inside the church.

The indoor and outdoor point clouds resulting from the integration in-situ surveys employing UAV-photogrammetry, TLS and Simultaneous localization and mapping (SLAM) scanning served as the starting point for the digital 3D documentation of the heritage site (Figure 53). These outputs were then converted in a web-ready Potree format and associated to the related survey contextual information inserted in a PostgreSQL database.


*Figure 53. Integrated outdoor scene point cloud of the case study, resulting from the co-registration of UAV-photogrammetry and TLS (Gaspari et al., 2025c).*

The annotating and damage mapping functionalities were used to identify and prioritise areas of intervention for the future restoration by repurposing the bi-directional link between the 3D scene and the PostGIS backend, which had already been tested for the P.O.N.T.I. case study. The main customisation involved the inclusion of a different dictionary for architectural and artistic defects, as well as the use of the bounding box definition to isolate façades or other relevant portions of the structure. This differs from the rigorous definition of structural elements in bridges and allows the annotations to be exported together with the bounding boxes (Figure 54). This proved particularly useful for generating additional documentation and reports, which typically include orthomosaics of walls and/or façades in the cultural heritage restoration domain (Caffarri et al., 2026). By importing the clipped point cloud and the associated annotations inside a CloudCompare project is hence possible to easily produce an orthophoto or execute additional advanced processing on the portion of interest (Figure 55).

The research proved that the technical core is domain-agnostic. The transition from documenting bridge spalling to historical masonry cracks as well as other defects to architectural or artistic elements was achieved without fully restructuring the central engine, confirming that the framework's management capabilities are adaptable across different structural types.

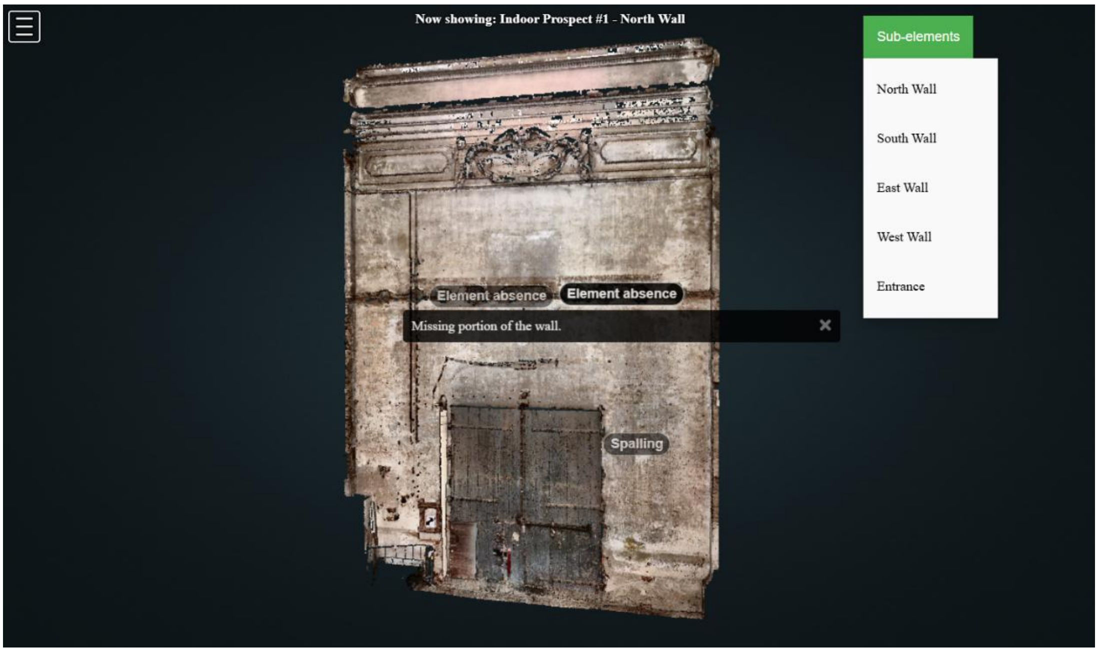


*Figure 54. Interactive 3D viewer displaying defect annotations on a selected sub-element, enabling documentation and visualisation within the high-resolution point cloud environment (Gaspari et al., 2025c).*


*Figure 55. Exported point cloud of structural sub-element and associated annotations in the CloudCompare environment. Additional processing, meshing and rasterization can be performed to produce other products as required without having to deal with the entire point cloud (Gaspari et al., 2025c).*

### 6.3.2 Functional scalability

To evaluate the framework's capacity to handle complex infrastructure assets beyond bridge networks, a dedicated testing phase was conducted in collaboration with TECNE – Gruppo Autostrade per l'Italia as part of the visiting semester included in the author's PhD programme. This collaboration involved mapping current workflows and practices in geodata management. It provided a critical use case focused on documenting and managing georeferenced planning and inspection data for highway tunnels. Unlike the bridge inspection protocol, the management of tunnel assets presents unique challenges regarding the volume and heterogeneity of the input data. The specific case study involved the integration of massive point clouds provided by external surveyors, extensive topographic network measurements and cartography in CAD format.

Figure 56 shows a screenshot of the P.O.N.T.I. viewer for the case study of a tunnel under renovation in central Italy. The application was used to enable interactive access to the point clouds, which are geolocated in the same reference system (WGS84 – UTM Zone 32 N, EPSG: 32632) as the vector data geometries associated with the planning CAD documentation (originally stored in .dxf format). Visualisation of the CAD data was made possible following a pre-processing step involving conversion to GeoPackage format (OGC, 2024) and georeferencing using known ground control points. By overlaying renovation planning documents stored as attachments with the TLS point cloud acquired during the works, the viewer enables structural and geomatics engineers to compare products in a single 3D space and access measuring or section extraction tools for the point cloud. This allows them to autonomously extract portions of interest that are considered at potential risk of deformation during execution of the works, in correspondence with specific sectors highlighted in the planning documentation. They can then assess compliance with safety parameters.

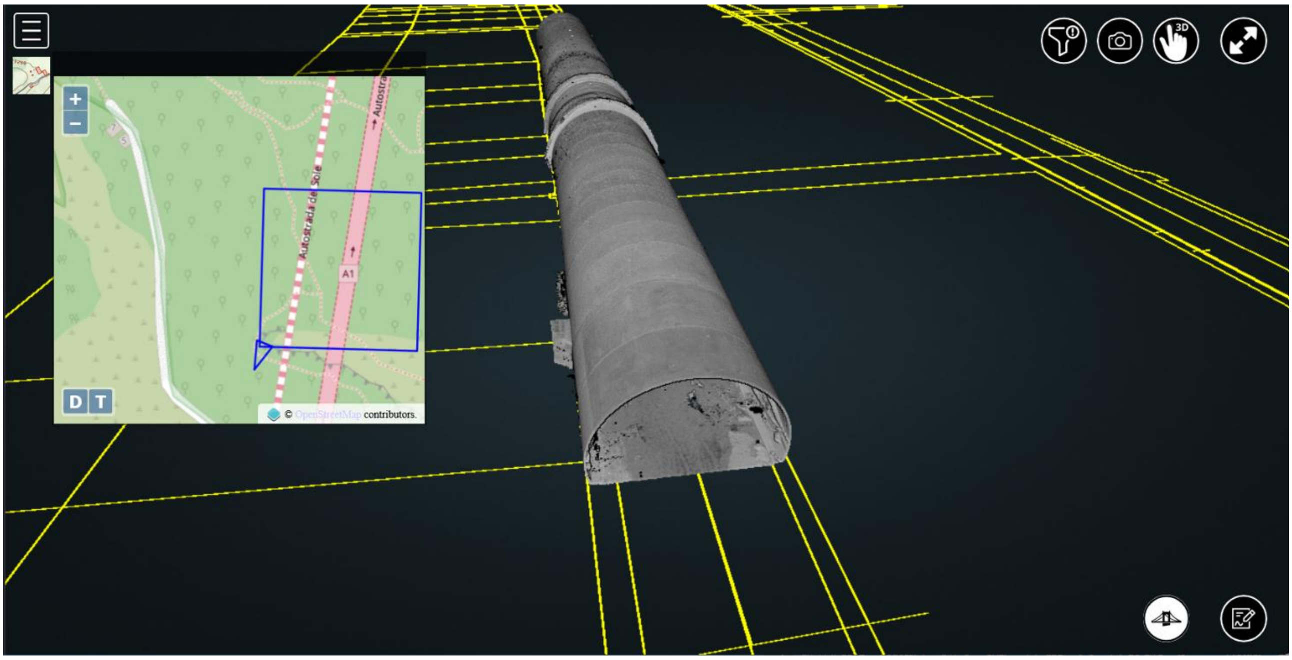


*Figure 56. Screenshot of the P.O.N.T.I. viewer template for the implementation dedicated to the highway tunnel case study. The scene uses the OpenLayers-based mini-map panel for contextualisation instead of the Cesium-based background to allow better comparison between vector data from the intervention planning and acquired point clouds from in situ surveys.*

A primary complexity identified during this evaluation was the challenge of consistency between the reference systems of the different datasets. Traditionally, the management of these products relies on separate proprietary software environments, which effectively manage individual formats but often create rigid data silos, starting from the definition of independent local reference systems in CAD environments, often inconsistent within them. The effort required to align these heterogeneous products proved to be significant. This experience highlights that the major constraint in adopting a unified management platform is not merely the choice of software, but an a priori issue regarding the historical documentation of data, their formats and metadata.

The application of the P.O.N.T.I. template to this scenario highlights that while the framework's multi-layer architecture can technically ingest and visualise these massive datasets, the pre-processing phase remains a critical bottleneck. The discrepancy between local reference systems used for high-precision surveys and the global coordinate systems requires for consisted geo-contextualised overlaying and visualisation underscores the necessity for rigorous data governance protocols before ingestion. Consequently, the framework proved its functional scalability as a visualisation and query tool, but the testing project emphasised that for large-scale transportation agencies, the transition to open standards requires a cultural and operational shift in how data is commissioned and documented at the source.

In this context combined with the advent of AI-driven solutions, while proprietary black-box solutions offer streamlined, one-click transitions to Digital Twins, they often bypass the critical phases of data infrastructure and governance. By automating the interface, these platforms frequently can mask inconsistencies and poor data quality in the input phase, fostering a state of automation complacency (Parasuraman and Manzey, 2010). This lack of transparency prevents users in organisations from developing a granular understanding of the underlying processes, ultimately suppressing problem-solving skills and reducing the capacity for critical oversight in geospatial data management, a phenomenon often referred to as the black-box challenge in complex software interfaces when transitioning to new platforms (Jeyaraj and Sethi, 2025).

In contrast to the risks of cognitive offloading associated with closed systems, the P.O.N.T.I. framework leverages the principles of FOSS to foster a process of technological democratisation (Berry and Moss, 2006). By prioritising transparent user engagement over total automation, the platform ensures that high-tech remains an accessible tool rather than an opaque black box, empowering inspectors, citizens, and researchers to actively interpret and manipulate underlying data structures.

Within this paradigm, users are treated as evolving learning entities. Rather than reducing the human element, the system acts as a pedagogical scaffold: each stage of technical advancement requires and facilitates a corresponding growth in the user's domain knowledge and cognitive ability. Ultimately, this approach transforms the Digital Twin from a passive visualization into a dynamic environment for skill acquisition, ensuring that the management of critical infrastructure remains grounded in human critical oversight.

# 7

# A roadmap for achieving digital twin maturity

*Current works and future developments towards an immersive geospatial ecosystem*

The case studies presented in this thesis were validated as effective, low-cost, minimal solutions that address the specific needs of target users. Furthermore, chapter 6 discussed the various customisations of the designed framework within a five-levels maturity module, defining and benchmarking the path towards customising applications that can address increasingly complex real-world scenarios. Having assessed the potential of the case studies, this chapter explores the technical and conceptual requirements for advancing the framework beyond its actual implementation with current and future development efforts. It proposes building on the framework's core structure to offer additional modules with compatible functionalities for more advanced customisations. A summary of the main planned future developments with respect to current implementation is illustrated in Figure 57.

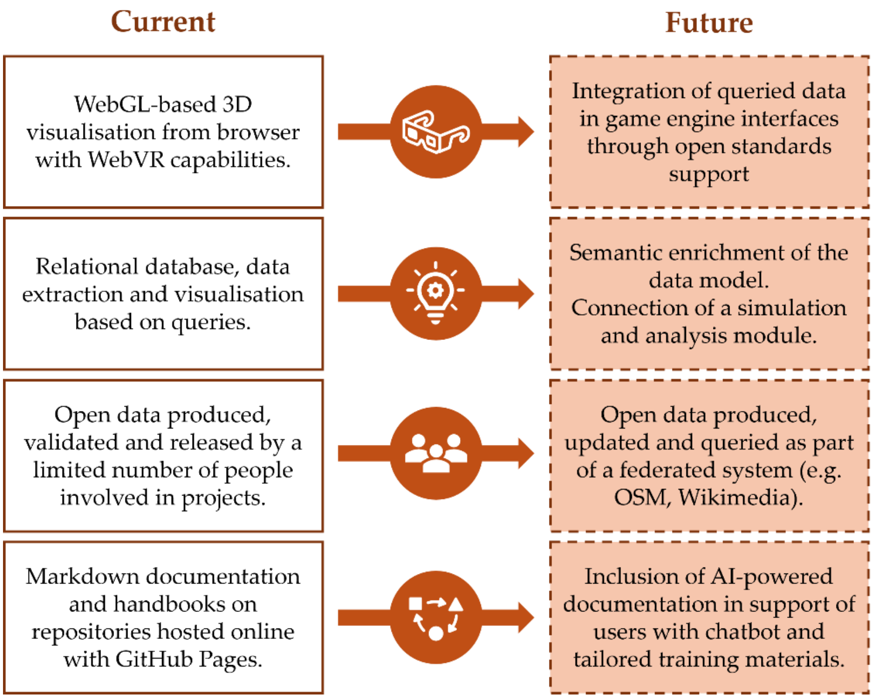


*Figure 57. Overview of the main themes of development for the current and future works on the designed framework.*

Table xx illustrates more in details of each enabling feature and its status:

- Implemented: already developed and tested within one of the thesis case studies.
- Prototyped: partial proof-of-concept exists, not yet fully integrated into production framework.
- Planned: design described in this chapter but not yet fully integrated into production framework.

*Table 10. Overview of enabling features for each theme of current and future development and related status.*

| Development theme | Enabling features | Status |
|---|---|---|
| VR workbench | WebVR support for the visualisation module | Implemented |
| | Open standards implementation in game engine | Planned |
| Transition to Digital Twin | CityGML 3.0 ADE integration for urban/infrastructure semantic enrichment | Planned |
| | Monitoring data inclusion with Observations, Measurements, and Samples schema | Planned |
| | Inclusion of physics and/or AI-based simulation module | Planned |
| Crowdsourced data integration | OpenStreetMap and WikiData linking integration in the visualisation module | Prototyped |
| Long-term sustainability | Community manual handbook/documentation preparation | Implemented |
| | AI-powered documentation | Prototyped |

The rest of this chapter is organised as follows:

- Section 7.1 discusses how to maintain the central role of application users as the framework evolves into a more automated system. It exposes the potential of VR immersive technologies to advance stakeholder agency, while maintaining consistency with the latest geospatial data standards and the capabilities already implemented in the framework's front end.
- Section 7.2 outlines the trends and technologies required to increase the framework's level of complexity and explains how the current design can be expanded to allow for greater customisation towards digital twin implementation.
- Section 7.3 details the framework customisation efforts aimed at enabling the integration of volunteered information into the system as observations of an active human network.
- Section 7.4 discusses the challenges of the long-term sustainability of community-developed open projects in detail, including the approach adopted for documenting customised open-source code.

## 7.1 Advancing user interaction

As the framework moves towards higher levels of maturity, the role of the human operator shifts from manual data entry to critical governance, understanding and analysis. The integration of XR technologies, encompassing VR and AR, has to transform the viewer interface from a passive visualisation tool into an active and engaging instrument. Such an evolution should rely on two pillars: the development of interactive immersive tools that empower user's analytical agency, and the adherence to OGC standards to ensure that immersive environments remain interoperable and data-driven, being more than simple advanced graphical interface.

### 7.1.1 Towards an immersive collaborative workbench

User agency in Digital Twins is defined by the ability to interact with the environment and extract analytical insights rather than merely viewing it. In literature about virtual modelling and twinning, Zhao et al. (2019) introduced the concept and definition of the Immersive Workbench where VR is used not just for hyper-realistic rendering and first-person exploration, but for quantitative scientific analysis: operators, through a different level of virtual spatial awareness, can understand and resolve scale mismatching often affecting the 2D scene representations, gaining a more intuitive understanding of massive datasets documenting both natural and built systems in their three-dimensional complexity, empowering spatial critical thinking and training in a risk-free virtual analogy (Tsou and Mejia, 2024; McDuff et al., 2025).

To enable the functionalities and potentials in VR, the management framework should be ready to implement and sustain on the long term two main specific interaction layers: dynamic measurement tools and multi-modal integration. Indeed, users must be able to perform real-time measurements of distance, area, and volume within the virtual space (Cook, 2024). In particular, one or more members of a team have to be able to explore not only the scene but its dynamic simulation evolution and interact with it from different angles without being physically exposed to real-worlds hazards (De Castro et al., 2025). Such a functionality is particularly effective for both climate change impact teaching and educational gaming (Bursztyn et al., 2025; Janovský, 2024) as well as for structure inspectors training (Kong et al., 2025; Yiğit and Uysal, 2025). Moreover, this workbench should maintain the seamless collaboration over toggling between different data representations, such as switching between photorealistic point clouds, and intensity-based LiDAR scans to reveal underlying geological or structural features evolution (Zhao et al., 2019). This high-fidelity interactivity is enabled by modern game engines (e.g., Unreal Engine, Unity), which offer advanced dynamic rendering technologies like Nanite (virtualised geometry), Lumen (global illumination), and 3D Gaussian Splatting (3DGS) for real-time radiance field visualisation (Perticarini and Giordano, 2024). These technologies allow for the visualisation of massive landscapes with realistic lighting and physics as well as simulation, far surpassing the capabilities of traditional web-based GIS viewers in giving a comprehensive first person understanding of the environment (Janovský, 2024).

Thanks to its viewer layer built on top of the Potree and Cesium JS libraries, the current architecture of the platform, which has been customised for the case studies in Chapters 4, 5 and 6, already implements basic WebVR functionalities. Indeed, when landing on web pages containing point clouds and meshes, it is possible to explore the scene with a dedicated VR headset, take distance measurements and resize 3D objects using hand gestures mapped to the virtual scene via interconnected controllers (Singh et al., 2025). These functionalities were tested using the Castello Farnese case study viewer with a Meta Quest 2 model (see Figure 58Figure 59). Unfortunately, the current version of the web viewer only allows interaction with objects that have already been loaded or linked to the scene and does not support dynamic simulation. However, the adoption of Cesium allows for the implementation of more advanced coded VR experiences in Game Engine environments by offering software development kits (SDKs) and APIs for applications like Unreal, Unity and Godot (Mitter et al., 2025).

*Figure 58. Screenshot of the outdoor scene point cloud of a bridge located in the Piacenza province, rendered in VR with Oculus Meta Quest 2.*


*Figure 59. View of the indoor scene of Farnese Castle case study with scale of representation defined interactively through the movement of the handheld Oculus Touch controllers.*

### 7.1.2 Open standards in game engine

The complexity of the integrated datasets, combining photogrammetry, LiDAR, and real-time sensor overlays, also requires the ability to access immersive environments while navigating different format of data, from al terrain and visualise "invisible" variables, such as subsurface temperature gradients or seismic anomalies, directly overlaid on the virtual geometries (Bensch et al., 2025).

A critical challenge in adopting game engines for geospatial science is the risk of creating isolated environments where data is trapped in proprietary inaccessible formats (Pavelka and Landa, 2024). To furtherly ensure the open science nature of the framework, the integration of XR ranging from VR to AR must strictly comply with open standards. In 2022, Würstle et al. (2022) tested the viability of OGC standards integrated in Unreal Engine and demonstrated that game engines can now function as consumers of standardised data streams, moving away from static file imports. However, the use cases of digital twins, especially outside the urban domain, empowered by game engine through real-world geodata and open standard still remain limited.

To resolve the technical bottleneck of manual data conversion between distinct environment in upgrading to higher maturity, the VR-enriched framework must adopt a streaming architecture. Implementations in literature validated the use of the OGC 3D GeoVolumes API (OGC, 2026), which provides a unified HyperText Transfer Protocol (HTTP) endpoint to access, based on the user's location and zoom level, heterogeneous 3D content such as City Geography Markup Language (CityGML), Graphic Library Transmission Format (glTF) and 3D tiles without requiring local storage or pre-processing on the client side (Santhanavanich et al., 2022). The use of this API allows clients like game engine to dynamically query and visualise 3D models from central servers, avoiding manual reconstructions or manipulation inside the software and thereby maximising interoperability and accessibility. Moreover, to optimise seamless connectivity between servers and virtual environments, dedicated plugins for Cesium have developed to enable the loading of 3D datasets as OGC 3D tiles directly in Unreal Engine, Unity, Open 3D Engine or Godot, preserving the link between geometry and its metadata.

Beyond static geometry streaming, the integration of data must support dynamic, procedural generation to achieve true Digital Twin status. The "Immersive Ocean" platform exemplifies this by using game engines not merely for visualisation but for generating 3D scenarios from 2D open geospatial data (Fonseca et al., 2025). By parsing standardised formats like GeoJSON and consuming real-time environmental APIs (e.g., weather, ecological heatmaps), the system procedurally instantiates 3D assets at runtime. This approach fully combines the requirements to move beyond digital shadow management system, to enabling interactive scenarios where stakeholders are directly involved in a progressive learning process by first-handy manipulating variables in a semantically rich environment. Similarly, in urban contexts, the integration of Message Queuing Telemetry Transport ISO protocols and REST APIs into Unreal Engine has been demonstrated to efficiently visualise real-time public transit flows and city events, proving that game engines can handle high-frequency dynamic data streams alongside static city models (Rantanen et al., 2023). Also, considering current standards for sensors, the OGC SensorThings API provides an open standard for interconnecting IoT devices. In an AR context, this allows users to view a physical asset (e.g., a room sensor or a bridge component) and see real-time data overlays, like CO2 levels or structural stress readings, streamed directly from a server (Würstle et al., 2022). This decouples the visualisation layer from the data layer, ensuring that the XR application always displays the most current environmental state without requiring application updates.

To support this transition towards real-time environmental and/or structural awareness, the framework's backend must evolve to handle continuous observational data. In particular, as the Belvedere Glacier monitoring is gradually entering a new phase with the active engagement of multi-disciplinary researcher teams, the core schema of the database can be upgraded to satisfy SensorThings API protocol requirements, which can be effectively adapted to run on PostgreSQL relational database management systems expanded with the Observations and Measurements OGC data model for sensor data archival (Horsburgh et al., 2025), ensuring compatibility with the proposed open-source stack (Figure 60). This next step will be particularly effective to deal with observations on a wide variety of properties, not strictly limited to GNSS measurements, while ensuring that more engaging strategies for outreach and dissemination can be built in VR environments compatible with the OGC standards.

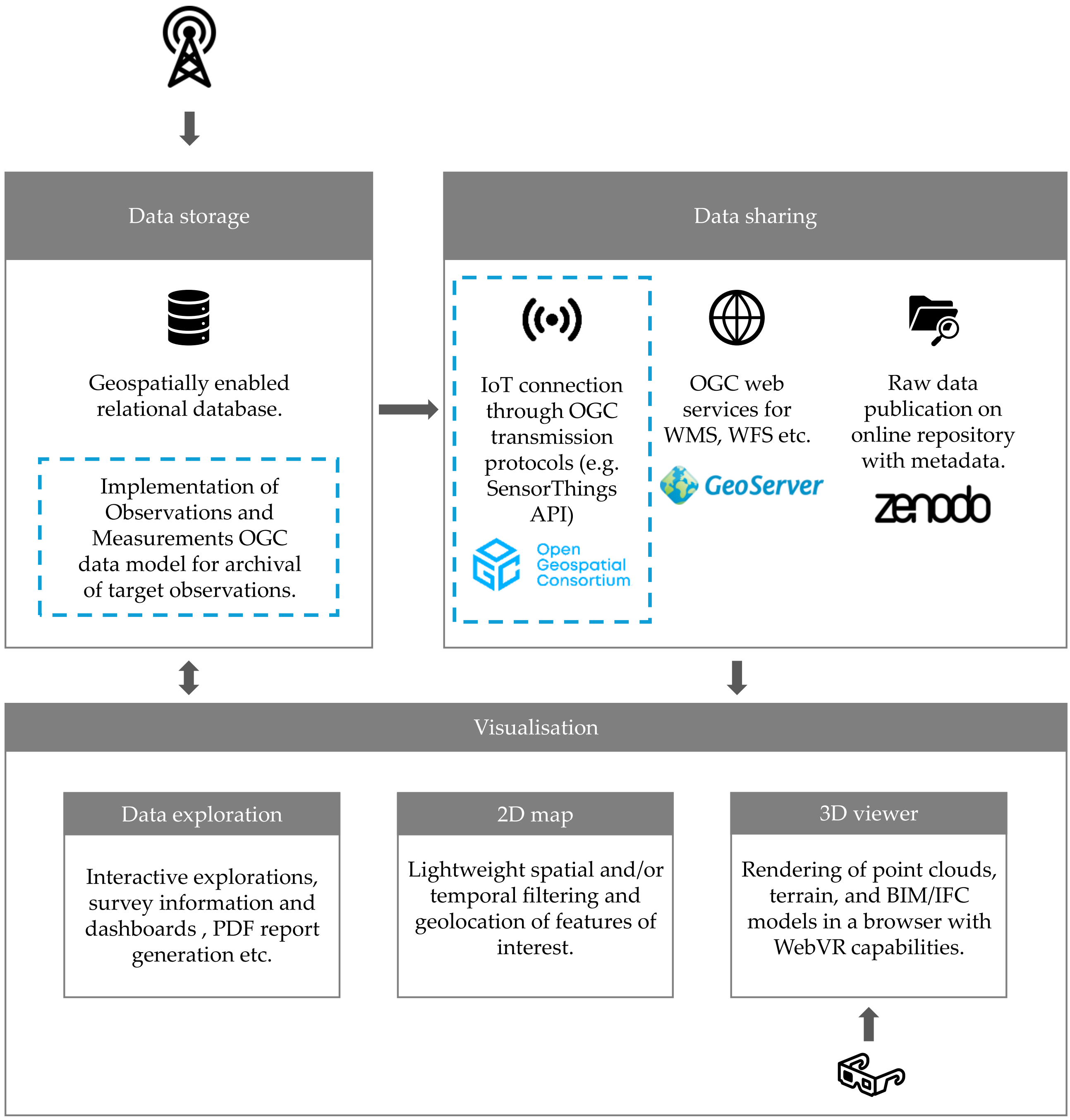


*Figure 60. Design of expanded structure of the framework with the inclusion of OGC protocols for sensor data transmission and WebVR technologies for advanced interactive 3D visualisation.*

## 7.2 Beyond the management system

The transition from the management system level, validated in this thesis as capable of organising inspection data and monitoring records, to a Digital Twin level requires also a fundamental shift in data capability. While the P.O.N.T.I. prototype and the Belvedere Glacier platform successfully enable the active management of static assets and time-series observations, a digital twin platform demands the ability to run predictive simulations and bi-directional synchronisation. This leap is not merely graphical but semantic: it requires a bridge between the disparate data standards of the built and natural environments to support automated reasoning and physics-based analysis.

### 7.2.1 Bridging urban and infrastructure semantics

In the domain of civil infrastructure, a fully mature system must be able to resolve the semantic loss that historically occurs when integrating high-fidelity construction models (BIM) into geospatial environments (GIS). While CityGML 3.0 has emerged as the standard for multi-scale city modelling, specific infrastructure classes like bridges and roads often remain geometrically isolated from their broader urban context, without a commonly agreed extension (Steyn and Broekman, 2022, Nasim et al., 2025).

For complex structures like the bridges managed in the P.O.N.T.I. prototype, the path to Level IV lies in harmonising the granular structural details of IFC with the topological context of CityGML (OGC, 2021). Recent research by Nakamura et al. (2025) demonstrates that this can be achieved through Application Domain Extensions (ADEs). By extending the conceptual data model, it is possible to create a one-source multi-use schema where a bridge is not treated as a static mesh, but as a hierarchical assembly of semantically rich components, such as superstructures, substructures, and abutments, linked via recursive associations. Crucially, this integration allows maintenance information, such as inspection records and damage ratings (e.g., identifying cracks or spalling), to be stored directly within the 3D model attributes rather than in external reports and be related to the larger context, at an urban or even regional scale (Yao et al., 2025).

Similarly, the management of road networks requires moving beyond simple centrelines to volumetrically defined transportation spaces. The recent revision and implementation of the CityGML 3.0's Transportation module allows for a multi-granular framework, dividing road infrastructure into area, way, and lane levels. For larger scale digital twin, Tsiranidou et al. (2025) highlight that mapping point cloud data to these semantic classes allows for the distinct modelling of driving lanes, sidewalks, and parking areas, which is essential for traffic simulation and autonomous driving scenarios (Deng et al., 2025). Furthermore, it would simplifying fusing physical models of the vehicle-road interaction with real-time sensor data to predict pavement performance and optimise maintenance (Haverkamp et al., 2025).

Aligning the framework to real cases requiring contextualisation of single structures to larger scale, the core data archival module can be expanded with 3dcitydb (Yao et al., 2018), a solution that would easily allow storing, representing, and managing virtual 3D city models on the foundations of a standard spatial relational database like the one chosen for the presented implementations with PostgreSQL and PostGIS. In this way, structure-specific products and observations could be linked to multi-scale models, ranging from regional landscapes (LoD0) to exterior architectural representations (LoD3), as mapped in CityGML. Such a data integration would also provide a complete semantically enriched scenario for developing and tuning advanced simulation scenarios across different domains (Lam et al., 2024). Aligned with the latest trends in infrastructure-urban integration, Figure 61 provides a workflow for preparing the framework to this semantic expansion. This process starts with the conversion of high-fidelity IFC structural models into geo-referenced CityGML representations, allowing the bridge to be contextualized within the broader urban or territorial landscape. However, it is important to highlight that this conversion step is effective only if substantial measures for data management and consistency are previously implemented. As discussed in the previous chapter in the Section 6.3.2, the leap to higher maturity requires a progressive system of advancing functionality. Without the persistent, state-aware database architecture developed in the P.O.N.T.I. prototype, the mere transformation of BIM data into a GIS format remains a "stateless" geometric exercise. To truly operationalise a Digital Twin, the framework must ensure that the semantic properties of the bridge, like material degradation or structural health indicators, remain consistent and queryable across both the urban CityGML container and the high-resolution structural IFC model, framed in consistent spatial reference systems.

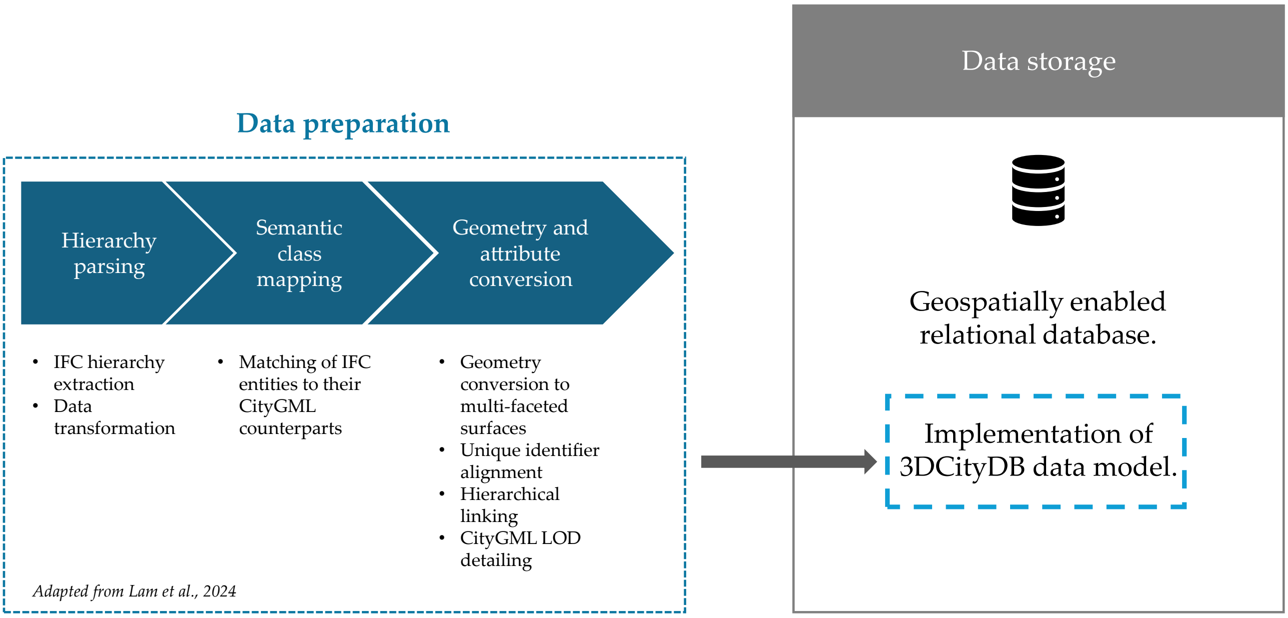


*Figure 61. Design of data preparation process to convert IFC models of bridges into CityGML entities, as a prerequisite to integrate them in a broader urban-scale digital twin system based on 3DCityDB data model.*

### 7.2.2 Digital twins of the natural environment

In the natural environment domain, specifically regarding the monitoring of glaciers, the concept of a digital twin remains largely theoretical and is frequently confused with the Digital Shadow (Maimour et al., 2024) limited to a one-way flow of data from the physical to the digital object. A true digital twin, instead, requires a bi-directional flow that includes automated feedback or intervention and simulation (Van Den Barg and Degeler, 2025). While the current framework successfully integrates repeated GNSS measurements, derived targets yearly velocities and photogrammetric surveys for graphs rendering and visualisation, enabling higher maturity requires bridging the gap between observation and predictive capability, moving beyond static geometric representation to include dynamic processes.

A significant challenge in modelling natural systems, unlike manufacturing systems, is the lack of a defined blueprint and the non-linear complexity of environmental variables (Van Den Barg and Degeler, 2025). Recent literature suggests that relying exclusively on physics-based numerical models (e.g., fluid dynamics for ice flow) is often computationally too expensive for real-time applications, while purely data-driven models (e.g., Deep Learning) may lack physical interpretability (Xue et al., 2025). Therefore, the future development of this framework should adopt a hybrid modelling approach. This involves integrating parameterised physical models with machine learning algorithms. In this architecture, the digital twin uses real-time data to calibrate physical models dynamically, while AI accelerates the processing of complex scenarios, such as predicting glacial lake outburst floods or ice-rock avalanches (Cui et al., 2024).

A critical finding of this research is that the implementation technologies chosen for the Belvedere Glacier customisation, specifically the PostGIS relational backend and the OGC 3D Tiles-ready CesiumJS-based streaming protocol, constitute a "future-proof" foundation for these advanced simulations. Because the framework's data tier can expose its contents through open, OGC-compliant interfaces (WMS, WFS, 3D Tiles, and in the planned migration OGC API and SensorThings API), and because its server-side runtime is based on commonly used scientific Python and JavaScript ecosystems, it is technologically prepared to interoperate with the outputs of external hybrid models without requiring proprietary connectors. The actual ingestion still demands the development of dedicated I/O adapters between each simulation library (OpenFOAM, TensorFlow, PyTorch, scikit-learn) and the database schema, but the absence of black box lock-in at any layer of the stack means that these adapters can be written, inspected, and shared. The transition to Digital Twin maturity does not require a replacement of the existing infrastructure but rather the plugging in of specialised open-source common simulation libraries, such as OpenFOAM for physics-based phenomena (Tamamadin et al., 2025) and TensorFlow, PyTorch or Scikit-lean for artificial intelligence (Nurakynov et al., 2024). By maintaining data sovereignty through a centralised, state-aware database, the framework ensures that the real-time IoT feeds used for monitoring today can seamlessly become the calibration inputs for the predictive simulations of tomorrow.

An updated architecture schema for the framework is detailed in Figure 62. In this design, the integrated simulation module is triggered when a target user in the visualisation interface in a dedicated GUI panel defines the parameters for a scenario of interest. Such parameters are used by the simulation module together with historical measurements and products from the database as input for physics and/or AI-based simulations. The results are then sent to the visualisation interface where the user can decide whether or not to save them in the database.

With the inclusion of these predictive capabilities, the system will move beyond simple geometric representation of past and current state of the real-world scene towards simulation intelligence. Following the theoretical framework for Alpine glaciers proposed by Fissore et al. (2023), the framework will then transition into Glacier Evolution Models. Indeed, for mountain environments like the one of the Belvedere Glacier, the transition to digital twin also implies a shift from hindcasting to forecasting and nowcasting (Cui et al., 2024). A cryospheric digital twin platform must integrate multisource data, including seismo-acoustic signals, hydro-meteorological data, and remote sensing, to identify key points in disaster evolution. By implementing such a system, the digital twin ceases to be a passive repository and becomes an active early-warning system. In this context, the actuation or feedback loop connecting the real and virtual world is not necessarily mechanical but informational: the system autonomously triggers alerts or guides mitigation measures based on real-time risk assessments (Maimour et al., 2024).

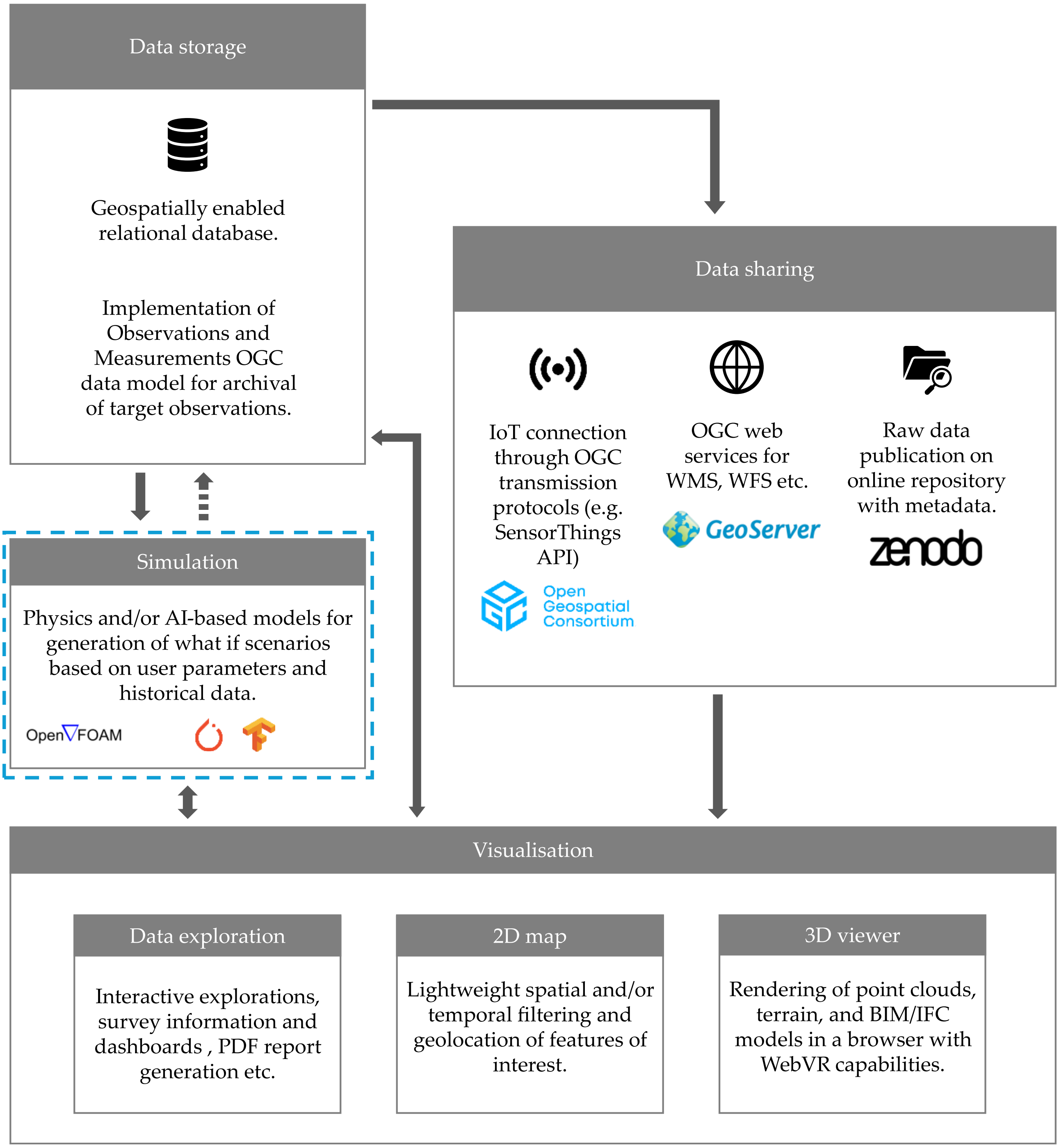


*Figure 62. Design of the integration of the simulation module in the framework.*

## 7.3 Enabling volunteered data integration

Another topic to be addressed in the next developments when discussing data integration in the design of multi-scale federated systems is also the role and potential of Volunteered Geographic Information (Goodchild, 2007), derived either from crowdsourced globally established initiatives like OpenStreetMap or more case-specific citizen science projects. Including such typologies of data and observations support the platform audience shift from passive user of pre-defined data to producer and aware explorer of larger shared knowledge.

In recent years, in particular, Wikimedia projects have attracted the interest of researchers. For example, images and documents have been successfully managed in collaborative environments, which facilitate easy participation and follow established standards for digitized texts and 2D images, especially for smaller scale stakeholders (Rossenova et al., 2022). While access to these resources often implies viewing siloed data with minimal descriptive metadata, these platforms enable diverse audiences to search, access, and enrich datasets through annotation and critical interpretation. Furthermore, Wikidata has emerged as a main player in the Linked Open Data ecosystem, acting as a semantic linking hub that connects scholarly reference corpora with community-driven content from initiatives like OpenStreetMap in interdisciplinary applications (Thiery et al., 2026). Indeed, this capacity to bridge domain-specific knowledge bases allows memory and data institutions to share structured metadata about their heritage, either natural or built, supporting the collections as data movement and enabling the creation of machine-actionable, federated knowledge graphs that integrate cultural, scientific, and vernacular knowledge (Sinha et al., 2025), accessible through the SPARQL query languages also in GIS environments (Páez and Vilches-Blázquez, 2022).

Moreover, in the cultural heritage context, sources like Wikimedia Commons images and historic documents have been already implemented in methodological approaches dedicated to produce 3D digital model of vandalised site (Morelli et al., 2024) as well as planned but unrealised architecture (Kuroczyński et al., 2024), demonstrating how crowdsourced data, combined with archival documents, can represent relevant elements in preserving the memory of lost or ephemeral sites (Denker, 2017; Spreafico and Chiabrando, 2024). Beyond the heritage domain, the utility of Wikidata and open data extends to dynamic fields such as natural disaster management, where immediate situational awareness is critical. For instance, researchers demonstrated how geospatial semantic web technologies enable the integration of Wikidata as an external knowledge base into decision support systems, allowing authorities to execute federated queries that identify critical infrastructure within a disaster's "hot-zone" (Hellmund et al., 2019). Similarly, other experimental applications proposed a data management model for flooding disasters that leverages open government datasets to construct knowledge graphs (Son et al., 2021). By linking these local datasets with global schemas like Wikidata and DBpedia, they enhance the interoperability and searchability of heterogeneous data essential for solving and managing disaster issues and implications at different scales.

Open volunteered data and knowledge graphs, such as OpenStreetMap and WikiData, can also be used to quickly prototype virtual replicas of physical exhibition spaces. These can be enriched with the interconnected properties of the Wikimedia, OpenStreetMap and the larger open data ecosystem and be exploited also in game engine environments (Keil et al., 2021, Klippel et al., 2025). The author of this thesis has already tested the potential of this low-cost approach by building a prototype virtual replica using the indoor mapping data of OpenStreetMap for the Egyptian Museum of Turin (Gaspari et al., 2025d). The resulting application was intentionally built with low-code solutions such as QGIS and its plugin qgis2threejs (Qgis2threejs, 2026). It consists of a ThreeJS-based viewer, based on the same library behind Potree and CesiumJS, that renders a virtual model of the museum site with the artworks located inside its rooms by extruding georeferenced indoor elements mapped in OSM. By clicking on specific exhibition elements within the web scene, users can access its detailed information, linking Wikidata pages (if wikidata tag is not null in the corresponding map features) and visualise a representative image from Wikimedia Commons, via Protocol And RDF Query Language (SPARQL) queries (Figure 63). The extruded model derived from the floor plan can also be exported in glTF format and used as a basis for creating more sophisticated virtual experiences in game engines.

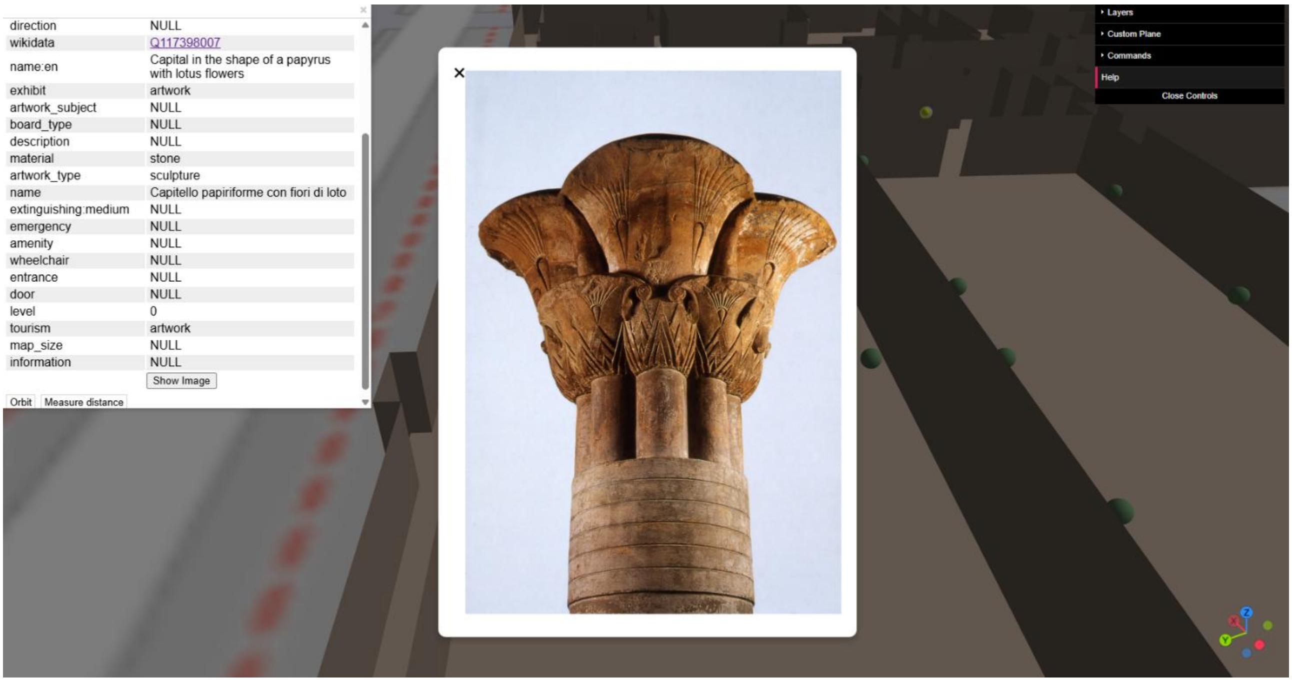


*Figure 63. Descriptive panel for a clicked artwork within the 3D interactive scene derived from indoor map features in OSM. The visible image is parsed from Wikimedia Commons through Wikidata API, thanks to the wikidata tag associated to the corresponding map feature geolocated in the scene (from Gaspari et al., 2025d).*

While this simple prototype demonstrated the potential for developing digital exhibitions in a low-code way using open geodata and linked graphs, especially for smaller cultural bodies with limited resources (Avgousti and Papaioannou, 2023), it also highlighted the current limitations of using and relying heavily on such data. Indeed, while the OSM community commonly agreed on the mapping schema, it is still not widely adopted around the world: there are few complete mapping case studies, most of which located in France, where the active local OSM community developed a series of mapping initiatives dedicated to the indoor mapping in museums and railway stations. However, this lack of data could present an opportunity for the shift in the role of platform users, enabling them to act as producer, taking part in community events and initiatives to encourage the general public to contribute to the documentation of both spaces and related information (Daga et al., 2022). This would enrich a shared knowledge base while learning new tools and skills.

Such participatory schemes are most effective when paired with structured onboarding such as mapping parties supervised by experienced contributors, validation workflows for new entries, and access to documentation tailored to non-specialist users, so that growth in coverage does not come at the cost of data reliability.

Expanding the domain of crowdsourced data integration to the natural environment and building up on the outcomes of the Belvedere Glacier project, especially for the general public, the participatory documentation of the glacier context could also target intangible heritage. This would provide a broader context for the scientific monitoring project in relation to the cultural impact of climate change in the Macugnaga municipality and region. Indeed, adopting an interdisciplinary approach and creating a digital archive of historical images of the glacier and its significance to the local Walser population, an ethnic Germanic minority that settled in the area in the 13th century and contributed to the development of the Macugnaga community. Framing the project within a multidisciplinary, participatory scenario will further engage the general public, not only as an audience, but also improving as consequence the possibility to enhance the interaction experience on the 3D viewer, by integrating narrative or trivia experiences within it based on real-time information retrieved from interconnected Wikipedia pages. Moreover, integrating open dataset, related publications and project in which they are framed in a linked Wikidata system would also represent a benefit for the larger scientific community, enhancing discoverability and tracking of the projects and multi-scale collaboration and transparency, thanks to the large number of Wikimedia-based tools dedicated to academics (e.g. Scholia (WDScholia, 2026)).

## 7.4 Sustainability and broader adoption

The adoption of FOSS is a complex process influenced by numerous variables rather than a simple binary choice, and it remains a core challenge for the development story of systems like the developed framework presented in this thesis. Literature identified a wide variety of adoption factors, ranging from technical to organisational passing through economic dimensions, highlighting the necessity for structured guidelines rather than ad-hoc decision-making (Sánchez et al., 2020). In specific contexts like developing countries or smaller entities with limited resources, adoption intentions are strongly driven by low costs, performance expectations, and social influence, alongside system quality factors such as security and interoperability (Silva et al., 2023), elements addressed by the designed framework in its distinct customisation detailed in Chapter 4, 5 and 6.

However, long-term sustainability requires rigorous engineering and community engagement. An assessment of global impact models reveals that sustainability correlates strongly with software engineering best practices, including comprehensive documentation, version control, and open-source licensing (Nyenah et al., 2024). Engagement history also plays a critical role: research on scientific software developments indicates that projects starting as open, community-oriented peer production efforts are significantly more likely to sustain activity compared to those attempting to transition into this model later (Cohoon et al., 2025). Hence, successful OSS strategies must align software with scientific needs while lowering entry barriers through robust documentation, which serves as the instruction manual for new users and contributors.

To address the needs of the research community and the guidelines it has identified, a sustainability strategy for the framework described in this thesis is currently under development. While the manual creation and periodic updating of documentation and handbooks for the various framework customisations have already been implemented, the current effort to ensure the long-term maintenance of the open-source code consists of implementing AI-powered documentation tools, which are attracting the attention of developers on GitHub, such as SourceBot, CodeWiki and DeepWiki. The latter, in particular, has been used to create interactive chatbot documentation for the Castello Farnese and P.O.N.T.I. projects (Figure 64). The Q&A interactive module is being tested as part of the modular framework, which is being adapted for thesis projects by students from LabMGF at the Politecnico di Milano. Current testing has revealed that students with limited or no background in coding were able to interact with the documentation to better understand the framework's foundations, asking specific questions on issues that could not be found in the manually updated documentation, thereby lowering the entry barriers.

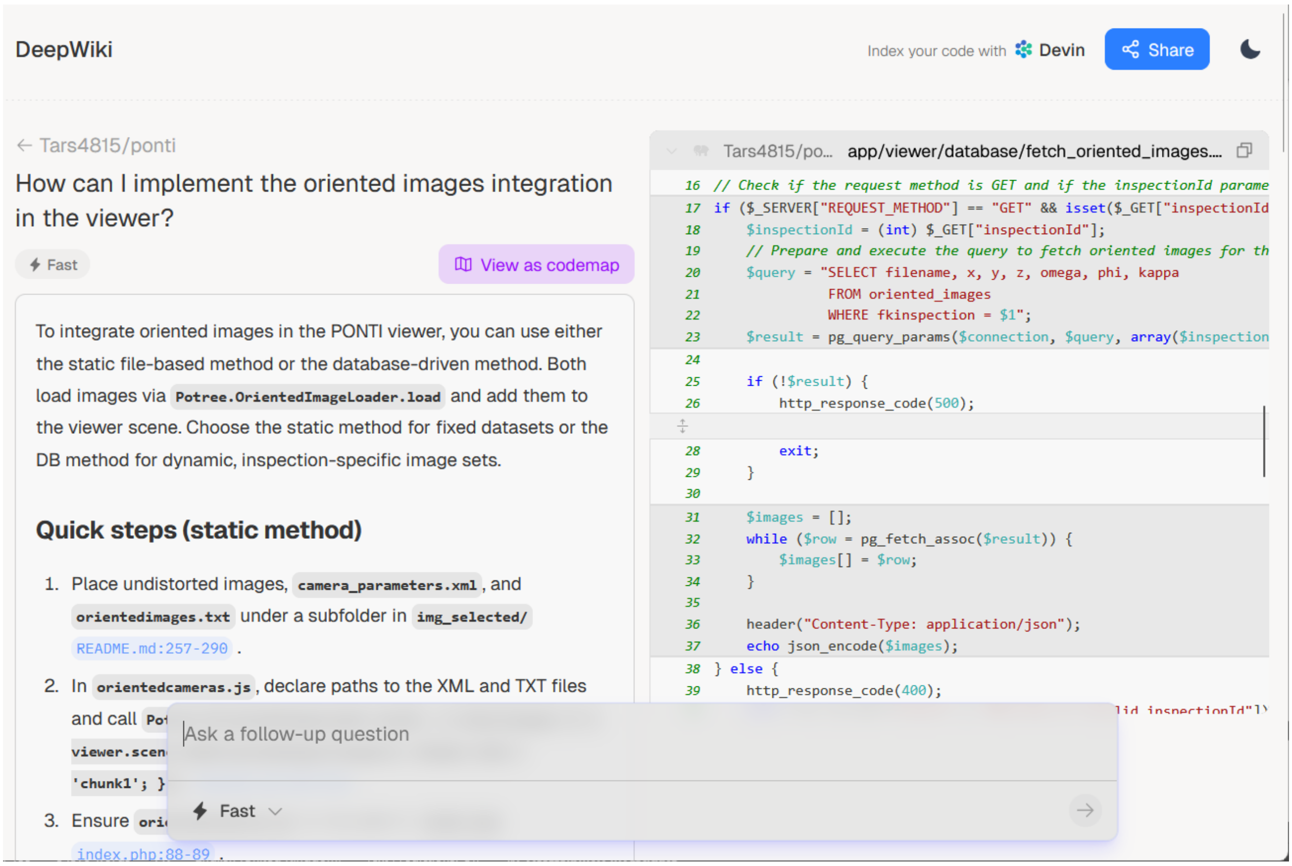


*Figure 64. Screenshot of the Q&A interface of DeepWiki for the P.O.N.T.I. framework customisation repository on GitHub. By asking a specific question on how to implement one of the viewer capabilities, the AI-powered interface provides a detailed answer, linking code snippets of interest within the repository.*

# 8

# Conclusions

The final chapter of this thesis focuses on summarising the materials and key findings illustrated in detail throughout the case studies descriptions and validation. The conclusions synthetise the results, framing them in a longitudinal perspective that highlights the framework's potential to bridge the gap between high-resolution reality capture and operational management, providing a scalable roadmap for the digital transition of geomatics practice.

## 8.1 Testing a cross-domain framework

This research addressed the critical data silo problem in Geomatics by designing and testing a modular, open-source framework from geospatial data visualisation to management. By shifting the focus from the process of reality capture to the logic of data accessibility and user agency, the thesis established a common ground where heterogeneous assets, from 16$^{th}$ century fortifications to alpine glaciers and modern civil infrastructures, can coexist in a synchronised digital environment.

The introduction (Chapter 1) established the theoretical foundation of the research by outlining the main challenges in the disconnection between the mature capability for high-resolution reality capture and the limited operational utility of the resulting data. It identified the data silo problem as the primary obstacle to a meaningful digital transition. By framing the research around the concepts of digital sovereignty and the democratisation of information, the chapter set the mission to develop a modular substrate capable of transforming static survey products into dynamic, persistent knowledge assets.

Then, Chapter 2 on the research context and case studies framed the work within the real-world activities of LabMGF and industrial partnerships like TECNE. It introduced the three target case studies of the Farnese Castle, the Belvedere Glacier, and the Piacenza bridge network as the contextual pillars of the research, highlighting their common data fragmentation challenges.

Building on the mentioned challenges, the evaluation of the literature in Chapter 3 expanded this foundation through a cross-domain overview of the technologies enabling digital platforms and geospatial twins. Moving beyond a simple review of sensors, the chapter analysed the state of the art in web-based visualisation and data orchestration. By synthesising the converging requirements of cultural heritage, natural environments, and infrastructure, the chapter isolated the specific research niche, the lack of a unified, documented, and modular open-source engine, and justified the selection of a FOSS stack as the necessary tool for scientific transparency and institutional accessibility.

The framework design is detailed in the Platform design chapter (Chapter 4). The design process is described starting with the requirements analysis, identifying the main needs of target users in the domains of cultural heritage dissemination, natural environment monitoring, civil infrastructure inspection data management. Based on this initial phase, a modular architecture structure is designed and detailed on each of its components, explaining necessary technologies, interactions and input and output data flows. Finally, a description of the data and customisation requirements specific for each case study is given, highlighting the peculiarities of each application.

The Implementations chapter (Chapter 5) details the practical application of the modular framework across three distinct implementation scenarios, beginning with the Castello Farnese customization. This initial case study aimed to develop a flexible, low-cost tool for visualising direct-from-survey 3D products—such as point clouds and drone imagery—overlaid with historical reconstructions from various epochs in a single, coherent viewer. To address the needs of the cultural association Ente Farnese, the implementation specialised in interactive storytelling features, including point-of-interest hotspots, descriptive panels, and guided animations, thereby providing engaging access to georeferenced products typically restricted from the general public. Transitioning to the natural environment domain, Chapter 5 further explores the Belvedere Glacier platform, which was customised for a diverse audience ranging from the general public to higher education students. Building upon the open-source technologies adopted for the heritage viewer, this implementation tests a one-directional connection to a geospatially enabled database designed to handle data from annual summer school surveying initiatives in the Italian Alps. The resulting platform integrates distinct features for user groups ranging from technical researchers to the general public, demonstrating a flexible approach to querying 2D and 3D survey data while releasing the underlying products as open data with metadata on Zenodo. Finally, Chapter 5 addresses the civil infrastructure domain through the development of the P.O.N.T.I. prototype, a 3D WebGIS focused on optimising bridge inspection data management. By evaluating the specific requirements of Italian bridge managers and national regulations, a specialized database schema and software architecture were developed to support features such as report exports, assessment rating formulas, and BIM data visualisation. This prototype ultimately enables the visualisation and querying of assets on a 2D web map, the evaluation of inspection timelines for individual structures, and the direct annotation of defects on point clouds within the 3D viewer through persistent CRUD operations.

Finally, Chapter 6 validates and conducts a cross-domain analysis of the three distinct framework customisations presented in previous chapters. First, it validates the different implementations against state-of-the-art solutions and trends, highlighting their specific characteristics and potential in relation to common software implementation alternatives. Then, a benchmark performance evaluation is performed across the domains, with each customisation framed within a five-level maturity model. The performance of each platform is evaluated in relation to the specific user needs of the case study in question.

The roadmap for achieving digital twin maturity (Chapter 7) framed the work within a longer-term research plan and discussed ongoing and planned development and maintenance strategies for the inclusion of monitoring and simulation modules, enhanced virtual reality interactions, the integration of crowdsourced data, and the updating and sustainability of documentation to achieve broader impact. This chapter provides a detailed development roadmap, outlining technologies and standards that are consistent with the current implementation level of the framework. It also highlights how the framework could be expanded to meet the evolving needs of users, moving towards digital twins and federated infrastructures. Examples of advanced functionalities under development are provided.

## 8.2 Impact on Geomatics research and practice

The research presented in this thesis contributes to the ongoing paradigm shift in Geomatics, transitioning the discipline from a provider of discrete, high-resolution measurements to a facilitator of integrated geospatial knowledge in support to digital transition and optimised survey data management. The impact of the proposed open-source framework can be summarized across three primary dimensions: methodology, technology and society.

Traditionally, geomatics products have been evaluated based on their geometric accuracy or radiometric quality. This research shifts the focus towards functional agency, providing a new perspective on the evaluation of geospatial platforms based on their ability to support users, from passive dissemination to productive asset management. By formalising the path from digital exhibition to management system, this thesis provides a theoretical roadmap for researchers and practitioners to design tools that are not only technically precise but operationally relevant. This shift in the focus of evaluation does not replace the established criteria of geometric accuracy and completeness, which remain prerequisites for reliable downstream analysis, but it adds a second dimension by which platforms can be judged. A platform with perfect functionality over inaccurate data is as misleading as one with perfectly accurate data that users cannot act upon meaningfully. Post-survey quality assessment of 2D and 3D products remains essential to avoid mistakes derived from unreliable data.

A significant practical impact of this study lies in its demonstration of technological portability. By adopting an entirely Free and Open-Source Software stack, the framework proves that high-performance geomatics management does not require black-box proprietary ecosystems. The successful adaptation of the P.O.N.T.I. management logic and the monitoring of the Belvedere Glacier to the documentation of the Benedettine Church confirms that the technical requirements for structural and environmental governance are domain-agnostic. This interoperability is a critical step towards the realisation of common ground geospatial infrastructures where data from different sources can finally interact in a synchronised spatio-temporal multi-epoch environment.

Finally, this research carries a substantial impact on the practice of public administration. As infrastructure and heritage management move towards the Digital Twin horizon, there is a growing risk of economic and technical vendor lock-in for smaller institutions. This framework offers a sustainable alternative, providing small and medium-sized administrations with the tools to maintain digital sovereignty over their assets. By lowering the financial barriers to entry, the framework supports a more democratic digital transition, ensuring that, thanks to a simplified interface, the benefits of high-resolution 3D documentation are accessible not just to specialised technicians, but to all stakeholders involved in the governance of the built and natural environment.

This broadening of access, however, brings with it corresponding obligations. Making rich spatial data legible to non-specialist users without supportive investment in their understanding of the data's limitations would replace one form of opacity with another. The framework therefore treats user-facing documentation and structured training as bearing components of each implementation, not as optional accessories: the Belvedere Glacier summer school open material release and associated navigation handbook (Section 5.2.2), the P.O.N.T.I. operator handbook (Section 5.3), and the AIassisted documentation chatbot integrated through DeepWiki (Section 7.4) are integral to the impact claims made above.

In conclusion, the case studies explored in this thesis demonstrate that the future of Geomatics lies in the transparency of the workflow and the agency of the user. Whether documenting the structural evolution of a 16th-century castle, the retreat of an alpine glacier, or the maintenance needs of a modern bridge, the underlying challenge remains the same: transforming complex data into accessible knowledge. The open-source framework proposed here provides the foundational readiness roadmap for this transformation, establishing a robust baseline upon which the autonomous and predictive geospatial ecosystems of tomorrow can be built.

## 8.3 Impact of open dissemination

The data-sharing and re-adaptability modules of the framework defined in Chapter 4 are the driving force behind it. Embracing the FOSS philosophy and open science approach enhances transparency by releasing source code, documentation and data, while ensuring that the developed tools and datasets are reusable assets and not merely short-term academic prototypes.

The choice of software and the architectural design in this research aligns strongly with the recent trends and perspectives mapped in the 2025 State of Open Source Report (OpenLogic by Perforce et al., 2025). Indeed, the report indicates that 96% of organisations have increased or expanded their use of open-source software, mentioning for overall license cost reduction as primary needs for 53% of respondents. This motivation aligns with the objective of providing a low-cost, accessible solution particularly for small and medium-sized public administrations that often face budget constraints preventing the adoption of expensive proprietary suites.

Furthermore, the technology stack selected for the framework places it at the center of current global development trends. The choice of PostgreSQL (and its extension PostGIS) as the system's core memory is supported by the report, which identifies it as the most widely used open-source database, significantly outpacing alternatives with the 51% of preferences. Moreover, the framework's reliance on JavaScript for the client-side presentation tier, with libraries such as Potree, CesiumJS and Leaflet, and PHP for server-side orchestration aligns with global usage, where JavaScript remains the top programming language (53%) and PHP mantains a strong presence (36%) in application development. Aligning with these languages preferences supports a smoother digital transition to more complex integrated management system, facilitating the adoption of advanced functionalities while preparing the users' skills for higher level of complexity in the path towards digital twin operational implementation. Eventually, the State of Open Source report highlights that data integration from multiple sources still stand out as the leading challenge for the majority of organisations managing big data. By designing an expandable platform specifically to solve the data silo problem, integrating BIM, GIS and point clouds, this research directly addresses one of the most critical pain points identified by the industry.

Finally, the report notes that lack of personnel skills and documentation are top barriers to open-source adoption. This reinforces the value of the Internal training and skill transfer strategies implemented in the Belvedere Glacier case study and the comprehensive GitHub documentation provided for the P.O.N.T.I. prototype. By prioritising detailed user guides and reproducible templates as capacity building strategies, the proposed framework mitigates the skill gap risks that typically hinder the deployment of open-source solutions in complex operational environments.

The iterative validation across three domains demonstrated that the framework's layered architecture, separating the data storage, server-side logic, and visualisation layers, is the primary enabler for this re-adaptability. For instance, while the Castello Farnese implementation focused on the interpretive interface for storytelling , the Belvedere Glacier project successfully extended the same architecture to include a state-aware database for temporal monitoring. Finally, the P.O.N.T.I. prototype for bridge management further expanded these capabilities to support active operational agency through CRUD operations. This modularity allows researchers to identify and readapt specific components, such as the oriented imagery projection JS script or the database schema templates and adapt them to local hardware configurations or domain-specific needs without rebuilding the entire system from scratch.

In addition to code accessibility, there is a commitment to open data sharing, as evidenced for example by the choice of employing Zenodo as a strategy to amplify the impact of the research within a wider community of scientists. This approach was specifically adopted for the Belvedere Glacier monitoring project, which, unlike the P.O.N.T.I. data management system, aligned to the licences and requirements of the public administration, did not involve sensitive asset information. The high frequency of downloads for the 3D datasets (2148 as of February 2026) demonstrates a clear demand for high-quality, documented geospatial data (Ioli et al., 2024). These metrics suggest that the datasets produced during this research are being utilised by the global community for a heterogeneous variety of purposes, from change detection climatology studies to 3D graphics performance testing, passing through algorithm training (Wegen et al., 2026; Schindler, 2025).

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# List of conferences

June 2022 – ISPRS 2022 Congress, Nice (France)

August 2022 – State of the Map and FOSS4G 2022, Florence (Italy)

April 2023 – EGU 2023, Vienna (Austria)

June 2023 – CIPA 2023 Symposium, Florence (Italy)

September 2023 – ISPRS 2023 Geospatial Week, Cairo (Egypt)

September 2023 – Convegno SIFET 2023, Arezzo (Italy)

April 2024 – EGU 2024, Vienna (Austria)

July 2024 – FOSS4G Europe 2024, Tartu (Estonia)

April 2025 – ISPRS 2025 Geospatial Week, Dubai (United Arab Emirates)

July 2025 – FOSS4G Europe 2025, Mostar (Bosnia and Herzegovina)

August 2025 – CIPA 2025 Symposium, Seoul (Republic of Korea)

November 2025 – FOSS4G 2025, Auckland (New Zealand)

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