geomatics

Article

A 3D WebGIS Open-Source Prototype for Bridge Inspection Data Management

Federica Gaspari [1,*], Rebecca Fascia [1], Federico Barbieri [1], Oscar Roman [2,3], Daniela Carrion [1] and Livio Pinto [1]

[1] Department of Civil and Environmental Engineering, Politecnico di Milano, 20133 Milano, Italy; rebecca.fascia@polimi.it (R.F.); federico2.barbieri@polimi.it (F.B.); daniela.carrion@polimi.it (D.C.); livio.pinto@polimi.it (L.P.)
[2] Program in Industrial Innovation, Department Information Engineering and Computer Science (IECS), University of Trento, 38123 Trento, Italy; oscar.roman@unitn.it
[3] 3D Optical Metrology (3DOM) Unit, Bruno Kessler Foundation (FBK), 38123 Trento, Italy
* Correspondence: federica.gaspari@polimi.it

Abstract

In response to the increasing demand for effective bridge management and the shortcomings of current proprietary solutions, this work presents an open-source, web-based platform designed to support bridge inspection and data management, particularly for small and medium-sized public administrations, which often lack personnel or funding for implementing context-specific tools. The system addresses fragmented workflows by integrating multi-format geospatial and 3D data—such as point clouds, CAD/BIM models, and georeferenced imagery—within a unified, modular architecture. The platform enables structured inventory, interactive 2D/3D visualization, defect annotation, and role-based user interaction, aligning with FAIR principles and interoperability standards. Built entirely with free and open-source tools, the P.O.N.T.I. prototype ensures scalability, transparency, and adaptability. A multi-layer navigation interface guides users through asset exploration, inspection history, and immersive 3D viewers. Fully documented and publicly available on GitHub, the system allows for deployment across varying institutional contexts. The platform's design anticipates future developments, including integration with IoT monitoring systems, AI-driven inspection tools, and chatbot interfaces for natural language querying. By overcoming existing proprietary limitations and providing access to a versatile single space, the proposed solution supports decision-makers in the digital transition towards a more accessible, transparent and integrated infrastructure asset management.

Keywords: location-based services; geodata management; open source; bridge inspection; geo-visualization; web-based platform

Academic Editor: Gloria Bordogna

Received: 29 September 2025
Revised: 8 November 2025
Accepted: 17 November 2025
Published: 24 November 2025

Citation: Gaspari, F.; Fascia, R.; Barbieri, F.; Roman, O.; Carrion, D.; Pinto, L. A 3D WebGIS Open-Source Prototype for Bridge Inspection Data Management. *Geomatics* **2025**, *5*, 68. https://doi.org/10.3390/geomatics5040068

1. Introduction

In the last decade Italy experienced a series of tragic road bridge collapses, including the Annone (2016) and Ancona (2017) overpasses, the Fossano viaduct (2017), and the Polcevera bridge (2018). While resulting from diverse underlying causes, these failures share a common theme: an insufficient understanding of the structure's actual condition [1], which in turn prevents the effective planning of maintenance interventions.

Problems such as missing as-built designs, inadequate construction and movement precautions, lack of heavy vehicle checking, and insufficient material decay monitoring have all contributed to inadequate data management and knowledge of what is occurring within these structures [2]. This underscores a significant challenge faced by Italian infrastructure, which is characterized by a large number of crossing constructions due to the country's geography, many of which are aging and showing signs of deterioration [3]. Consequently, there is a pressing need to address the preservation, restoration, or replacement of these existing constructions, and to evaluate the safety of infrastructural assets within an updated and organized regulatory framework.

The critical need for improved bridge management, highlighted by these events, is driving many countries to seek innovative approaches and digital solutions capable of handling the complex, heterogeneous data required for effective maintenance and safety assessment [4]. Managing bridges throughout their lifecycle requires a comprehensive understanding of their condition, which involves collecting and integrating data from various sources and in multiple formats, often across different points in time [5]. For data acquisition, Unmanned Aerial Vehicles (UAVs) are used for remote visual surveys and 3D mapping, while Internet of Things (IoT) sensors provide continuous, real-time data for Structural Health Monitoring (SHM). Collected data is then managed during processing and advanced analysis, where Artificial Intelligence (AI) can be applied for tasks like automated defect recognition, and Building Information Modeling (BIM) provides a framework for a detailed, semantic 3D model of the individual asset. Finally, for visualization and integration, Geographic Information System (GIS) and WebGIS platforms serve as the central hub, managing the geospatial context of the whole asset network and integrating these diverse data streams and sources into a unified environment. These digital tools promise to enhance monitoring, defect detection, structural health assessment, and planning for interventions.

The concept of bridge management systems (BMSs) was introduced in the last century, introducing significant changes to asset administration [6]. Functionally, a BMS is a decision-support tool that combines digital asset inventory, inspection data and maintenance tools to preserve infrastructure value and ensure long-term safe serviceability [7]. However, practical implementation is often problematic due to fragmentation of software and of regulations. This occurs at a regulatory level, with varying national guidelines, and at a data level, where information modeling is not yet significantly embraced in holistic, integrated frameworks [8]. Many asset managers rely on proprietary "black-box" systems that are rigid and cannot be adapted to specific local needs. To address these needs, research has focused on developing web GIS-based bridge management systems that allow for advanced geospatial visualization and data integration on centralized cloud platforms, with first cases of implementation documented in the United States in the 90s and more recent country-specific applications in Eastern Asia and Europe [9,10]. While these technologies are foundational, it is important to distinguish their integration in a WebGIS environment from a full bridge Digital Twin (DT), whereas a DT implies a live, bi-directional data exchange with the physical asset for real-time operational control [11], WebGIS-based approaches primarily aims to manage and visualize static inspection data and their products, optimizing the data collection and management workflow. However, despite decades of effort and the increasing development of Information and Communication Technologies (ICTs), there has not been a complete convergence towards the development of truly interoperable and all-encompassing open-source solutions for bridge management [9,12,13]. Current BMSs often suffer from significant limitations, including a limited ability to retrieve and share data electronically, difficulties in visualizing geospatial information, and a lack of comprehensive integration across different platforms. Traditional approaches and existing systems often rely on standalone platforms or provide data in fragmented, isolated formats (like disaggregated Excel files in the Italian context), preventing seamless data exchange, orderly consultation, and full integration with collaborative BIM platforms and interoperable data models necessary for effective bridge management [3,14]. This fragmentation and lack of comprehensive, integrated digital solutions represent a significant gap in current practice.

This work presents the design and prototyping of an open-source, web-based application aimed at supporting bridge inspection and data management. The platform is conceived to address current limitations in fragmented workflows by outlining a unified environment capable of integrating heterogeneous geospatial data—such as point clouds, Computer Aided Design (CAD)-derived 3D models, and images. Specifically tailored to the requirements of small and medium-sized public administrations, the system architecture supports structured data organization, interactive 3D visualization, and role-based access control. Aligned with digital transition goals, the prototype developed as part of the collaboration with the Province of Piacenza (Italy) emphasizes interoperability, transparency, and scalability as foundational principles.

2. Current Technologies in Bridge Management

In response to the urgent need for more effective bridge governance, the landscape of inspection and data management systems has evolved rapidly in recent decades [10–15]. Currently, modern approaches are based on a layered system of data acquisition, processing, integration, and visualization, where the main objective is to generate usable information-based environments to support timely and informed decision-making maintenance operations.

2.1. Bridge Data Acquisition Techniques

In this framework, data acquisition can represent the first step of the management process. Traditionally, bridge inspections have relied on visual surveys; however, these approaches often present technical challenges, as they can be time-consuming, costly and risky for inspectors, particularly, when dealing with damaged or hard-to-reach structures [16,17]. In this context, geomatics techniques, combined with traditional non-destructive testing (NDT) methods and sensor monitoring, have proven to be effective tools for the remote acquisition of accurate data on the geometry and degradation state of structures, providing a solid basis for 2D/3D reconstruction and analysis of phenomena such as deformations and displacements [18]. The integration of these technologies provides an objective survey of the assets' structural condition, enabling the timely diagnosis of possible structural anomalies and the planning of targeted maintenance interventions.

Photogrammetry is one of the techniques widely used in the geomatics field for built environment surveying, especially with the development of UAV technology, as drones can overcome some limitations that may arise during an inspection, such as site accessibility [19]. These instruments can rapidly acquire videos and images that are useful for digitally reproducing the asset, gathering geometric and material-pathological information, also thanks to integration with complementary technologies, such as thermography [16,19,20].

Another technique used to monitor bridges is laser surveying, which can be carried out through static or mobile devices. Stationary instruments, such as terrestrial laser scanners (TLS), can quickly and accurately acquire the geometric characteristics of bridges and monitor structural deformation through time-series comparison analysis [21,22]. In addition to TLSs, Simultaneous Localisation and Mapping (SLAM) mobile laser scanners, that are equipped with an Inertial Measurement Unit (IMU) which traces the tool trajectory, allow for faster acquisition, which can be useful for large, complex structures [23]. Furthermore, LiDAR systems have been used to detect defects such as cracks, partly as they can be integrated into mobile tools such as SLAM lasers, drones and vehicles [24–26].

In addition to the previously cited tools, advanced bridge monitoring relies on satellite and remote sensing technologies to expand spatial and temporal analysis capabilities. For example, Global Navigation Satellite System (GNSS) allows for geo-oriented surveying and monitoring of structural deformations or displacements via Global Positioning System (GPS) networks [27,28]. Another well-established technology is Synthetic Aperture Radar Interferometry (InSAR), which uses satellite radar to detect structural issues related to spatial phenomena such as displacements induced by thermal variations [29,30]. These advanced tools complement traditional Structural Health Monitoring (SHM) methods, where data collection can be either point-based or continuous: in fact, SHM has relied on non-destructive techniques [20,31,32] and the integration of various sensory systems [33–35], all of which are now established in civil engineering to ensure the safety and reliability of infrastructure. In this context, the geomatic and structural techniques mentioned allow for the acquisition of raw data that can be subsequently processed by proprietary software [36–38], open-source programs [39,40] or innovative methods [41–43] for the generation of various outputs, which allow for the digital visualization of the asset.

2.2. Output Types for Bridge Survey

A direct product of laser scanning or photogrammetric processing is the point cloud, which represents the geometry of the surveyed structure with high density and additional sensor data, such as intensity or number of returns, or chromatic information [44]. This chromatic data, when properly calibrated, is critical for visual inspection as it allows for the identification of bi-dimensional pathologies, such as humidity, molds, or efflorescence, which are often not perceivable from the 3D geometry alone. From this dataset it is possible to generate meshes, continuous surfaces suitable for material analysis and the detection of structural defects [45,46]. The point cloud can also be used as the basis for developing CAD [47,48], BIM [49,50] and Industry Foundation Classes (IFC) [51,52] models used to improve static/phase-by-phase maintenance management. Furthermore, when these models are integrated with IoT sensors that provide real-time data, they become digital twins (DTs), virtual replicas that enable comprehensive and dynamic lifecycle management of the assets [53,54]. Additional information can be obtained from the survey technologies themselves, including oriented images produced by photogrammetry, which maps the locations of UAV photos [55], and data from non-destructive testing (NDT), which can be integrated into the final visualized model, providing a detailed digital representation of the asset condition [56].

2.3. Bridge Data Management and Visualization Solutions

While the acquisition and processing of heterogeneous data are the first step in the digitization of civil assets, an equally important challenge is the effective management and visualization of this information. 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 [57,58]. 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 IFC format and displayed using free desktop viewers, which allow users to visualize the model without commercial licensing [59,60]. Nevertheless, it is now recognized 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 recognized limitations of standalone BIM models, the challenge of effective infrastructure management is increasingly being overcome by WebGIS solutions [4,61] which integrate GIS with web technologies, allow users to access, visualize, and analyze complex spatial data through a simple web browser. This architecture emerged to overcome the limitations of traditional BMSs, which often suffered from flat graphics, user-unfriendly interfaces, and a limited capacity for visualizing geospatial data [4,9,62]. 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 [25,63], railways [64] and power and supply networks [65–67]. 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 [9].

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 [57,68], summary graphs of asset conditions [69], and condition records via analytical outputs such as degradation mapping [70]. Additionally, emerging commercial cloud-based solutions [71] or game-based solutions [72] are being used to visualize sensor data via digital devices such as computers or immersive devices. This enables real-time condition monitoring and augmented reality interactions in situ [72,73]. In particular, the comprehensive tools and combinations developed by Esri and Bentley Systems in recent years have explored the development of fully integrated digital twin-like platforms involving the adoption of ArcGIS and iTwin [63,74,75]. 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 customized solutions using open source: these systems aim to provide a flexible and scalable environment for managing structured data, overcoming the limitations imposed by commercial platforms. These solutions have proven to be effective and versatile, with applications documented in the literature ranging from cultural heritage promotion [76,77] and power supply management [66,67] to environment and sustainability monitoring [78,79]. In this context, some authors have proposed BMSs based on Free and Open-Source Software (FOSS) platforms for defining their architecture: in fact, in this framework, data are usually organized through relational databases, which allow for efficient storage and retrieval, while spatial mapping of infrastructure assets is managed through GISs, which can provide a complete overview of the infrastructure network [4]. 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 [5–80]. This integrated, modular approach enables the creation of an interoperable, extensible, and accessible digital ecosystem for infrastructure monitoring and management.

Based on the overview and key points highlighted in the introduction, it is crucial to develop a comprehensive framework for creating a visualization platform suitable for bridge management. This system should be able to integrate different data sources and adapt to a wide range of real-world scenarios, from environments with a large amount of data to those requiring the incorporation of entirely new information.

3. Platform Design

The proposed solution aims at supporting the complexity of the variety of product formats resulting from bridge inspections with dedicated workflows, leveraging the potential of open-source software. This section outlines the key steps involved in designing a WebGIS platform prototype for bridge inspection data management, including user requirements analysis, software architecture design choice, and functional modules overview.

3.1. User Requirements

In order to design and implement platform functionalities effectively, it is necessary to evaluate the needs of the target users, as the dimensions of resources and managed assets can vary significantly at different scales (Figure 1). Indeed, in the last decade, the digital transformation phenomenon led government organizations and public administration bodies to rethink their traditional documentation and data management workflows, often relying on highly detailed proprietary e-solutions [81]. In this constantly evolving scenario, the European Commission highlighted the potential of open-source tools to enhance transparency and reusability, recommending their adoption in its Open-source software strategy 2020–2023 [82]. This was also remarked upon by country members such as Italy [83]. However, the transition is ongoing and faces obstacles, as proprietary solutions are still heavily relied upon due to their perceived reliability. Differences in financial resources and technical expertise lead to discrepancies at both the national level and among small and medium-sized entities, which often lack the specialized personnel or funding required to implement context-specific tools [84,85]. In this context, an easy-to-implement and adaptable combination of FOSS tools could represent an opportunity for a more efficient, digitalized approach for smaller agents [86].

Considering the current challenges in data management software adoption, the target users for this study are the road asset managers of medium and small size administrative divisions. In particular, the case studies illustrated in this paper specifically cover the examples of the Italian Province, as the WebGIS prototype illustrated in this paper has been developed as part of a collaboration with the Province of Piacenza (Italy). Since the formulation of the multi-level Guidelines for Risk Classification and Management [87] and their subsequent implementation [88], such entities have been required to carry out periodic inspections to assign an "Attention Class" to each managed structure, assessing the possible need for more detailed inspection or monitoring procedures. Similarly to regulations in other countries, the initial stage consists of a visual inspection, in which operators in the field collect large amounts of data and observations. These are usually stored fragmentarily on personal memory disks, thus increasing the risk of data loss and misinterpretation. In addition, given the extent of infrastructure networks and possible limited internal resources, small/middle administrations are often unable to carry out systematic inspections: consequently, they turn to specialized external entities to ensure consistent and adequate data monitoring and management. Similarly, the results of processing steps such as laser scanning or photogrammetric reconstruction, including geometrical models, are often archived in disorganized system local folders. This makes it impossible to preserve both thematic and geospatial components in a coherent common and queryable space. As a result, data managers experience difficulties in retrieving information. This is because relevant information is dispersed in duplicated text or spreadsheet files [89].

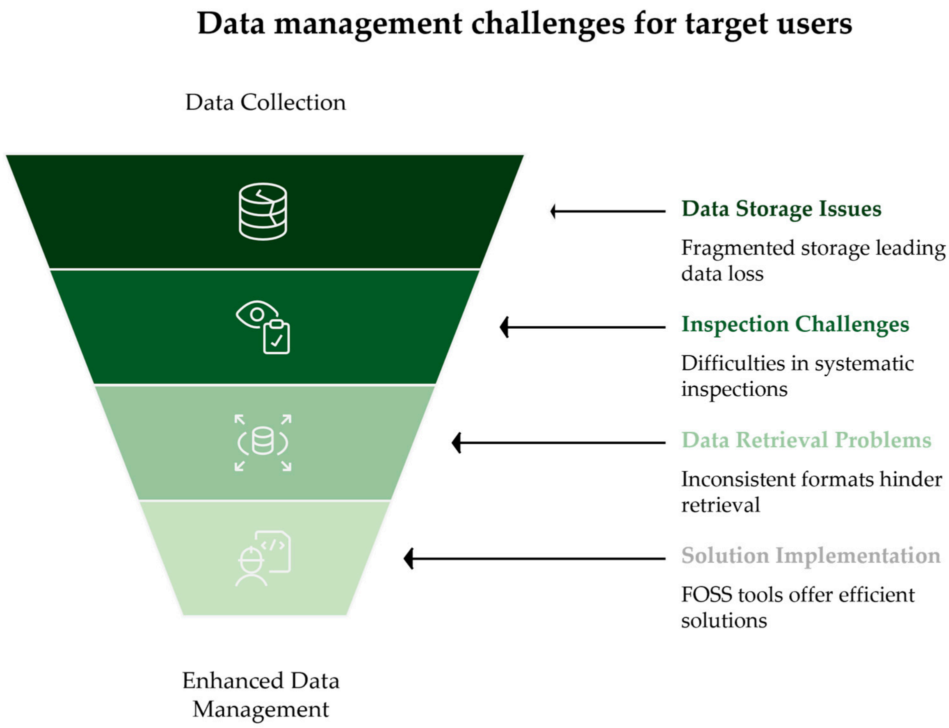

Figure 1. The inverted pyramid visualizes a progressive refinement from broader issues—data storage, inspection, and retrieval—down to the core solution implementation phase. This structure reflects the priorities and practical needs expressed by infrastructure stakeholders and guides the system design from problem identification to functional response.

Therefore, the designed platform requires the ability to manage and interactively query the geodata and products that are traditionally acquired during the periodical inspections, the processed output resulting from them as well as historical data (e.g., digitally scanned report or document) related to the structure design or existing time-series of observations from sensors previously installed on the bridge. In the case of the Italian Province administration, this usually consists of CAD 3D drawings, point clouds, georeferenced images or BIM models. This finding aligns directly with the outputs identified in the state-of-the-art overview in Section 2.2, such as point clouds [44], BIM/IFC models [49–52] and oriented images [55], confirming that a primary requirement for the platform is to ingest and manage such heterogeneous data types. Moreover, the prototype must enable and enhance interactivity and user-role-based access of interactions, as well as support the filtering and annotation of visible defects detected on the structure during exploration.

A key consideration in this design is defining the appropriate level of access for different users. The user definition followed a preliminary step conducted in collaboration with the Province of Piacenza, a local authority in the Italian region of Emilia Romagna which required to conduct periodical inspection on bridges. Such collaboration helped identifying the key personnel and their existing workflows: primarily, the staff responsible for the current Road Cadaster inventory, already familiar with routine database and GIS operations and editing, and the structural assessment group, which typically handles separately defect recognition through fragmented visual inspections (e.g., written reports and unstructured photo collection) lacking a unified geospatial context.

While future development may include public-facing access, the current prototype focuses on the primary internal user groups within public administrations. These groups require distinct permissions managed by a role-based access control system to ensure data integrity. The three core user groups identified are: IT technicians, responsible for the system's maintenance and user management; GIS specialists or data managers, responsible for uploading and organizing geospatial data and inspection products; and bridge engineers or inspectors, responsible for the technical assessment, defect annotation and rating of the structures.

3.2. System Design Principles

The proposed system is designed to meet the following goals: modularity, geospatial interoperability, user-centric design and re-adaptability.

Recent literature on the topic highlights the need for, and diffuse trend of, modular bridge data management solutions [10]. It is now common practice to identify a strict structure in operating solutions, which are mainly composed of four modules: inventory; data integration; asset assessment and prognosis; decision-making support and forecasting [4,11,25]. This choice allows users to clearly identify the functionalities of each distinct component while supporting future scalability and extension.

As bridge management inherently involves spatial relationships, the system must also handle georeferenced data through Open Geospatial Consortium (OGC)-compliant services [63]. Spatial queries combine asset locations with regional infrastructure networks, while coordinate reference system transformations ensure consistency across UAV survey products (WGS84), CAD drawings and other geodata in different formats. An abstraction layer uses dedicated pipelines to convert heterogeneous inputs, including point clouds (LAS/LAZ) and BIM models (IFC), into unified, web-ready formats [90]. In this way, the proposed prototype addresses the limitations of standalone platforms lock-in identified in Section 2.3, adopting the more flexible, integrated WebGIS approach advocated in recent research [4,14,63].

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 [91]. This approach results in a platform that adapts to the context of use, offering tailored visualization presets for inspectors and planners, as well as streamlined access to advanced tools only when required [92]. The design prioritizes clarity and usability, supporting both desktop and mobile inspection activities, including scenarios where offline access is necessary. In parallel, a role-based access control system is required in accordance with established standards, allowing for precise management of permissions. 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 [93].

Re-adaptability and extensibility are addressed through the adoption of a microservices architecture, which enables individual components to be updated or replaced without disrupting the overall system. The platform's modular design needs to be complemented with clear and up-to-date documentation and access points (e.g., database connections, APIs), facilitating integration with external tools for advanced spatial analysis, development of custom dashboards and reporting solutions. This architecture choice not only supports the incremental enhancement of platform capabilities but also encourages the adoption of open standards and the Findable, Accessible, Interoperable, and Reusable (FAIR) data principles [94]. As a result, the system remains adaptable to evolving requirements and can be readily extended to accommodate new data types or functionalities as bridge management practices continue to advance.

3.3. Functional Modules Overview

In light of the underlying design principles, the proposed system comprises four interconnected core modules: inventory and data storage; visualization and query interface; annotation and update tools; a re-adaptability and documentation module. Defined based on insights from a state-of-the-art review and user requirements, these modules form the backbone of the system and provide a foundation for the development of additional functionalities in the future (Figure 2).

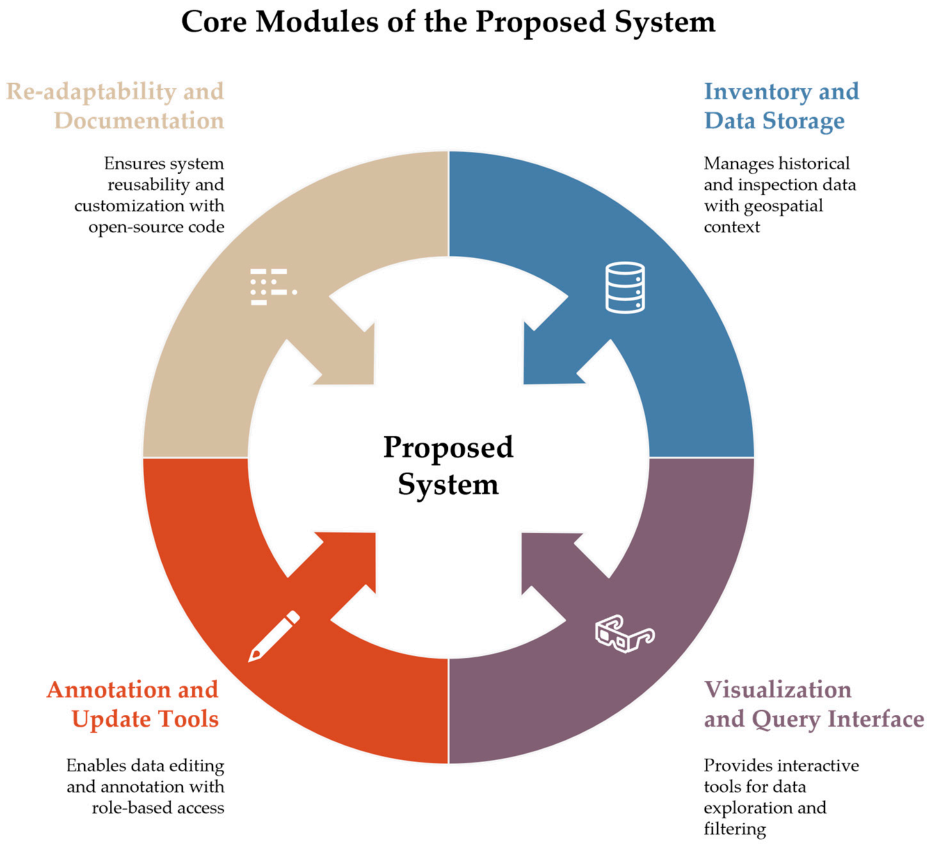

Figure 2. Modular schema of the developed open-source platform for infrastructure data management. The 4 modules support the full lifecycle of infrastructure inspection and monitoring data, from storage to visualization and iterative updates. The circular layout emphasizes continuous feedback and extensibility.

3.3.1. Inventory and Data Storage

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 organize 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 recognized 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 Entity Relationship Diagram (ERD) is provided in Figure 3. 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 centered 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.

Figure 3. Entity Relationship Diagram (ERD) for the platform made with MySQL Workbench.

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.

3.3.2. Visualization and Query Interface

The visualization 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 graphical user interfaces (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 visualize 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.

3.3.3. Annotation and Update Tools

This component of the proposed system manages all user-platform interactions aimed at creating, editing or deleting data and objects connected to the bridge inspection information system. It complements the viewing capabilities of the visualization module by providing full support for Create, Read, Update and Delete (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 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 authorized users can modify or approve critical data, thus maintaining data integrity and supporting collaborative workflows among inspectors, engineers, and administrators (Table 1). 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 1. Definition of the three internal user role groups and their corresponding platform permissions.

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.

3.3.4. Re-Adaptability and Documentation

The structure of the proposed solution is completed with the re-adaptability module, whose primary role is to ensure that the entire toolset can be efficiently reused and customized for a wide range of case studies, extending well beyond the domain of bridge management. This module is grounded in a commitment to open-source development and transparency, with the full codebase made publicly accessible via a dedicated repository on open developer platforms (https://github.com/Tars4815/ponti, accessed on 26 October 2025). To facilitate rapid deployment and adaptation, the platform provides a comprehensive database schema accompanied by SQL initialization scripts, enabling users to set up and tailor the data model to their specific requirements. A detailed user manual accompanies the repository, describing the platform's setup procedures and core functionalities to support both novice and advanced users. Furthermore, explicit guidelines need to be included to assist with interface customization and the transferability of the platform to new domains, ensuring that organizations can readily adapt the system to their operational context. Collectively, these resources—open-source code, structured documentation, and practical guides—form the foundation for the platform's reusability and long-term sustainability in diverse geospatial and asset management applications.

4. System Architecture and Prototype

The proposed system design addresses the need for survey data storage, integration and exploration to support virtual and interactive assessment. This forms the basis for the future implementation of country- or case-specific rating computations and the implementation of dedicated national maintenance strategies. Based on that, a minimal prototype—called Potree-based platfOrm for iNfrasTructure Inspection (P.O.N.T.I.)—has been developed and tested, implementing the designed modules and essential interaction components for bridge inspection data management.

4.1. Prototype Components

Following the theoretical definition of the functional modules, 6 distinct operational components have been distinguished for identifying suitable technologies for implementation. The Free and Open-Source technology stack adopted for the prototype is detailed in Table 2 while their roles and interaction within the theoretical modules is illustrated in Figure 4.

Table 2. Technologies and functions for which each component of the prototype architecture is responsible for.

Component	Technology	Functions
Data storage	PostgreSQL + PostGIS	Stores structured data (assets, inspections, defects), supports spatial queries
Map interface	Leaflet.js	Displays bridge locations, filters records, opens asset panels
3D viewer	Potree + CesiumJS + XEOKIT	Renders point clouds and BIM/CAD models, supports spatial exploration
Annotation & uploads	HTML5 forms + DB logic	Allows authenticated users to update files, annotate images, and tag defects
Role-based access	PostgreSQL roles, login system	Manages user permissions for viewing, editing, and administration
Deployment & reuse	GitHub repository + documentation	Open-source release with ERD schema, customization tips, and installation guide

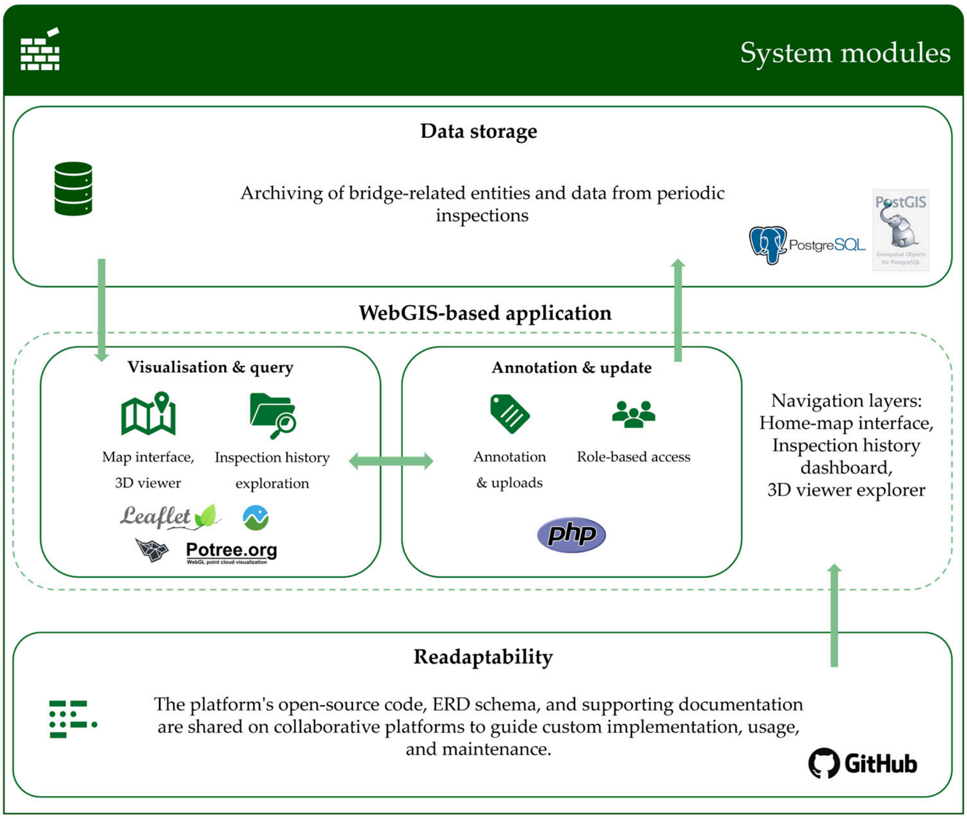

Figure 4. System modules and architecture of the P.O.N.T.I. platform prototype. The architecture integrates a spatially enabled data storage backend, a WebGIS-based application for visualization, querying, annotation, and updates, and a re-adaptability module to support reuse and customization. Key technologies include PostgreSQL/PostGIS, Leaflet, Potree, PHP scripting, and open-source resources shared via GitHub.

The core element of the Inventory module is represented by the relational database, built with PostgreSQL and PostGIS [95], already used by the Province of Piacenza stakeholders. This choice is further motivated by its object relational nature, which makes it highly extensible, and its scalability to efficiently manage the large data quantities anticipated for a future monitoring module integration. Furthermore, for web-based 3D GIS applications, PostGIS enables direct conversion of spatial data to 3D tiles and other OGC standard formats using native functions, while alternatives like MySQL not only limits the possibility of managing different formats making it less extensible but would also require complex manual processing. Moreover, PostgreSQL natively manages simultaneous user requests using a sophisticated Multi-version Concurrency Control (MVCC) model, which ensures that multiple users can read and write to the database at the same time without interfering with each other or causing data corruption, with special support on writing operations.

Regarding the server architecture, the current proposed prototype is deployed locally using XAMPP [96], 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 REST 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-optimized, 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 optimized 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.

The defined data inventory interacts with a web-based platform that, in its final implementation, does not require any local installation. Currently, the prototype is under testing and evaluation on a local server. Such platform works thanks to the integration of the visualization and query interface through the underlying annotation and update tools that communicate with the database. For 2D visualization purposes, the JavaScript library Leaflet was adopted, supporting lightweight rendering and interactive web-mapping operations [97]; while the 3D viewer is built on top of well-established libraries for pointcloud rendering (Potree) [98], large geospatial integration in web GIS environments (CesiumJS) [99] and BIM visualization (XEOKIT) [100]. Their integration supports the flexible exploration of geodata at different scales, enhancing user experience. 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 managed through the open-source PROJ.4 library to facilitate globe-based representation.

The entire system prototype was tested using XAMPP, a free and open-source cross-platform web server solution developed by Apache Friends [96]. This environment enabled local deployment and testing of the web application components (including PHP scripts, database connections, and file handling) in an integrated and reproducible setup.

4.2. Navigation Layers and Interface Functions

Aligning to the design principles, the prototype consists of 3 web navigation layers, supporting asset exploration at different scales while allowing for flexible rendering of 2D and 3D objects in an interactive scene. Figure 5 summarizes the roles and functions of each layer.

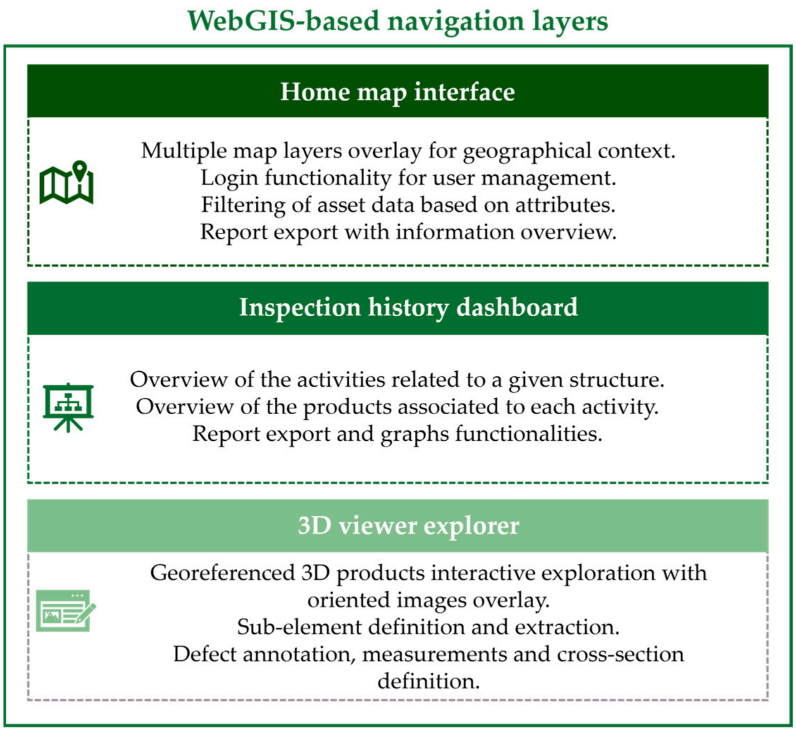

Figure 5. Application navigation layers of the P.O.N.T.I. platform. The interface offers progressive access through a home map, an inspection history dashboard, and a 3D viewer explorer, supporting spatial browsing, inspection data retrieval, and immersive survey product visualization.

4.2.1. 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 6). 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 [101].

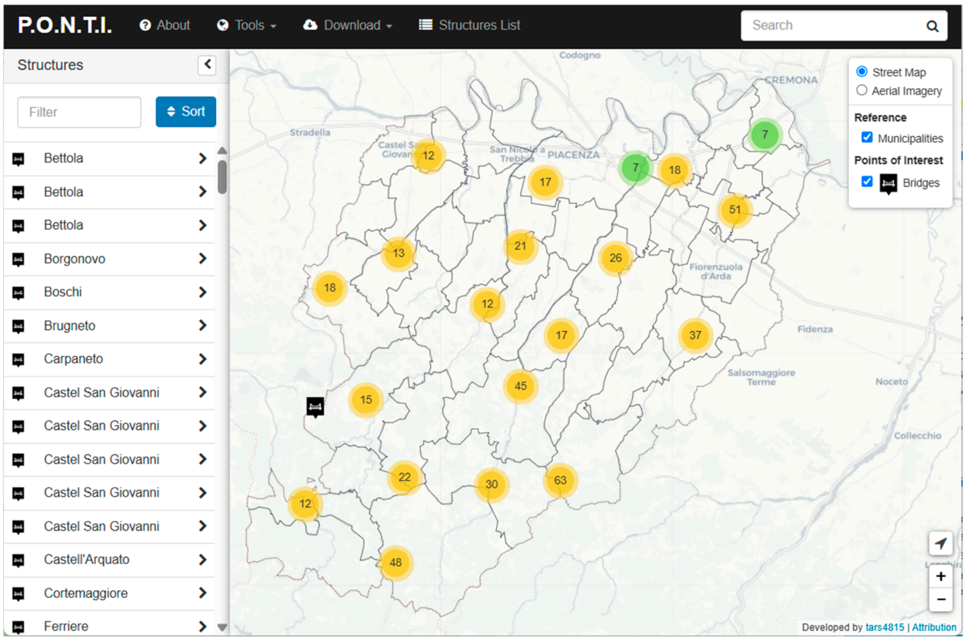

Figure 6. Home page of the prototype with bridge asset overview in the interactive Leaflet-based map. The sidebar on the left allows users to filter structures based on attributes (e.g., official name, municipality). Based on the scale of visualization, point map features are clustered thanks to the Leaflet.markerCluster plugin, with varying colors based on numerosity of clusters.

This view provides a dedicated entry point for visualizing the geolocation of assets on the territory and for filtering the structure list according to attributes of interest in the sidebar. 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 visualized 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. As specified in Section 4.1, 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 4 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, mentioned in Section 4.1, 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 characterizing the territorial context, such as hydraulic risk, cataloged gravitational phenomena or seismic zonation. Moreover, the rendering legend of the asset can be customized according to the end users' preferences. Structures can be symbolized 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, by clicking its icon the logged user can have an overview of the main information associated with 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 7). This action triggers the automatic generation of PDF file, thanks to the JSPDF library. The output document is created starting from a predefined template filled with information on the structure retrieved from the underlying database. This functionality can be useful and timesaving when country-specific regulations—like the Italian one—ask asset managers to fill standard PDF tables.

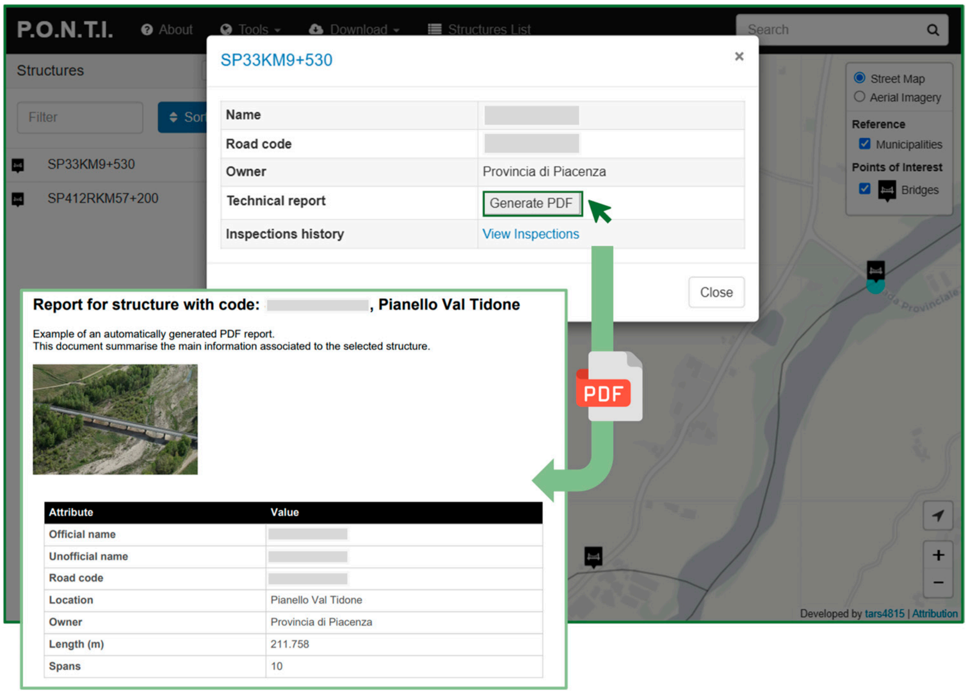

Figure 7. Example of the export mode from the home page that leverages the functionalities of JSPDF for the automatic generation of PDF report files with bridge information that could be accessed also offline.

4.2.2. Inspection History Dashboard

After exploring the network-scale viewer and selecting a bridge of interest, users can access the single structure menu, which includes 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 (Figure 8). According to their specific needs, the interface can be customized to include additional filters to simplify the search for activities within a specific time range or that produced specific products (e.g., pointclouds and/or oriented images).

When a single inspection entry is selected, an informative panel summarizing the quantity and variety of products (such as number of images or the presence of point clouds or BIM models), as well as the defects identified during the inspection (both in situ and a posteriori through the viewer), is made visible. If the annotated defects have also been associated with a specific severity degree and a grading formula has been implemented in the code, an overall structure assessment rating is shown. 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 is embedded in the inspection info panel, showing a Potree preview of the associated point cloud, if available for the give inspection.

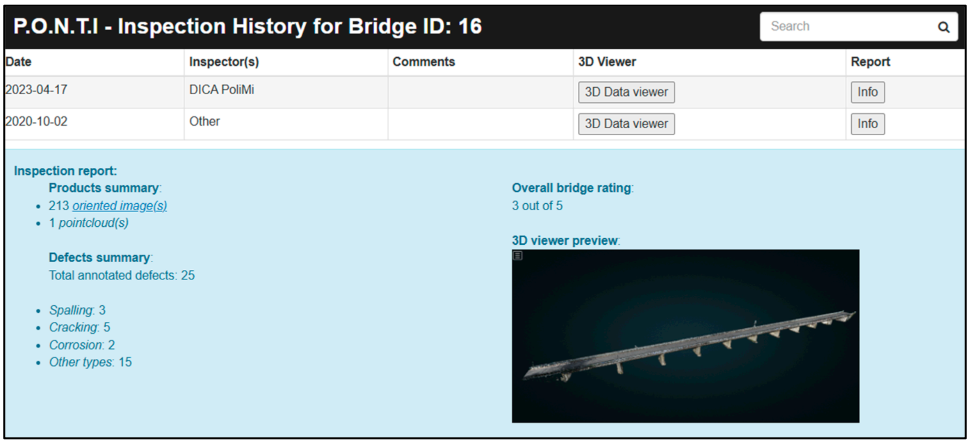

Figure 8. Inspection dashboard for a selected structure. This page summarizes the timeline of the bridge inspections, providing a simple interface for exploring the available survey products, computed bridge assessment rating and preview of the viewer.

4.2.3. Three-Dimensional Viewer Explorer

The 3D viewer explorer within the platform enables advanced interaction with bridge inspection data, supporting interactive exploration of georeferenced 3D products like point clouds and BIM models embedded directly in the browser.

The 3D viewer explorer adopts a modular approach, using specialized libraries for specific data type. In its current implementation, indeed, the prototype does not combine point clouds and BIM in the same 3D view. Instead, it links the user from the dashboard to the appropriate specialized viewer (e.g., Figures 9 and 10 for point clouds, Figure 11 for BIM), depending on the attached 3D product (for example point cloud or BIM) to a given inspection record. However, for users requiring enhanced geospatial contextualization, a possible customization would be to pre-process the IFC model into OGC 3D Tiles and visualize it directly within the Potree-Cesium viewer alongside the point cloud, using its 3D tiles loader function from CesiumJS.

Figure 9. 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.

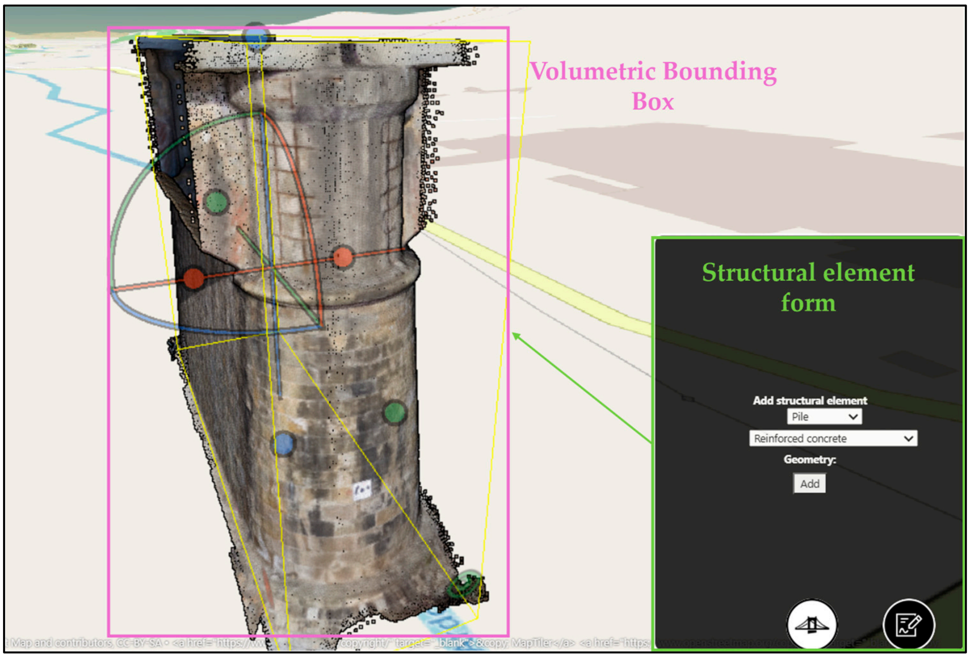

Figure 10. Example of a user-input procedure for defining a structural element directly within the 3D viewer. This approach allows users to define a bounding box to quickly filter the point cloud view and hide irrelevant parts. The OpenStreetMap basemap on the background is visualized through CesiumJS functionalities.

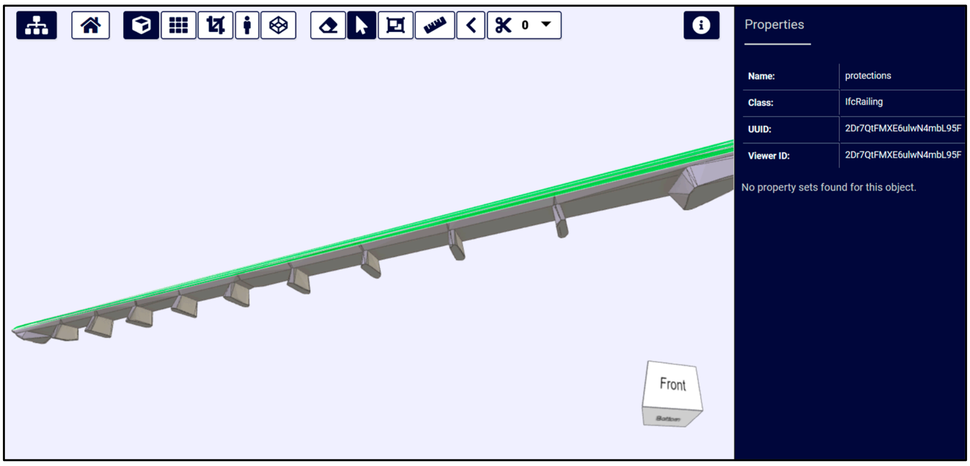

Figure 11. Screenshot of user interface for the 3D viewer component based on XEOKIT library for visualizing BIM models and inspecting their properties.

The use of CesiumJS and XEOKIT reflects a common technology choice for GIS-module and BIM-module functionalities, an approach also validated in recent open-source bridge data visualization research [5]. CesiumJS was chosen for its strength in providing the overarching 3D global geospatial context and handling 3D tiles when available, while XEOKIT was chosen for its specific, high-performance capabilities in parsing and visualizing semantic BIM/IFC models for detailed component inspection.

Point clouds are overlaid with oriented images captured during surveys (Figure 9). When a given image is clicked in the 3D space, it is overlaid in the 3D space. The camera parameters, stored in the database, are used to link the 2D image pixels to the 3D point cloud geometry with a dedicated native Potree functionality, as illustrated in Figure 9. This allows users to compare textures and localize defects by clicking on the photo to generate a 3D annotation.

Users can define and extract specific sub-elements from the point cloud with polygon clipping or filtering tools, facilitating isolation and analysis of structural components such as beams or decks (Figure 10). Such operations are made possible thanks to the integration of PotreeJS (built on top of ThreeJS), powered by CesiumJS to provide geographical context (e.g., OpenStreetMap standard basemap and terrain). The viewer supports BIM visualization through libraries like XEOKIT, enabling detailed exploration of IFC-based models, including navigation, object selection, model sectioning, and semantic metadata inspection within the browser (Figure 11).

A key feature 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 8). 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 [102]. 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.

4.3. Re-Adaptability and Deployment

In accordance with the design principles and functional modules defined for the platform in Section 3, the prototyped code, written in HTML, CSS and JavaScript languages, is available on a GitHub repository (https://github.com/Tars4815/ponti) (accessed on 3 November 2025). In this way not only is the entire development process traced and versioned transparently, but also collaboration with other developers as well as researchers active in the field is made possible, enabling the reporting of issues or code improvements for future versions. Moreover, the open sharing of the code, with its main functions commented and documented, provides guidelines on how to re-adapt, expand and implement the core structure of the platform with highlighted snippets as well as illustrated examples supported by images and videos.

5. Discussion

One of the most significant advantages of the prototyped system is its flexibility and adaptability: users can tailor the platform to their specific operational needs, integrate new data types, and extend functionalities without being constrained by vendor-imposed limitations. This flexibility is particularly relevant for small and medium-sized public administrations, which often lack the resources to invest in expensive, proprietary software suites. The open-source model also fosters transparency and collaboration, enabling a wider community of practitioners and researchers to contribute improvements, identify bugs, and share best practices. In practice, the availability of detailed user guides and technical documentation on GitHub facilitate adoption and ensure that even users with limited technical backgrounds can effectively operate the platform.

Moreover, the system's modular and extensible architecture offers considerable potential for future expansion. In particular, it can be developed to include comprehensive tracking of maintenance interventions, such as updating a defect's status from "pending" to "solved" after a repair, and monitoring activities, thereby supporting a complete life-cycle management approach for bridge infrastructure. This enhancement would enable systematic recording, scheduling, and evaluation of maintenance work, fostering more proactive asset management and data-driven decision-making.

In its current state, the prototype is accessible only to registered users internally to the public administration that, after logging in with authorized user credentials, can access the different components of the WebGIS. In future development, after evaluating and defining external user roles, adopting a public interface could fulfill critical functions. Exposing read-only data, such as general inventory information and non-sensitive condition ratings, while restricting access to detailed inspection reports and defect annotations, enhances public trust and awareness without compromising data security or the integrity of specific condition assessments, like raw survey data like point clouds or structured inspection data (e.g., CSV exports).

Another enhancement for long-term upgrade planning of the platform is to separate the "Contributor" role into two distinct user groups: Internal Editors and Public Editors. Internal Editors would be organizational staff or certified personnel responsible for authoritative data entry and validation. Public editors, on the other hand, would include members of the general public, such as citizens who actively participate in the process by suggesting edits or reporting new observations in the field. Public editors' contributions would follow the crowdsourcing models seen in citizen science and on platforms like OpenStreetMap, where volunteered information is contributed through features like georeferenced notes. A dedicated workflow based on a "suggestion/validation" model could be implemented where public input is submitted for review and approval by a certified administrator before being committed to the database. This system would significantly improve asset managers' monitoring capabilities by leveraging collective knowledge to quickly identify potential infrastructure network issues without exposing sensitive technical operation information. However, this kind of development requires additional considerations regarding the storage capabilities and plans of the asset manager's administration.

Another key strength of the platform lies in its innovative approach to defect annotation. By guiding annotations with a photo oriented on a 3D point cloud, the system provides a robust alternative to traditional textual documentation or positional references limited to 2D images or orthophotos. Such conventional methods often suffer from fragmented archiving and a lack of direct georeferencing, reducing data coherence and hindering effective analysis. In contrast, the 3D annotation framework enhances smarter data exploration by enabling transparent filtering across three dimensions, improving spatial context and accuracy in defect reporting.

However, the open-source nature of the system also presents certain limitations. While reduced licensing costs are a clear benefit, the platform's technical capabilities may be constrained by the availability of contributors and the pace of community-driven updates. The effectiveness of open-source projects depends heavily on the quality and currency of documentation and user guides. Without regular updates and clear instructions, the risk of adoption barriers increases, especially as the underlying technologies evolve.

Commercial platforms often provide highly polished user interfaces, advanced analytics, and integrated support, but at the cost of flexibility, data ownership, and long-term affordability. Many proprietary systems are also closed, limiting interoperability and making it difficult to integrate with existing workflows or external data sources. In contrast, most existing open-source solutions in the field offer either strong geospatial capabilities (such as QGIS or GeoNode) or robust 3D visualization (such as Potree), but rarely combine these features in a single, unified environment tailored for bridge management. P.O.N.T.I. bridges this gap by integrating multi-source geospatial data, 3D visualization, and role-based access control in a modular, extensible architecture.

The role of open-source tools in public digital infrastructure is increasingly recognized as strategic [4,103]. By reducing dependency on proprietary vendors, public administrations gain greater control over their data and workflows, supporting long-term sustainability and digital sovereignty, if adequate development capabilities are available to keep the system updated and operational. Open-source platforms also encourage the adoption of open standards, which is critical for ensuring interoperability between different systems and stakeholders. This is particularly important in the context of infrastructure management, where data must often be exchanged across organizational and jurisdictional boundaries.

However, achieving interoperability and usability within an open-source framework involves careful trade-offs. While strict adherence to open standards (such as OGC protocols and open data formats) maximizes compatibility, it can also introduce complexity to the user experience, especially for non-expert users. Conversely, efforts to streamline and simplify the interface may sometimes limit the system's flexibility or the range of supported data types. The integration with mobile GIS solutions such as QField and Mergin Maps exemplifies this balance: it allows for direct, field-based data updates via QGIS, enhancing usability for inspectors, but requires ongoing maintenance to ensure seamless synchronization and compatibility with evolving database schemas [104].

6. Conclusions

This work presented the design and prototyping of an open-source, web-based platform tailored to support bridge inspection and data management, with a particular focus on the needs of small and medium-sized public administrations. The platform was conceived as a response to the persistent fragmentation in current workflows and the lack of integrated, interoperable solutions for managing and visualizing geospatial and 3D data in the bridge management domain. By integrating structured database storage, interactive 2D and 3D web geo-visualization, and role-based user interaction, the proposed prototype offers a lightweight, transparent, and modular toolset. Its design prioritizes the following:

- Multi-format compatibility with standard inspection products or structural historical data (e.g., point clouds, CAD/BIM models, georeferenced images).
- Scalable and reproducible architecture, built entirely on a free and open-source software stack.
- User-centered functionalities, such as defect annotation, measurement extraction, inspection history management, and web-based access control.
- The prototype is fully documented and openly available via a public GitHub repository, ensuring adaptability and facilitating deployment in diverse institutional or research contexts.

Current and planned developments are focused on strengthening the platform's usability and extensibility. As the ongoing collaboration with the Province of Piacenza's technicians team continues, feedback on new functionalities and alignment with new regulations is collected. Moreover, scalability from regional to national level institution as well as on different types of critical structures (e.g., tunnels) are also under evaluation with the collaboration with TECNE—Gruppo Autostrade per l'Italia and will be part of future dedicated studies. Efforts include testing and integrating additional modules for real-time monitoring, as well as advanced analysis of sensor observations compatible with geospatial FOSS (FOSS4G) tools and compliant with the latest OGC standards. This will enable seamless interconnection between IoT devices, data, and applications, representing a significant step toward a fully open operating system with digital twin capabilities to support smart maintenance planning and condition forecasting.

Looking ahead on the long term, the integration of AI-powered features represents a promising direction for the platform. For example, the implementation of chatbot interfaces could enable users to construct complex queries through natural language, simplifying data retrieval and analysis. Additionally, automatic defect recognition on bridge imagery using machine and deep learning algorithms could significantly accelerate and standardize the inspection process, improving both efficiency and reliability.

The backend architecture of the prototype can also be further enhanced by adopting frameworks such as Flask or Node.js to expose REST endpoints supporting the platform's APIs. This would not only improve scalability and maintainability but also facilitate integration with external systems and future AI modules.

A dedicated set of recommendations will be developed to support technical teams in adapting the platform to various domains beyond bridges. These guidelines will address data schema adjustments, viewer configurations, and interface customizations, ensuring that new use cases preserve interoperability and system coherence. Finally, efforts will continue to focus on collecting user feedback and further developing user documentation and installation packages (e.g., Docker images) to support deployment by non-specialists.

Author Contributions: Conceptualization, F.G., R.F. and D.C.; methodology, F.G. and R.F.; software, F.G.; validation, R.F.; investigation, F.B., R.F., F.G. and O.R.; resources, F.B., R.F., F.G. and L.P.; data curation, F.G., R.F., F.B. and O.R.; writing—original draft preparation, F.G. and R.F.; writing—review and editing, F.B., O.R., D.C. and L.P.; visualization, F.G.; supervision, D.C. and L.P.; project administration, L.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The source-code of the platform and its documentation are openly accessible in the GitHub repository: https://github.com/Tars4815/ponti (accessed on 16 September 2025). The actual data of the case studies illustrated in this paper are not for download, due to the restrictions of the Province of Piacenza, the bridge managing entity, on third party use.

Acknowledgments: Acknowledgment is extended to the engineers of the Province of Piacenza, the local authority responsible for the inspected bridges, for their support in the development of the research project.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Malerba, P.G. Bridge vulnerabilities and collapses: The Italian experience. *Struct. Infrastruct. Eng.* **2024**, *20*, 976–1001. [CrossRef]
2. Bazzucchi, F.; Restuccia, L.; Ferro, G.A. Considerations over the Italian road bridge infrastructure safety after the Polcevera viaduct collapse: Past errors and future perspectives. *Fract. Struct. Integr. Frat. Integrità Strutt.* **2018**, *46*, 400–421. [CrossRef]
3. Ciccone, A.; Suglia, P.; Asprone, D.; Salzano, A.; Nicolella, M. Defining a digital strategy in a BIM environment to manage existing reinforced concrete bridges in the context of Italian regulation. *Sustainability* **2022**, *14*, 11767. [CrossRef]
4. Mangiameli, M.; Cappello, A.; Mussumeci, G. A new bridge management system based on spatial database and open source GIS. *Environ. Syst. Decis.* **2024**, *44*, 500–513. [CrossRef]
5. Gao, Y.; Xiong, G.; Hu, Z.; Chai, C.; Li, H. Bridge digital twin for practical bridge operation and maintenance by integrating GIS and BIM. *Buildings* **2024**, *14*, 3731. [CrossRef]
6. Hawk, H.; Small, E.P. The BRIDGIT bridge management system. *Struct. Eng. Int.* **1998**, *8*, 309–314. [CrossRef]
7. Caldera, S.; Mostafa, S.; Desha, C.; Mohamed, S. Exploring the role of digital infrastructure asset management tools for resilient linear infrastructure outcomes in cities and towns: A systematic literature review. *Sustainability* **2021**, *13*, 11965. [CrossRef]

8. Dayan, V.; Chileshe, N.; Hassanli, R. A scoping review of information-modeling development in bridge management systems. *J. Constr. Eng. Manag.* **2022**, *148*, 03122006. [CrossRef]
9. Liu, H.; Wu, D.; Zhao, J. *Towards an Open-Source Web GIS-Based Bridge Management System Using Advanced Geo-Spatial Data Visualization and Integration Technologies*; Southern Plains Transportation Center: Norman, OK, USA, 2018.
10. Brighenti, F.; Caspani, V.F.; Costa, G.; Giordano, P.F.; Limongelli, M.P.; Zonta, D. Bridge management systems: A review on current practice in a digitizing world. *Eng. Struct.* **2024**, *321*, 118971. [CrossRef]
11. Mousavi, V.; Rashidi, M.; Mohammadi, M.; Samali, B. Evolution of digital twin frameworks in bridge management: Review and future directions. *Remote Sens.* **2024**, *16*, 1887. [CrossRef]
12. Belcore, E.; Di Pietra, V.; Grasso, N.; Piras, M.; Tondolo, F.; Savino, P.; Rodriguez Polania, D.; Osello, A. Towards a FOSS Automatic Classification of Defects for Bridges Structural Health Monitoring. In Proceedings of the Italian Conference on Geomatics and Geospatial Technologies, Genoa, Italy, 1–23 July 2021; Springer International Publishing: Cham, Switzerland, 2021; pp. 298–312.
13. Lozano-Galant, F.; Montalvo, A.; Atencio, E.; Porras, R.; Lozano-Galant, J.A. An open-source GIS app for digitalising bridge inspections and automating BIM model integration. *Struct. Infrastruct. Eng.* **2025**, 1–12. [CrossRef]
14. Lin, J.R. OpenBridgeGraph: Integrating Open Government Data for Bridge Management. In Proceedings of the International Symposium on Automation and Robotics in Construction (ISARC), Kitakyushu, Japan, 27–28 October 2020; IAARC Publications: Kitakyushu, Japan, 2020; pp. 1255–1262.
15. Gkoumas, K.; Stepniak, M.; Cheimariotis, I.; Marques dos Santos, F. New technologies for bridge inspection and monitoring: A perspective from European Union research and innovation projects. *Struct. Infrastruct. Eng.* **2024**, *20*, 1120–1132. [CrossRef]
16. Mandirola, M.; Casarotti, C.; Peloso, S.; Lanese, I.; Brunesi, E.; Senaldi, I. Use of UAS for damage inspection and assessment of bridge infrastructures. *Int. J. Disaster Risk Reduct.* **2022**, *72*, 102824. [CrossRef]
17. Belloni, V.; Sjölander, A.; Ravanelli, R.; Crespi, M.; Nascetti, A. Crack Monitoring from Motion (CMfM): Crack detection and measurement using cameras with non-fixed positions. *Autom. Constr.* **2023**, *156*, 105072. [CrossRef]
18. Casas, J.R.; Chacón, R.; Catbas, N.; Riveiro, B.; Tonelli, D. Remote sensing in bridge digitalization: A review. *Remote Sens.* **2024**, *16*, 4438. [CrossRef]
19. Panigati, T.; Zini, M.; Striccoli, D.; Giordano, P.F.; Tonelli, D.; Limongelli, M.P.; Zonta, D. Drone-based bridge inspections: Current practices and future directions. *Autom. Constr.* **2025**, *173*, 106101. [CrossRef]
20. Pozzer, S.; Ramos, G.; Nooralishahi, P.; Azar, E.R.; El Refai, A.; López, F.; Ibarra-Castanedo, C.; Maldague, X. Integration of thermographic inspection data with BIM for enhanced concrete infrastructure assessment. *Autom. Constr.* **2025**, *171*, 105965. [CrossRef]
21. Mohammadi, M.; Rashidi, M.; Mousavi, V.; Yu, Y.; Samali, B. Application of TLS Method in Digitization of Bridge Infrastructures: A Path to BrIM Development. *Remote Sens.* **2022**, *14*, 1148. [CrossRef]
22. Zhou, Y.; Zhu, J.; Zhao, L.; Hu, G.; Xin, J.; Zhang, H.; Yang, J. High-Precision Monitoring Method for Bridge Deformation Measurement and Error Analysis Based on Terrestrial Laser Scanning. *Remote Sens.* **2024**, *16*, 2263. [CrossRef]
23. Urban, R.; Štroner, M.; Braun, J.; Suk, T.; Kovanič, L'.; Blistan, P. Determination of accuracy and usability of a SLAM scanner GeoSLAM Zeb Horizon: A bridge structure case study. *Appl. Sci.* **2024**, *14*, 5258. [CrossRef]
24. Feng, C.Q.; Li, B.L.; Liu, Y.F.; Zhang, F.; Yue, Y.; Fan, J.S. Crack assessment using multi-sensor fusion simultaneous localization and mapping (SLAM) and image super-resolution for bridge inspection. *Autom. Constr.* **2023**, *155*, 105047. [CrossRef]
25. Pascucci, N.; Dominici, D.; Habib, A. LiDAR-Based Road Cracking Detection: Machine Learning Comparison, Intensity Normalization, and Open-Source WebGIS for Infrastructure Maintenance. *Remote Sens.* **2025**, *17*, 1543. [CrossRef]
26. Gaspari, F.; Ioli, F.; Barbieri, F.; Belcore, E.; Pinto, L. Integration of UAV-LiDAR and UAV-photogrammetry for infrastructure monitoring and bridge assessment. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2022**, *43*, 995–1002. [CrossRef]
27. Bianchi, S.; Capacci, L.; Anghileri, M.; Biondini, F.; Rosati, G.; Cazzulani, G.; Barindelli, S.; Caldera, S. Structural Health Monitoring of Bridges Based on GNSS. In *Life-Cycle of Structures and Infrastructure Systems*; CRC Press: Boca Raton, FL, USA, 2023; pp. 2001–2008.
28. Cinque, D.; Saccone, M.; Capua, R.; Spina, D.; Falcolini, C.; Gabriele, S. Experimental validation of a high precision GNSS system for monitoring of civil infrastructures. *Sustainability* **2022**, *14*, 10984. [CrossRef]
29. Lasri, O.; Giordano, P.F.; Previtali, M.; Limongelli, M.P. Remote monitoring of a concrete bridge through InSAR and GNSS measurements. In *Life-Cycle of Structures and Infrastructure Systems*; CRC Press: Boca Raton, FL, USA, 2023; pp. 2009–2016.
30. Tonelli, D.; Caspani, V.F.; Valentini, A.; Rocca, A.; Torboli, R.; Vitti, A.; Perissin, D.; Zonta, D. Interpretation of bridge health monitoring data from satellite InSAR technology. *Remote Sens.* **2023**, *15*, 5242. [CrossRef]
31. Khedmatgozar Dolati, S.S.; Caluk, N.; Mehrabi, A.; Khedmatgozar Dolati, S.S. Non-destructive testing applications for steel bridges. *Appl. Sci.* **2021**, *11*, 9757. [CrossRef]

32. Quaglini, V.; Pettorruso, C.; Cattaneo, S.; Rossi, D. Assessment of bridge Post-Tensioning systems using non-destructive (ND) inspection methods. *ce/papers* **2023**, *6*, 9–17. [CrossRef]
33. Armijo, A.; Zamora-Sánchez, D. Integration of Railway Bridge Structural Health Monitoring into the Internet of Things with a Digital Twin: A Case Study. *Sensors* **2024**, *24*, 2115. [CrossRef] [PubMed]
34. Cheng, L.; Cigada, A.; Zappa, E.; Gilbert, M.; Lang, Z.Q. Dynamic monitoring of a masonry arch rail bridge using a distributed fiber optic sensing system. *J. Civ. Struct. Health Monit.* **2024**, *14*, 1075–1090. [CrossRef]
35. Romanello, R.; Miraglia, E.; Miceli, G.; Gazzo, S.; Contrafatto, L.; Cuomo, M.; Scalisi, S. New advanced monitoring systems of Bridges with Actionable Real Time Sensor Data. *Procedia Struct. Integr.* **2024**, *62*, 856–863. [CrossRef]
36. Willkens, D.S.; Liu, J.; Alathamneh, S. A case study of integrating terrestrial laser scanning (TLS) and building information modeling (BIM) in heritage bridge documentation: The Edmund Pettus Bridge. *Buildings* **2024**, *14*, 1940. [CrossRef]
37. Di Pietro, A.; Buffarini, G.; Clemente, P.; Fresilli, B.; Giocoli, A.; Giorgi, A.; Lipari, A.; Morriello, I.; Ormando, C.; Paolini, S.; et al. UAS-based methodology to create digital models of bridges and viaducts. *Procedia Struct. Integr.* **2024**, *62*, 755–762. [CrossRef]
38. Castellani, M.; Meoni, A.; García-Macías, E.; Antonini, F.; Ubertini, F. UAV photogrammetry and laser scanning of bridges: A new methodology and its application to a case study. *Procedia Struct. Integr.* **2024**, *62*, 193–200. [CrossRef]
39. Vacca, G. Overview of open source software for close range photogrammetry. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2019**, *42*, 239–245. [CrossRef]
40. Cutugno, M.; Robustelli, U.; Pugliano, G. Structure-from-motion 3d reconstruction of the historical overpass ponte della cerra: A comparison between MicMac open source software and Metashape. *Drones* **2022**, *6*, 242. [CrossRef]
41. Xia, T.; Yang, J.; Chen, L. Automated semantic segmentation of bridge point cloud based on local descriptor and machine learning. *Autom. Constr.* **2022**, *133*, 103992.
42. Saovana, N.; Yabuki, N.; Fukuda, T. Automated point cloud classification using an image-based instance segmentation for structure from motion. *Autom. Constr.* **2021**, *129*, 103804. [CrossRef]
43. Hajdin, R.; Richter, R.; Rakic, L.; Diederich, H.; Hildebrand, J.; Schulz, S.; Dollner, J.; Bednorz, J. Digitalization of bridge inventory via automated analysis of point clouds for generation of BIM models. *ce/papers* **2023**, *6*, 1189–1197. [CrossRef]
44. Mugnai, F.; Bonora, V.; Tucci, G. Integration, harmonization, and processing of geomatic data for bridge health assessment: The Lastra a Signa case study. *Appl. Geomat.* **2023**, *15*, 533–550. [CrossRef]
45. Rodriguez Polania, D.; Tondolo, F.; Osello, A.; Piras, M.; Di Pietra, V.; Grasso, N. Bridges monitoring and assessment using an integrated BIM methodology. *Innov. Infrastruct. Solut.* **2025**, *10*, 59. [CrossRef]
46. Musicco, A.; Buldo, M.; Rossi, N.; Tavolare, R.; Verdoscia, C. Enhancing 3D Modeling Efficiency via Semi-Automatic Point Cloud Segmentation and Multi-Lod Mesh Reconstruction. *SCIRES-IT-Sci. Res. Inf. Technol.* **2024**, *14*, 233–250. [CrossRef]
47. Antova, G.; Tanev, V. Creation of 3D geometry in scan-to-CAD/BIM environment. In Proceedings of the IOP Conference Series: Earth and Environmental Science, Prague, Czech Republic, 7–11 September 2020; IOP Publishing: Bristol, UK, 2020; Volume 609.
48. Mallis, D.; Ali, S.A.; Dupont, E.; Cherenkova, K.; Karadeniz, A.S.; Khan, M.S.; Kacem, A.; Gusev, G.; Aouada, D. SHARP Challenge 2023: Solving CAD History and pArameters Recovery from Point clouds and 3D scans. Overview, Datasets, Metrics, and Baselines. In Proceedings of the 2023 IEEE/CVF International Conference on Computer Vision Workshops (ICCVW), Paris, France, 2–6 October 2023; IEEE: Piscataway, NJ, USA, 2023; pp. 1778–1787.
49. Aricò, M.; Ferro, C.; La Guardia, M.; Lo Brutto, M.; Taranto, G.; Ventimiglia, G.M. Scan-to-BIM Process and Architectural Conservation: Towards an Effective Tool for the Thematic Mapping of Decay and Alteration Phenomena. *Heritage* **2024**, *7*, 6257–6281. [CrossRef]
50. Liu, J.; Li, B. Terrestrial laser scanning (TLS) survey and building information modeling (BIM) of the Edmund Pettus Bridge: A case study. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2024**, *48*, 379–386. [CrossRef]
51. Justo, A.; Soilán, M.; Sánchez-Rodríguez, A.; Riveiro, B. Scan-to-BIM for the infrastructure domain: Generation of IFC-compliant models of road infrastructure assets and semantics using 3D point cloud data. *Autom. Constr.* **2021**, *127*, 103703. [CrossRef]
52. Sánchez-Rodríguez, A.; Esser, S.; Abualdenien, J.; Borrmann, A.; Riveiro, B. From Point Cloud to IFC: A Masonry Arch Bridge Case Study. In Proceedings of the EG-ICE 2020 Workshop on Intelligent Computing in Engineering, Berlin, Germany, 30 June–3 July 2020; pp. 422–431.
53. Scianna, A.; Gaglio, G.F.; La Guardia, M. Structure monitoring with BIM and IoT: The case study of a bridge beam model. *ISPRS Int. J. Geo-Inf.* **2022**, *11*, 173. [CrossRef]
54. Chacón, R.; Posada, H.; Ramonell, C.; Jungmann, M.; Hartmann, T.; Khan, R.; Tomar, R. Digital twinning of building construction processes. Case study: A reinforced concrete cast-in structure. *J. Build. Eng.* **2024**, *84*, 108522. [CrossRef]
55. Fascia, R.; Barbieri, F.; Gaspari, F.; Ioli, F.; Pinto, L. PONTI: An Open WebGL-Based Tool in Support to Defect Analysis and 3D Visualisation of Bridges. In *Bridge Maintenance, Safety, Management, Digitalization and Sustainability*; CRC Press: Boca Raton, FL, USA, 2024; pp. 2353–2361.

56. Solla, M.; Gonçalves, L.M.; Gonçalves, G.; Francisco, C.; Puente, I.; Providência, P.; Gaspar, F.; Rodrigues, H. A building information modeling approach to integrate geomatic data for the documentation and preservation of cultural heritage. *Remote Sens.* **2020**, *12*, 4028. [CrossRef]
57. Salzano, A.; Parisi, C.M.; Acampa, G.; Nicolella, M. Existing assets maintenance management: Optimizing maintenance procedures and costs through BIM tools. *Autom. Constr.* **2023**, *149*, 104788. [CrossRef]
58. Chelaru, B.; Onuțu, C.; Ungureanu, G.; Șerbănoiu, A.A. Integration of point cloud, historical records, and condition assessment data in HBIM. *Autom. Constr.* **2024**, *161*, 105347. [CrossRef]
59. Santos, C.; Luleci, F.; Amado, J.; Matos, J.C.; Catbas, F.N. Automating inspection data from bridge management system into bridge information model. *Autom. Constr.* **2025**, *174*, 106128.
60. Moyano, J.; Carreño, E.; Nieto-Julián, J.E.; Gil-Arizón, I.; Bruno, S. Systematic approach to generate Historical Building Information Modelling (HBIM) in architectural restoration project. *Autom. Constr.* **2022**, *143*, 104551. [CrossRef]
61. Vinueza-Martinez, J.; Correa-Peralta, M.; Ramirez-Anormaliza, R.; Franco Arias, O.; Vera Paredes, D. Geographic information systems (giss) based on webgis architecture: Bibliometric analysis of the current status and research trends. *Sustainability* **2024**, *16*, 6439. [CrossRef]
62. Giuffrida, N.; Viscio, S.; Binetti, M. State of the art on mapping tools in the context of CCAM and Smart Infrastructure. *Transp. Res. Procedia* **2025**, *90*, 943–950. [CrossRef]
63. Zhu, J.; Tan, Y.; Wang, X.; Wu, P. BIM/GIS integration for web GIS-based bridge management. *Ann. GIS* **2021**, *27*, 99–109. [CrossRef]
64. Xu, Y.; Huang, W.; Xiao, J.; Shan, J.; Liu, M.; Guo, W.; Zhu, Y.; Zhang, J.; Yan, Y. A WebGIS-based digital twin platform for intelligent operation and maintenance of rail transit infrastructure. *Expert Syst. Appl.* **2026**, *296*, 129180. [CrossRef]
65. Rahman, M.A.; Maulud, K.A.; Bahri, M.S.; Hussain, M.S.; Oon, A.R.; Suhatdi, S.; Che Hashim, C.H.; Mohd, F.A. Development of GIS database for infrastructure management: Power distribution network system. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *540*, 012067. [CrossRef]
66. La Guardia, M.; D'Ippolito, F.; Cellura, M. Construction of a webgis tool based on a gis semiautomated processing for the localization of p2g plants in sicily (Italy). *ISPRS Int. J. Geo-Inf.* **2021**, *10*, 671. [CrossRef]
67. Amović, M.; Arnaut, V.; Koprena, D. Implementation of a 2D/3D WebGIS for Electricity Network Management System. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2025**, *48*, 25–31. [CrossRef]
68. Ciccone, A.; Stasio, S.D.; Asprone, D.; Salzano, A.; Nicolella, M. Application of openBIM for the management of existing railway infrastructure: Case study of the Cancello–Benevento railway line. *Sustainability* **2022**, *14*, 2283. [CrossRef]
69. Spallarossa, E.; Bonicelli, A. Digital Twin, BIM and Asset Management Systems Implementation. In *Bridge Maintenance, Safety, Management, Digitalization and Sustainability*; CRC Press: Boca Raton, FL, USA, 2024; pp. 1845–1852.
70. Buggiani, D.; Malavisi, M.; Baldacci, A. Digital Technologies for Bridge Damage Detection: Drones and AI for Remote Inspections. In *Bridge Maintenance, Safety, Management, Digitalization and Sustainability*; CRC Press: Boca Raton, FL, USA, 2024; pp. 3161–3168.
71. Aglietti, A.; Biagini, C.; Bongini, A.; Ottobri, P. Historic bridges monitoring through sensor data management with BIM methodologies. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2023**, *48*, 33–41. [CrossRef]
72. Fawad, M.; Salamak, M.; Chen, Q.; Uscilowski, M.; Koris, K.; Jasinski, M.; Lazinski, P.; Piotrowski, D. Development of immersive bridge digital twin platform to facilitate bridge damage assessment and asset model updates. *Comput. Ind.* **2025**, *164*, 104189. [CrossRef]
73. Martins, A.C.P.; Castellano, I.R.; Júnior, K.M.L.C.; de Carvalho, J.M.F.; Bellon, F.G.; de Oliveira, D.S.; Ribeiro, J.C.L. BIM-based mixed reality application for bridge inspection. *Autom. Constr.* **2024**, *168*, 105775.
74. Javadnejad, F.; Gillins, D.T.; Higgins, C.C.; Gillins, M.N. BridgeDex: Proposed web GIS platform for managing and interrogating multiyear and multiscale bridge-inspection images. *J. Comput. Civ. Eng.* **2017**, *31*, 04017061. [CrossRef]
75. Jayasinghe, S.; Sun, Z.; Sidiq, A.; Mahmoodian, M.; Shahrivar, F.; Setunge, S. Smart Structural Monitoring: Real-Time Bridge Response Using Digital Twins and Inverse Analysis. *Sensors* **2025**, *25*, 3513. [CrossRef]
76. Capolupo, A.; Monterisi, C.; Tarantino, E. Development of an Open-Source 3D WebGIS Framework to Promote Cultural Heritage Dissemination. In Proceedings of the International Conference on Extended Reality, Lecce, Italy, 6–8 July 2022; Springer Nature: Cham, Switzerland, 2022; pp. 254–268.
77. Nishanbaev, I.; Champion, E.; McMeekin, D.A. A web GIS-based integration of 3D digital models with linked open data for cultural heritage exploration. *ISPRS Int. J. Geo-Inf.* **2021**, *10*, 684. [CrossRef]
78. Kipkemboi, W.; Kuria, B.T.; Kuria, D.N.; Sichangi, A.W.; Mundia, C.N.; Wanjala, J.A.; Muthee, S.W.; Goebel, M.; Rienow, A. Development of a web-GIS platform for environmental monitoring and conservation of the Muringato catchment in Kenya. *J. Geovisualization Spat. Anal.* **2023**, *7*, 13. [CrossRef]

79. Aschieri, D.L.D.; Sobrino, N.; Macii, E. Web-GIS Application for Hydrogeological Risk Prevention: The Case Study of Cervo Valley. *Sustainability* **2024**, *16*, 9833. [CrossRef]
80. Spettu, F.; Achille, C.; Fassi, F. State-of-the-Art Web Platforms for the Management and Sharing of Data: Applications, Uses, and Potentialities. *Heritage* **2024**, *7*, 6008–6035. [CrossRef]
81. Mountasser, T.; Abdellatif, M. Digital transformation in public administration: A systematic literature review. *Int. J. Prof. Bus. Rev.* **2023**, *8*, 1. [CrossRef]
82. European Commission—EC. Open Source Software Strategy 2020–2023. Available online: https://ec.europa.eu/info/departments/informatics/open-source-software-strategy_en (accessed on 19 May 2025).
83. Agenzia per l'Italia Digitale—AGID. Linee Guida Acquisizione e Riuso Software PA. 2019. Available online: https://www.agid.gov.it/it/design-servizi/riuso-open-source/linee-guida-acquisizione-riuso-software-pa (accessed on 19 May 2025).
84. Tosi, D.; Lavazza, L.; Morasca, S.; Chiappa, M. Surveying the adoption of FLOSS by public administration local organizations. In Proceedings of the Open Source Systems: Adoption and Impact: 11th IFIP WG 2.13 International Conference, OSS 2015, Florence, Italy, 16–17 May 2015; Springer International Publishing: Cham, Switzerland; pp. 114–123.
85. Petrov, D.; Obwegeser, N. Adoption Barriers of Open-Source Software: A systematic review. *Soc. Sci. Res. Netw.* **2018**, 1–22. [CrossRef]
86. Majerova, I.; Dolak, R.; Murys, M. Smart Solution for a Smart City: Using Open Source Maps in Municipal Waste Management. In Proceedings of the International Conference on Computational Science and Its Applications, Malaga, Spain, 4–7 July 2022; Springer International Publishing: Cham, Switzerland; pp. 125–140.
87. Ministry of Infrastructure and Transport—MIT. Linee Guida per la Classificazione e Gestione del Rischio, la Valutazione Della Sicurezza ed il Monitoraggio dei Ponti Esistenti. 2020. Available online: https://www.mit.gov.it/sites/default/files/media/notizia/2020-05/1_Testo_Linee_Guida_ponti.pdf (accessed on 19 May 2025).
88. Agenzia Nazionale per la Sicurezza delle Ferrovie e delle Infrastrutture Stradali e Autostradali—ANSFISA. Istruzioni Operative per l'Applicazione delle Linee Guida per la Classificazione e Gestione del Rischio, la Valutazione della Sicurezza ed il Monitoraggio dei Ponti Esistenti. 2022. Available online: https://www.ansfisa.gov.it/documents/20142/1205643/IstrOp_ANSFISA_LLGGPonti.pdf/140d8306-3dd8-2269-dee8-2cb42901a2c3 (accessed on 19 May 2025).
89. Gaspari, F.; Barbieri, F.; Duque, J.P.; Fascia, R.; Ioli, F.; Zani, G.; Carrion, D.; Pinto, L. A geo-database for 3D-aided multi-epoch documentation of bridge inspections. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2023**, *48*, 299–306. [CrossRef]
90. Hakimi, O.; Liu, H.; Abudayyeh, O.; Houshyar, A.; Almatared, M.; Alhawiti, A. Data fusion for smart civil infrastructure management: A conceptual digital twin framework. *Buildings* **2023**, *13*, 2725. [CrossRef]
91. Hognogi, G.G.; Pop, A.M.; Marian-Potra, A.C.; Someșfălean, T. The role of UAS–GIS in digital Era governance. A systematic literature review. *Sustainability* **2021**, *13*, 11097.
92. Zejdlik, J.; Vozenilek, V. Exploring Cartographic Differences in Web Map Applications: Evaluating Design, Scale, and Usability. *ISPRS Int. J. Geo-Inf.* **2024**, *14*, 9. [CrossRef]
93. Rowland, A.; Folmer, E.; Beek, W. Towards Self-Service GIS—Combining the Best of the Semantic Web and Web GIS. *ISPRS Int. J. Geo-Inf.* **2020**, *9*, 753. [CrossRef]
94. Hu, T.; Liu, T.; Jarugumalli, V.S.D.; Cheng, S.; Deng, C. FAIR principles in workflows: A GIScience workflow management system for reproducible and replicable studies. *Int. J. Appl. Earth Obs. Geoinf.* **2025**, *138*, 104477. [CrossRef]
95. Obe, R.; Hsu, L.S. *PostGIS in Action*; Simon and Schuster: New York, NY, USA, 2021.
96. Apache Friends, XAMPP Apache + MariaDB + PHP + Perl. Available online: https://www.apachefriends.org/ (accessed on 8 July 2025).
97. Crickard, P., III. *Leaflet.js Essentials*; Packt Publishing Ltd.: Birmingham, UK, 2014.
98. Schuetz, M. Potree: Rendering Large Point Clouds in Web Browsers. Bachelor's Thesis, Vienna University of Technology, Vienna, Austria, 2016.
99. Gede, M. Using cesium for 3D thematic visualisations on the web. In Proceedings of the International Cartographic Association (ICA), Washington, DC, USA, 2–7 July 2017; Copernicus GmbH: Katlenburg-Lindau, Germany, 2018; Volume 1, pp. 1–4.
100. Ma, Z.; Wan, F.; Zhang, Q.; Deng, C. Research on distributed collaboration framework for BIM big data model. In Proceedings of the International Conference on Cloud Computing, Performance Computing and Deep Learning (CCPCDL 2022), Wuhan, China, 11–13 March 2022; SPIE: Bellingham, WA, USA, 2022; Volume 12287, pp. 403–411.
101. Balla, D.; Gede, M. Vector Data Rendering Performance Analysis of Open-Source Web Mapping Libraries. *ISPRS Int. J. Geo-Inf.* **2025**, *14*, 336. [CrossRef]
102. Iacovino, C.; Turksezer, Z.I.; Giordano, P.F.; Limongelli, M.P. A survey of bridge condition rating systems. In Proceedings of the International Conference of the European Association on Quality Control of Bridges and Structures, Padova, Italy, 29 August–1 September 2021; Springer International Publishing: Cham, Switzerland, 2011; pp. 14–22.

103. Santarsiero, G. Automated Assessment of Bridge Guardrails for Regional Prioritization based on Open-Source Data and Deep Learning Algorithms. *Results Eng.* **2025**, *26*, 105210. [CrossRef]
104. Gaspari, F.; Barbieri, F.; Demnati, I.; Ioli, F.; Pinto, L.; Toscani, V. Mobile mapping solutions for the update and management of traffic signs in a road cadastre free open-source GIS architecture. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2023**, *48*, 61–66. [CrossRef]