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Cross-National Bridge Management Systems: A Geomatics Framework for Italian and Swiss Authorities

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Abstract

Effective bridge management requires structured methods that integrate information gained through visual inspections, non-destructive tests or monitoring systems to prioritize maintenance activities on bridges at a territorial level. The Italian and Swiss authorities offer different perspectives on maintenance prioritization, with Italy emphasizing multi-level classification and flexible data integration for risk assessment, and Switzerland relying on condition assessment and a centralized BMS including damage predictive capabilities to determine maintenance policy, while minimizing the long-term costs. Both approaches highlight the need for interoperable digital solutions to collect, analyse and process large amount of heterogeneous data. In addition, recent federal regulations enforce the "open by default" principle, promoting transparency, participation, and innovation using open-source software to fulfil Public Authority tasks. Moving from these considerations, the study proposes a modular framework for bridge management that includes inventory and data management, inspection workflows, risk analysis, predictive monitoring, GIS/BIM integration, intervention planning, and regulatory compliance. By leveraging open source and widely used tools, the framework improves data accessibility, interoperability, and decision-making efficiency. A comparative analysis with existing proprietary solutions highlights large possibilities of improvement in terms of adaptability and integration, underscoring the need for a flexible, standardized digital approach to bridge infrastructure management.

Keywords

Bridge Management System, geospatial data integration, bridge inspection, asset management, FOSS4G

1 Introduction

Over the past decade, several bridge failures have highlighted the vulnerability of critical infrastructures and the need to define an efficient and scalable strategy for their management [1]. As many bridges approach the end of their design life, coupled with the increasing impact of climate change on surrounding environments and materials, researchers have intensified efforts to assess risks and assist road asset managers in defining guidelines and best practices for maintenance by integrating the concept of risk and change management in asset management [2-3]. However, the lack of shared condition assessment procedures and performance goals has caused large variation in the quality of roadway bridges, jeopardizing the resilience of infrastructure at a large scale. In fact, inspection practices and rating systems vary from country to country, according to different national guidelines. European initiatives such as BridgeSpec [4] have extensively analysed regulatory frameworks and state of practice evidence [5-7] to propose a standardized procedure for the assessment of performance indicators and a set of performance goals with the aim to achieve the European economic and societal needs. Nevertheless, a comparison of bridge management approaches between Switzerland and Italy, needs to be updated considering new regulations recently entered in force in both countries. Moreover, Swiss and Italian Public Authorities face the climate-related challenges on infrastructures, like severe material degradation and exceptional actions, and tackle the opportunities offered by innovative technologies and processes in quite different ways. On one side of the border, few years ago, Italy proposed a risk assessment method to manage maintenance prioritization, on the other side, Switzerland authorities have been kept adopting a proprietary BMS solution that includes condition forecasting of documented defects, based on data collected during inspections. However, things have recently changed. In fact, the Federal Act on the Use of Electronic Means for the Fulfilment of Public Authorities Tasks, entered in force in January 2024,

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has laid down the legal basis for massive open-source software adoption in current federal duties, introducing a significant paradigm shift towards more openness, transparency and practical reuse of software and data [8]. For the federal administration and the economy, this results in numerous opportunities, but also some challenges. In Italy, the use of interoperable solutions is stressed too, but up to now is not an explicit requirement to be adopted. In either case, timely inspection and monitoring measures are essential to ensure the durability and serviceability of structures in a cost-effective manner. These approaches require comprehensive knowledge of the structure geometry, design history and past maintenance [9]. Collecting accurate and up-to-date data, using both traditional and innovative techniques during periodic inspections, widens the structure knowledge and helps in prioritising interventions [10-11]. However, the amount of data collected through such routine operations also requires an efficient framework for its management and analysis. For this reason, since the late 90s, road agencies around the world started developing their own Bridge Management System (BMS), with the first implementation cases in the United States [12] and in Denmark [13].Most existing national BMSs focus on archiving and updating asset data, but rely primarily on 2D information, which can limit visualisation and defect localisation [14-15]. Over the last decade, a series of technical research projects has recognized the need to develop flexible and interoperable inspection and condition assessment data management systems for highway bridges, besides BMSs [16].

Advancements in geomatics led to wide adoption of drones, photogrammetry [17] and Light Detection and Ranging (LiDAR) [18] combined with traditional Terrestrial Laser Scanning (TLS) [19] for 3D bridge reconstruction and assessment. These methods generate detailed geometrical 2D and 3D products, including point clouds, meshes and oriented images, often integrated with Building Information Modelling (BIM) [20]. Moreover, image-based defect identification [21] and semantic segmentation [22], made possible by these products, enrich condition assessment capabilities. Their proper integration into traditional bridge management procedures could support the documentation, transparency and reproducibility of inspection and maintenance operations [23-24], besides providing a priori knowledge for focused forecasting and prediction models for a cost-effective maintenance and intervention prioritisation [25-26]. That said, the research aims to increase the awareness of bridge owners, managers, and practitioners on the possibility and advantages of integrating into traditional BMS georeferenced data on the geometry, structural behaviour, state of conservation, and previous maintenance interventions. The proposed framework leverages widely adopted digital solutions to enhance data exchange and facilitates multi-source data integration that is essential in the safety assessment of existing bridges, a complex, time-consuming and cumbersome multi-parties process. In addition, in line with the underlying principle of BridgeSpec, the research highlights the importance of building a common knowledge-framework on easy-available tools of which cross-border authorities, often responsible for shared assets, can profit of to overcome traditional barriers in data exchange and asset management and, in the end, to ensure a comparable level of quality of roadway bridges. To achieve this goal, understanding shared points and potential common practices compliant to national regulations in force for bridge management is pivotal. This study adopts a comprehensive analytical approach to comparing the regulatory frameworks steering bridge management in Italy and Switzerland. The research objectives are manifold:

- Identifying which type of geomatics data could cope with specific inspection needs, focusing on the type of data collected, the technologies employed and related challenges.
- Assessing the functionality, interoperability, and adaptability to different regulatory contexts of proprietary software currently available on the market. Particular attention is given to the limitations of these solutions, especially regarding data accessibility, standardisation, and integration with other digital tools such as GIS and BIM.
- Identifying good practices for the implementation of a modular software framework to define an open and adaptable approach , ensuring greater interoperability, scalability, and long-term sustainability in bridge management, even across borders.

To ensure this, first, a detailed examination of national guidelines, focusing on inspection procedures, classification systems, and data management strategies has been carried out. Then, a critical appraisal of geomatics solutions for supporting bridge management has been developed. Finally, research efforts concentrate on the development of a modular framework based on open-source solutions for collecting, managing, and updating information to support decision-making strategies across different levels of infrastructure monitoring and maintenance.

2 Regulations and Guidelines for risk and condition assessment of bridges

2.1 Italian experience

The collapse of the motorway viaduct in the Polcevera Valley (Genoa) in 2018 pinpointed the need for a standardised condition assessment procedure for the entire Italian road infrastructure [27]. Consequently, on July, 1st 2022, the Italian Ministry of Infrastructure issued in the Official Journal (G.U.) the new ministerial decree DM 204 that forces highway concessionaries, regions, provinces, metropolitan cities and municipalities to adopt the Guidelines on Risk Classification and Management, Safety Assessment and Monitoring of Existing Bridges [28] to detect risks, keep them under control and intervene only where really necessary. These guidelines require road management agencies to examine the current condition of structures and the risks they are exposed to by adopting a multi-level strategy for the prioritisation of interventions through a set of coordinated inspections and monitoring procedures [29]. Hence, their application strongly influences the maintenance and rehabilitation operations of management bodies at different scales, as the Italian road networks are managed by national companies (ANAS, AISCAT) as well as local public administrations [30].

In particular, the process proposed by the guideline consists of 6 levels of assessment of increasing complexity. Through a rating system based on detected defects and risks, an *attention class* from low to high-level is assigned to the structure. Based on it, the guideline suggests further interventions and tests according to the increasing level of risk [31]. The first Level 0 aims at establishing a national census of existing structures by collecting information on design plans, construction time and location. Currently, these data are partially stored in the National Computer Archive of Public Works (AINOP), a digital archive of public structures created after the Polcevera viaduct collapse [32]. Despite not requiring specific data or complex products to be processed, Level 0 already represents a challenge for administrations as most of the requested information on their assets is incomplete or missing [33].

Level 1 then requires reporting of defects and damages found on various structural elements during periodic visual inspection carried out every 6 to 24 months. The condition state of a bridge results from a weighted average of a set of coded defect types, varying according to material, severity level (1 to 5 scale), intensity and extent, . According to the information retrieved on this level and to specific parameters for hazard, vulnerability and exposure, at Level 2 a so-called *attention class* is assigned to each bridge with a conservative approach [34]. This level represents the core of the entire process as it influences subsequent steps. In detail, structures falling within medium and medium-high attention class are subjected to specific Level 3 inspection procedures for a preliminary safety assessment, comprising non-destructive testing. Severely damaged or structures exposed to risks (high *attention class*) are instead subjected to Level 4 detailed procedures including load tests and continuous monitoring [35]. Level 5, currently not detailed in the guideline, consists of a network scale analysis.

Despite the guidelines do not recommend the use of any specific commercial software, they suggest the adoption of solutions that allow interoperability between software used for specific functions and analysis at different scales, promoting in particular the integration of BIM models with GIS interfaces, as well as user-friendly dashboards and efficient connection with the AINOP database.

2.2 Swiss state of practice

The safety and reliability of the Swiss road network are under the responsibility of several authorities at local, cantonal, and federal level [36]. The Federal Roads Office provide indications on how to execute assessment programs on aterritorial and operational basis [37], distinguishing between primary, intermediate and specific inspections. The aim is identifying damages at an early stage and expected deterioration processes, including their severity, to select suggested interventions and estimate associated costs [38]. At a cantonal level, the case of Canton Ticino can be selected as a reference scenario. The Office of Bridge Management is responsible for primary inspections which are carried out every 5 years. Specialised engineers assess the condition of bridge elements and rate them on a scale from 1 (good) to 5 (alarming) through visual inspections. The overall rating of the bridge is derived from that of the single elements rating, and it is accompanied by suggestions for interventions, and cost estimation [39]. Indeed, time priority is based on budgetary constraints on a 4-year timeframe. Intermediate inspections, are carried out in case of need, including laboratory tests. Lastly, specific inspections are executed in the occurrence of natural events or car accidents in the proximity of the structure. Moreover, yearly routine operational maintenance activities involving team of operators from the cantonal maintenance centres are carried out to ascertain the functionality of bridge ancillary elements like guardrails and pavement.

All the data collected during visual surveys are stored in KUBA-DB, the database associated with KUBA, a modular BMS developed for the Swiss Federal Roads Authority since 2003 and adopted by 20 cantons [40]. The tool allows to manage the structural inventory, to plan interventions, to generate condition assessment report and evaluate the impact of heavyweight on the whole road network [41]. In particular, the BMS include a processing module KUBA-MS dedicated to the condition forecasting of the future progression of defects documented during an inspection [42].

In this the Swiss framework differs from the Italian one, as no space to the concept of risk is introduced into the strategy for maintenance prioritization. Recent research efforts pinpointed the opportunity to resort to risk-based methodology to include element failure consequences in bridge condition assessment to evaluate the impact of damage on safety leading to more objective decisions [38]. Nevertheless, no reference is made to other possible sources of risks, like floodings and debris.

3 Common data and technology needs

Both the Italian and Swiss guidelines aim to establish systematic frameworks for bridge risk and condition assessment for prioritising maintenance interventions based on the outcomes of periodic inspections and eventually in-depth testing, continuous monitoring and safety assessment. However, key differences emerge in these methodologies, classification systems, and digital management tools (Figure 1).

	Italy	Switzerland
Regulation	*Linee guida per la classificazione e gestione del rischio, la valutazione della sicurezza ed il monitoraggio dei ponti esistenti* (MIT, 2022)	Guides on inspection execution (*ASTRA 12002, 2005; ASTRA 62016, 2021; ASTRA 28010, 2016*)
Software	National Computer Archive of Public Works (AINOP), no recommended/approved BMS	KUBA (since 2008)
Survey	Visual inspection with "ground/remote measurements and photographic tools for accurate visual and geometric documentation"	Visual inspection without strict indication on equipment needs
Strategy	Multi-level prioritization on structural elements quantitative params and hydrogeo assessment	Principal periodic inspections with generic element ratings and suggested interventions
Rating	Level 2 formula for "Attention Class" that defines next steps for special inspections/monitoring needs	Average/Worst-conditioned structure rating based on single elements, intervention cost estimation and recommendations

Figure 1. Key aspects in bridge management: overview.

The Italian guidelines follow a structured multiple-level approach, of progressively increasing complexity, starting from a national census of existing structures to in-depth monitoring procedures. In contrast, the Swiss system employs a three-tiered inspection strategy—primary, intermediate, and specific—each addressing different stages of deterioration and event-triggered evaluations. The condition of bridges is assessed through a qualitative rating system (from 1 to 5), influencing intervention prioritisation and cost estimation. Unlike the Italian framework, the Swiss approach incorporates predictive analysis through KUBA, a dedicated BMS that archives inspection data and forecasts damage progression . A fundamental distinction lies in the integration of digital tools: while Italy emphasizes structured reporting and multi-source data fusion within a flexible framework, Switzerland centralises data management within a long-established BMS platform. This contrast reflects varying levels of standardisation in risk assessment approaches, influencing how road agencies interact with inspection data and prioritise infrastructure interventions.

In such a context, the variety of data formats and collection methods used for bridge assessment reflects the balance between the level of detail required and the number of structures involved (Figure 2). Periodic inspections, covering a vast number of bridges, rely on standardised datasets such as GNSS-based localisation, point clouds, and defect imagery to ensure broad yet consistent monitoring. While interoperability with BIM and GIS is encouraged, there is no prescribed software, though integration with the AINOP database is recommended for the Italian assets. Special inspections introduce higher-detail analyses, including material testing, BIM-based parametrization, and finite element modelling (FEM) for structural evaluation. Continuous monitoring, applied to a limited number of critical structures, generates high-resolution time series data from sensors, enabling real-time assessment of structural performance. Given the heterogeneity of data sources, scales, and objectives, a modular digital framework is essential to integrate different collection methods while ensuring interoperability across inspection levels, which could converge into a complete digital twin implementation when real-time interaction between the virtual and real assets is ensured [43].

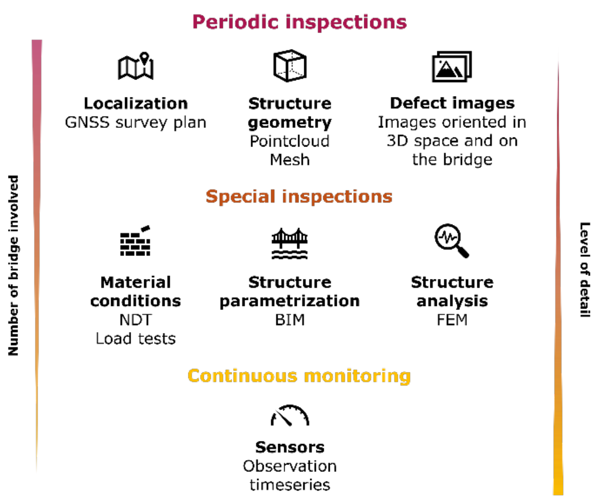

Figure 2. Common data needs for bridge inspections and possible monitoring of bridges in Italy and Switzerland.

The proposed modular structure integrates interconnected customisable components to enable flexible data management, balancing large-scale monitoring with detailed structural analysis while ensuring compliance with national guidelines. A bridge inventory and data management module serve as the foundation, structuring and maintaining information on all monitored assets and defining its sharing strategy. An inspection and condition assessment component, instead, processes and organises data from periodic and special inspections, supporting standardised evaluations as well as defect identification and labelling. A risk analysis and prioritisation module enables decision-makers to classify bridges based on condition and risk factors, guiding maintenance strategies that could be designed compliant with country-specific guidelines. An additional step is represented by the predictive maintenance and monitoring module that, leveraging historical data and sensor networks, enables the possibility to model and simulate structural behaviour and degradation over its life cycle. Meanwhile, GIS & BIM integration in a single platform ensures seamless visualisation and spatial analysis, enhancing multi-source data fusion. Intervention Planning & Cost Estimation aids in resource allocation, balancing technical needs with financial constraints. Finally, Regulatory Compliance & Reporting facilitates alignment with national and international standards, ensuring traceability and structured documentation.

4 Existing management solutions

Several proprietary solutions are available for bridge management, offering functionalities that align with multiple aspects of the modular framework identified earlier. However, their adaptability, interoperability, and accessibility vary, often presenting limitations for integration for country-specific regulations as well as for open-source approaches.

SwissInspect [44] leverages AI and digital twins for infrastructure monitoring, enhancing automation and predictive analytics, but its proprietary nature limits customisation. PROPONTI [45] and Inbee [46] specialise in digital bridge inspections aligned with Italian guidelines, though they may lack flexibility for international adaptation. Trimble Quadri [47] facilitates BIM integration for multidisciplinary design and maintenance but relies on proprietary formats, reducing interoperability. Built on top of a combination of Trimble and OpenBIM authoring solutions, PontiSicuri [48] answers the needs of the Italian context but still lacks functionalities for intervention planning at the road network scale. Bentley AssetWise [49] provides comprehensive asset monitoring with IoT and digital twin integration but may be complex and costly for smaller administrations. dTIMS [50] enables predictive maintenance and lifecycle cost analysis but may not seamlessly integrate with diverse national guidelines. usBIM by ACCA Software [51] with its modular architecture offers a comprehensive combination of BIM and GIS for bridge inspections, aiding visualisation and team collaboration but potentially limiting data portability across external systems.

These solutions address key modules of the proposed framework. Most support structured data management but often rely on closed formats, hindering interoperability. AI-driven tools like SwissInspect enhance monitoring, while predictive platforms like dTIMS aid decision-making, yet many operate within proprietary ecosystems. While solutions such as Bentley AssetWise offer structured asset prioritisation, their cost and complexity may be barriers for public authorities. Overall, while these tools provide valuable functionalities, an open, modular framework incorporating widely adopted open-source components would enhance flexibility, data accessibility, and long-term sustainability.

5 Open-source alternatives

For the management of bridge inventory data, a Common Data Environment (CDE) can be essential to ensure the centralisation and consistency of the data [42]. An open-source CDE can be built using tools like GeoServer [52] for serving geospatial data and PostgreSQL with PostGIS for database management [53]. These tools allow for the seamless storage and management of geospatial data, including bridge-specific information such as location, dimensions, materials, and inspection history. To facilitate field data collection and synchronisation, QField and MerginMaps provide mobile applications that allow for real-time data collection and editing, which can be directly integrated into the central database. QGIS [54] serves as the primary desktop tool for geospatial analysis and visualisation, allowing the display and custom processing of bridge locations, spatial patterns, and infrastructure networks. Moreover, the OGC Observation Measurements and Sample standard (O&M) [55] can be adopted to structure measurement data and observations, ensuring interoperability across systems and platforms.

The assessment of bridge conditions requires robust tools for defect classification and prioritisation according to specific country guidelines. OpenCV, an open-source computer vision library, is invaluable for processing and analysing images or videos taken during inspections, enabling automated defect detection and analysis [56]. Coupled with the Segment Anything Model (SAM) in target training sessions, this can improve the quality and efficiency of condition assessments by automating image processing tasks [57]. For more advanced defect classification, deep learning models like You Only Look Once (YOLO), a real-time object detection system, can be integrated to identify and classify cracks in bridge structures [58]. Scikit-learn, an open-source Python library for machine learning, can be used to develop models for defect classification and to implement country-specific rating formulas for prioritising bridge repairs and maintenance [56]. These tools enable the creation of predictive models based on inspection data, providing insights into the future condition of bridges and helping to allocate maintenance resources effectively.

Predictive maintenance in bridge monitoring relies on continuous data collection, analysis and appropriate modelling. Therefore, the integration of sensors for real-time monitoring is fundamental to this approach. Open-source standards such as OGC O&M enable the consistent representation of sensor data. Additionally, the SensorThings API facilitates the transmission of sensor data from the field to centralised systems, allowing for seamless integration with other data sources [59]. This API allows for the efficient exchange of information across various sensors and monitoring platforms, enabling predictive analytics to foresee maintenance needs and optimise the timing of repairs based on real-time data.

The integration of GIS and BIM technologies is crucial for visualising and managing the lifecycle of bridge assets. In the context of regulatory compliance and reporting, an open-source Viewer and Dashboard solution can be built using web-mapping libraries as OpenLayers or Leaflet for GIS functionalities, and tools such as Deck.GL or KeplerGL if custom advanced styling and animation are needed [60]. For detailed 3D visualisation, Potree [61], Cesium [62] and Babylon.JS [63] respectively offer large point cloud rendering capabilities from inspections, GIS and BIM integration with support to OGC 3D tiles standard [64] and CAD data rendering.

To manage and share data effectively, MapStore and GeoNode are open-source platforms that can be used to create geospatial dashboards and data repositories, enabling collaboration between stakeholders and ensuring that all bridge-related data is stored, analysed, and shared in accordance with regulatory requirements [65]. Additionally, OpenProject facilitates intervention planning by structuring maintenance workflows and task management, while Odoo Maintenance supports asset lifecycle management, scheduling preventive maintenance activities, and tracking costs. These tools enhance the decision-making process by integrating condition assessment insights with structured intervention planning, contributing to a more efficient and sustainable bridge management framework. Figure 3 illustrates the different modules of the proposed framework, showing the suggested tools and their interactions.

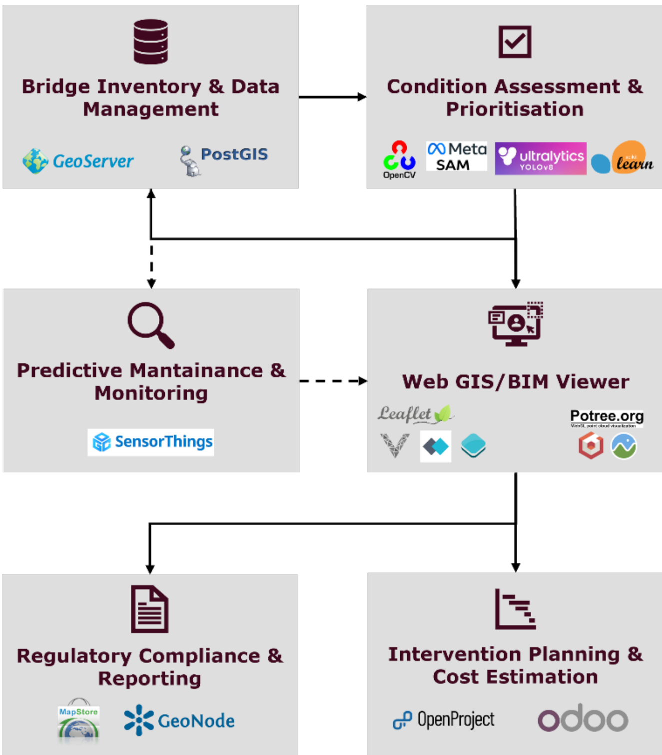

Figure 3. The illustrated modular workflow leverages geospatial databases, AI-driven damage detection, IoT-based monitoring, and Web GIS/BIM visualization to support regulatory compliance and cost estimation through available Free and Open Source Software (FOSS).

6 Conclusions

Current bridge management solutions often rely on user-specific applications, with proprietary software providing structured and scarcely adaptative workflows. This fragmentation hinders interoperability and the seamless exchange of inspection and monitoring data between several stakeholders. This state of practice is expected to be soon overcome in Switzerland thanks to the entrance in force in 2024 of the Federal Act for the Use of Electronic Means for the Fulfilment of Public Authority Tasks [8]. Implementing EMBAG means to adoption the "digital by default" principle and the requirements for OSS and OGD within federal administration offices. This represents a thrust towards openness, transparency, innovation and collaboration across the public sector. Therefore, the proposed framework implementation with a FOSS approach perfectly aligns with this strategy as it offers a flexible and scalable framework that integrates core functionalities essential for bridge assessment and maintenance. By ensuring interoperability with additional extensions, this solution can be adapted to various countries while maintaining a standardised foundation for data management, visualisation, and risk/condition assessment. Such an open and modular structure fosters collaboration, enhances long-term sustainability, and facilitates the adoption of evolving geomatics and digital tools, ultimately improving the efficiency of bridge management worldwide.

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