



GIS-ENABLED DIGITAL INTEGRATION FOR RAILWAY MAINTENANCE

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Abstract

Digital Twins for railway infrastructures depends on both the integration of heterogeneous data sources and the consolidation of their information into interoperable digital models that can be consistently analysed and visualised. Achieving such levels of integration remains, however, a complex task due to inconsistencies in data formats, coordinate systems, and semantic standards. This paper presents a methodology developed within the EU project NRPCEs, implemented through a dedicated interface that automates the ingestion of external datasets into an ArcGIS Pro project environment. The methodology consolidates multi-source information, including inspection datasets and 3D digital models of the asset, and configures layer-level associations that enable element-linked access to inspection records with minimal manual GIS setup. A case study on a segment of the Leixões railway line, in Portugal, demonstrates the methodology through an integrated 3D consultation and pop-up access to inspection information for structural elements. The results highlight the feasibility of using a GIS-based environment as a DT-ready foundation for railway maintenance information integration, supporting traceability, stakeholder consultation, and the future incorporation of outcomes from additional partners.

Keywords: railway infrastructure, digital twins, BIM-GIS integration, interoperability

1 Introduction

Railway infrastructures operate under increasingly demanding requirements for availability, safety, and service continuity, which makes maintenance planning and asset information management a crucial issue. In this context, digital transformation is often seen as a way to better combine condition, geometry, and operational data to support decision-making. Within infrastructure asset management, the combined use of Building Information Modelling (BIM) and Geographic Information Systems (GIS) has been highlighted to upgrade the management, analysis, and visualisation of information, improving insight for asset-related decisions, including risk reduction and value-oriented management [1].

BIM- and GIS-oriented environments contribute different capabilities and operate at different scales. BIM can provide highly detailed geometric and semantic representations, but it does not include the surrounding information. Conversely, GIS supports spatial analysis and contextual interpretation at large-scale but lacks detailed and comprehensive digital repository of infrastructure information [2]. For asset management, this complementarity motivates the development of integration workflows that can keep both contextual geospatial reference and element-level infrastructure information accessible within a single working environment. Despite this potential, the literature continues to report interoperability frictions that limit operational adoption, especially for existing assets, where data are fragmented and extraction and transformation are costly.

In railway asset management contexts, challenges include time-consuming procedures for the extraction of information and the fact that conversion between standards often produces data loss [1]. From an operational perspective, these limitations are critical since the operation and maintenance phase is the longest in the lifecycle, and inspection and monitoring data are often dispersed and poorly integrated, increasing information loss and reducing efficiency [3]. BIM and GIS are described as complementary technologies that, when combined with enabling technologies, support the development of infrastructure Digital Twins (DTs). Proprietary applications tailored to infrastructure needs can improve information access by enabling independent 3D model access and intuitive database analytics [4]. However, many solutions still rely on isolated platforms with limited integration between BIM and GIS [5]. Also, in the domain of interoperability and semantic integration, it is noted that addressing data interoperability may motivate semantic technologies that enable the application of complex queries across multiple data sources [6].

This paper presents an ArcGIS Pro [7] integration framework developed within the NRPCEs-EU project based on Leixões railway line. It focuses on making railway maintenance information usable in a single environment by importing heterogeneous datasets into the ArcGIS Pro geodatabase, integrating a 3D infrastructure model, and automating layer-level associations that link physical elements to inspection records with minimal GIS configuration. The approach is pragmatic, targeting the integration bottleneck and emphasising repeatability and usability for non-specialist users.

2 Methodology

The proposed methodology is implemented as an integration workflow with a dedicated interface that automates data ingestion and dataset-to-asset association within ArcGIS Pro. Figure 1 summarises the distribution of tasks between the interface layer and the ArcGIS environment. The interface layer manages project selection and runs automated import, conversion, and association routines, while reporting execution status and traceability. ArcGIS Pro hosts the geodatabase tables and model-derived layers, enabling 3D scene viewing and element-linked access to data through standard interactions such as pop-ups and attribute views.

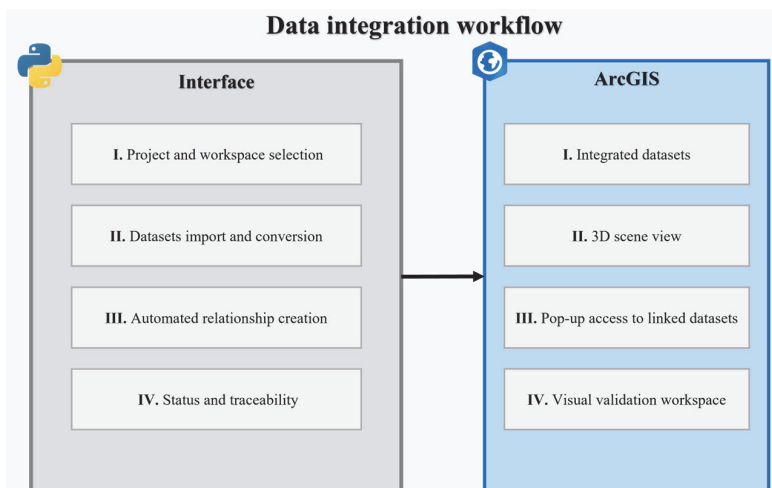


Figure 1 Data integration workflow into the ArcGIS Pro environment

2.1 Interface workflow

The workflow starts with project context definition, selecting either the currently open ArcGIS Pro project or a project specified by path, ensuring that operations target the intended workspace and project geodatabase. External datasets are then ingested from Excel and JSON and stored as tables using a one-table-per-file strategy, with optional timestamping to preserve provenance across successive deliveries. In parallel, a 3D digital model of the asset is imported and converted into model-derived GIS layers and feature classes suitable for 3D visualisation and attribute interaction, in the current configuration using an IFC model. Associations between imported inspection tables and model-derived layers are configured automatically by detecting candidate correspondences and applying map-level relates and joins in ArcGIS Pro. The associations are established primarily through identifier-based linking, enabling access to dataset records by selecting a specific element. Each execution reports status and traceability outputs, confirming successful operations and flagging validation issues.

2.2 Project outputs

The workflow outputs an ArcGIS Pro project configured for consultation and validation of the integrated content. Model-derived layers are available for inspection in a 3D scene view, supported by existing GIS context layers and basemap imagery to facilitate spatial interpretation and plausibility checking. Configured relates and joins enable element-linked access to inspection information through standard interactions, including pop-ups and attribute views, allowing users to retrieve records directly from selected model elements. This supports element-level consultation of inspection records without requiring manual relationship configuration by the user.

3 Observed outcomes

The Linha de Leixões, inaugurated in 1938, connects Porto to the port area of Leixões and has historically alternated between freight-only operation and intermittent passenger service. Passenger trains returned on 9 February 2025, with the reopening of a 19 km section linking Porto to Leça do Balio and serving intermediate stops, integrating the line into CP's Porto suburban network [8]. In the first three months after reopening, demand exceeded 155, 000 validations, with Hospital de São João emerging as the most used new stop, and peak days surpassing 2 500 validations [9], indicating rapid uptake of the service and reinforcing the line's suitability as a real-world pilot for the integration workflow presented in this paper.

3.1 Data integration

The workflow produced an ArcGIS Pro project where the IFC-based digital model and the imported inspection data coexist in the same 3D scene environment. The model was imported and converted into model-derived layers, enabling element-level visualisation of the viaduct within the GIS context. To support contextual interpretation, the scene was complemented with base map imagery and 3D buildings, allowing the infrastructure elements to be examined within their surrounding urban environment. Within the scope of this case study, inspection data were incorporated as geodatabase tables following a one table per file strategy, with timestamped naming available as an optional user setting to support traceability across successive imports. Figure 2 presents the integrated 3D scene in ArcGIS Pro, showing the imported viaduct geometry, as well as the railway, within contextual base map imagery and 3D buildings.

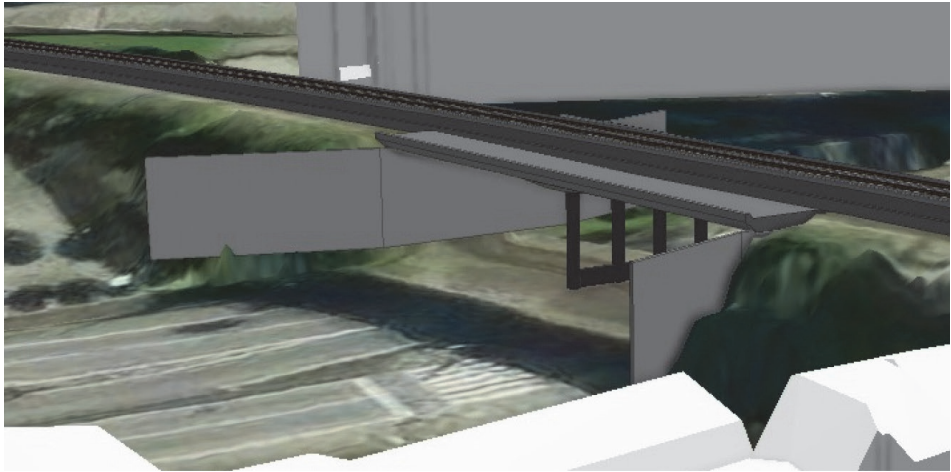


Figure 2 Integrated ArcGIS Pro 3D scene showing IFC-derived viaduct model within contextual base map imagery

3.2 Relationship outcome and traceability

Associations between inspection tables and model-derived layers were configured as map-level relates, enabling navigation between physical elements and their corresponding records within the ArcGIS Pro scene. In this case study, relates were established for the viaduct column layer, allowing a user to select a column element and access the corresponding inspection information through the element pop-up. The interface supports this process by automatically identifying candidate field correspondences, reducing the need for manual key selection. This outcome depends on the availability of consistent identification attributes between inspection tables and model-derived layers. Figure 3 shows an example of this outcome, where a selected column element exposes inspection-related attributes in the ArcGIS Pro interface.

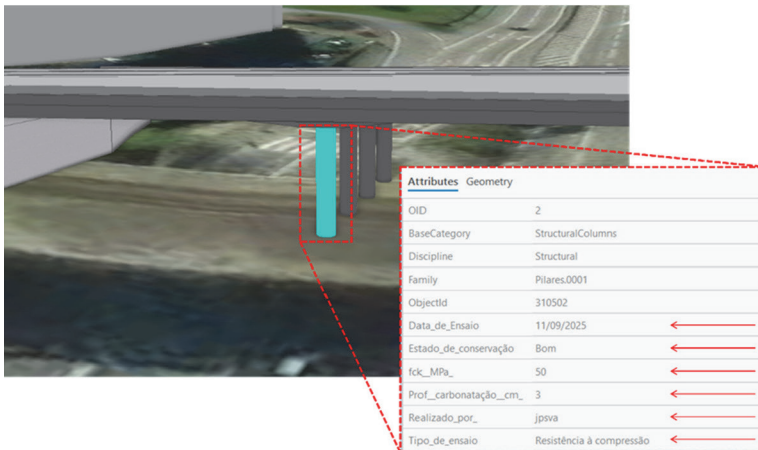


Figure 3 Example of inspection information accessible from a selected IFC-derived viaduct column through the configured relate

4 Conclusion

This paper presented an integration framework, developed within the NRPCES-EU project, to consolidate heterogeneous railway maintenance information into a single, consultable environment. The approach focuses on practical integration foundations: importing datasets into the project geodatabase, integrating a 3D digital model within the same project context, and automating layer-level associations that enable navigation between physical elements and inspection records with minimal manual configuration. The methodology is intentionally positioned as DT-ready, prioritising structured and traceable integration and element-level accessibility as prerequisites for future analytical and decision-support modules. The case study on a segment of the Linha de Leixões demonstrated the feasibility of the workflow in a real asset context, including a viaduct representation in a 3D scene supported by contextual layers. Inspection tables and model-derived layers were integrated within the same project, and map-level relates enabled retrieval of inspection information from selected elements, supporting consultation by non-specialist stakeholders.

Current limitations are mainly related to data consistency. Element-level association depends on the presence of compatible identification attributes between inspection tables and model-derived layers, and the quality of the integrated view is influenced by the completeness and alignment of incoming datasets. In addition, the current implementation applies associations at map level, which supports iterative configuration and rapid refresh but remains dependent on the project context. Future work will incorporate partner datasets and analysis outputs and validate the workflow with information produced across project activities. Additionally, tools developed by other project partners are being integrated so that future analysis workflows do not depend on multiple applications or separate interfaces. The objective is to centralise functionalities within a unified environment, allowing stakeholders to interact through a single interface to access integrated data and derived outputs. The association strategy will also be extended beyond identifier-based linking to include chainage-based referencing along the alignment, coordinate-based matching, and linkage to specific reference points when identifiers are unavailable.

Acknowledgments

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