Algorithmic Workflow for Digitising Inspection Data in Railway Tunnel Maintenance

Inês Caetano[a] (corresponding author)
ines.caetano@tecnico.ulisboa.pt / 0000-0003-3178-7785

Debora Pinto[b]
debora.pinto@builtcolab.pt / 0000-0001-9468-7779

Margarida Amândio[b]
margarida.amandio@builtcolab.pt / 0000-0002-6340-0648

João Silva[b]
joao.silva@builtcolab.pt / 0000-0003-2233-8160

Luís Sanhudo[b]
luis.sanhudo@builtcolab.pt / 0000-0002-2578-6981

Miguel Azenha[c]
miguel.azenha@civil.uminho.pt / 0000-0003-1374-9427

Mohammad El Sibaii[c]
mohamadelsibaii@gmail.com / 0000-0002-0810-9241

José Granja[c]
granja@civil.uminho.pt / 0000-0002-0858-4990

Hugo Patrício[d]
patricio@uic.org

Francisco Ganhão[e]
francisco.ganhao@infraestruturasdeportugal.pt

João Poças Martins[f]
jppm@fe.up.pt / 0000-0001-9878-3792

[a] INESC-ID – Instituto de Engenharia de Sistemas e Computadores: Investigação e Desenvolvimento em Lisboa, Computer Science and Engineering Department, Instituto Superior Técnico, University of Lisbon Rua Alves Redol 9, 1000-029 Lisboa

[b] BUILT CoLAB, Rua de Campo Alegre, 760 4150-003 Porto

[c] ISISE - Institute for Sustainability and Innovation in Structural Engineering, Department of Civil Engineering, University of Minho, Campus de Azurém, 4800-058 Guimarães

[d] UIC - International Union of Railways, 16 rue Jean Rey - 75015 Paris

[e] IP - Infraestruturas de Portugal, Praça da Portagem, 2809-013 Almada

[f] CONSTRUCT - Institute of R&D in Structures and Construction, Department of Civil Engineering, Faculdade de Engenharia da Universidade do Porto, Rua Dr. Roberto Frias, 4200-465 Porto

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Purpose:

This study addresses the lack of structured, data-driven approaches to infrastructure asset management, demonstrating how integrating Building Information Modelling (BIM) and digital twin methodologies can enhance the maintenance and lifecycle management of railway tunnels.

Design/methodology/approach:

A structured data-to-BIM workflow was co-developed with *Infraestruturas de Portugal* (IP), using inspection and monitoring data from 79 railway tunnels. The workflow includes automated data acquisition and systematisation, algorithmic generation of structured, data-rich BIM models, and a centralised digital twin platform for lifecycle monitoring.

Findings:

Implementation enabled real-time data manipulation, predictive maintenance, and improved decision-making. Key outputs include standardised data exchange protocols, Product Data Templates, BIM object classes for tunnel components, and digital twinning algorithms. Benefits observed include improved collaboration, automatic anomaly detection, and enhanced visualisation of tunnel condition.

Originality:

The research presents a framework for integrating digital twins into infrastructure asset management, demonstrating the operational value of computational methods in transforming conventional maintenance and lifecycle management workflows and supporting data-driven decision-making.

Research limitations/implications:

Further research is needed to improve the algorithms performance, minimise manual interventions, and validate the workflow's scalability across diverse asset typologies and operational contexts.

KEYWORDS: Data interoperability; Infrastructure asset management; Data-to-BIM methodology; Predictive maintenance; Tunnel digital twinning; Built environment digitalisation.

1. Introduction

The Architecture, Engineering, and Construction (AEC) industry faces growing pressure to improve built environment safety, quality, and sustainability (Evins, 2013; Touloupaki and Theodosiou, 2017) and adopt Industry

4.0 methodologies. This has motivated methodologies, such as Building Information Modelling (BIM), that standardise design and construction processes to improve efficiency, interoperability, accuracy, and resource optimisation, and facilitate lifecycle monitoring and maintenance (Bensalah *et al.*, 2019; Eastman *et al.*, 2008; Garber, 2014; Sharples, 2009). Despite its benefits for the tunnelling industry (Erharter *et al.*, 2023; Li *et al.*, 2023), BIM adoption has lagged behind other sectors (Song *et al.*, 2019; Wang and Zhang, 2021), particularly because of the often complex terrain conditions of tunnel infrastructures, which complicate classification and create substantial differences between industry standards (Song *et al.*, 2019). The lack of standardised data (Neves *et al.*, 2019; Song *et al.*, 2019) and Industry Foundation Classes (IFC) objects for tunnel components (Acerra *et al.*, 2022; Barros *et al.*, 2024) further complicates the process. Updating *as-is* models of existing tunnels remains labour-intensive, even for experienced modellers (Cheng *et al.*, 2019; Wang and Zhang, 2021), requiring integrating multidisciplinary data, including *as-built* information, documents, and spreadsheets, which are typically diverse and fragmented (Foria *et al.*, 2023; Machado and Futai, 2024; Wang and Zhang, 2021).

This research explores BIM integration within *Infraestruturas de Portugal* (IP), delivering a digital platform for tunnel structural monitoring that goes beyond existing approaches by addressing data fragmentation, limited standardisation, and the labour-intensive nature of tunnel as-is modelling.

2. METHODOLOGY

2.1. RESEARCH CONTEXT

This investigation was part of a project aimed at improving Portuguese railway infrastructure monitoring through:

- Goal 1. A BIM-based tunnel data platform.
- Goal 2. A novel constitutive model for fibre-reinforced concrete (FRC) structures.
- Goal 3. An optimisation method for FRC-based robotic technology.
- Goal 4. Strategies for robotic arm control based on tunnel stability projects.
- Goal 5. A new generation of shotcreting guns for robotic arms.

It addressed Goal 1, delivering a digital platform for tunnel structural monitoring and maintenance that enhanced data integration, standardisation, and visualisation.

Since 2004, IP has been digitising inspection, monitoring, and diagnostics information from railway tunnels, storing data in multiple formats and dispersed across servers. While tunnel laser scan data and topographic surveys (including cross-sections and high-density point clouds) were stored in different repositories, tunnel *as-built* data (construction date, location, railway line, dimensions, and materials) remained in multiple spreadsheets, and inspection records (including time-series anomaly mapping) were centralised in Tunnel-Inspector, a specialised software for inspection data analysis. The platform aimed to centralise and standardise these datasets, simplifying access, management, and application in structural monitoring and maintenance activities, while supporting collaboration and decision-making through intuitive and synchronised data visualisation.

2.2. Methods

Centralising dispersed tunnel data into a unified workflow entailed the following steps:

1) **Literature review** to identify gaps and solutions for data systematisation into BIM models.
2) **Data systematisation and standardisation** to compile and uniformise dispersed datasets.
3) **Data-to-BIM algorithms** to convert tunnel data into BIM objects.
4) **Digital platform** to centralise and manage tunnel as-is models.
5) **Discussion** on research outcomes, challenges, and future directions.

2.3. Contributions

This work provides the following contributions:

1) Guidelines for systematising and coordinating tunnel lifecycle data within a unified framework, enhancing consistency, interoperability, and collaboration.
2) Product Data Templates (PDTs) and BIM object classes for railway tunnel components, standardising *as-is* modelling across projects.
3) Algorithmic strategies automating multi-source data integration, continuous updating, and tunnel *as-is* modelling.
4) A collaborative platform architecture integrating BIM with tunnel lifecycle monitoring, structural inspection, and maintenance data.

2.4. Limitations

Due to the short collaboration timeframe (4 months), some limitations remained, namely:

1) The high processing times of data-to-BIM algorithms when handling larger datasets.
2) The need for user intervention between modelling phases.
3) Non-automated generation of tunnel elements like niches, rail systems, and portals.
4) Absence of quantitative assessment of the proposal's usability and practical relevance.

2.5. Paper Outline

Section 1 introduces the research scope, Section 2 outlines the goals, challenges, and methodology, and Sections 3-6 detail the research methods: literature review (Section 3), data standardisation (Section 4), data-to-BIM algorithmic process (Section 5), and digital platform development (Section 6). Section 7 discusses application results, Section 8 reflects on contributions, challenges, and future work, and Section 9 concludes the paper.

3. Literature Review

3.1. Scan-to-BIM Workflows

Laser scanning data enables the creation of 3D as-built models, reducing errors, costs, and inspection time while improving collaboration through real-time updates (Abreu *et al.*, 2023). However, converting point clouds into parametric objects remains challenging due to the time and effort required for cleaning, structuring, and classifying raw data (Benallal *et al.*, 2022; Park and Cho, 2022; Tang *et al.*, 2022), particularly in irregular elements that lack predefined shapes (Barazzetti, 2016), as often seen in tunnel infrastructures.

Some work has been done to support point cloud cleaning for BIM (Benallal *et al.*, 2022; Rakotosaona *et al.*, 2020), as well as to automate the generation of irregular BIM objects. Barazzetti's (2016) developed a semi-automated method for converting photogrammetric and laser scanning data into parametric models using Non-Uniform Rational B-Splines (NURBS), and Buldo et al. (2023) tested an iterative Scan-to-BIM methodology for the parametric reconstruction of masonry vaulted systems based on point cloud data-driven NURBS. Other examples include Cheng et al. (2019) classification method for converting point cloud data into parametric *as-is* models of railway tunnel components, such as rails, cross-sections, pipes, and refuges, and Li et al. (2024) approach for constructing high-precision tunnel models from image and point cloud data.

3.2. Data Coordination and Management

The interest in BIM for transport infrastructure has grown, particularly to enhance data integration, communication, project accuracy, resource allocation, and planning (Bensalah *et al.*, 2019). Large-scale examples include the Crossrail project (Malcolm Taylor, 2018; Pollalis and Lappas, 2019), which combined Geographic Information System (GIS) and augmented reality technologies with BIM from design to construction, resulting in 3D, 4D, and 5D models; and the Rail Baltica project (Starynina and Busmanis, 2019), which benefited from BIM in design and construction phases and aims to extend its use to railway infrastructure management.

Other examples are Acerra et al. (2022) integrated model centralising multidisciplinary data for part of Bologna's future Red Tramway Line. Despite demonstrating BIM's potential for optimising time, cost, and resources, the study remains limited to tram infrastructure and relies on manual, project-specific BIM modelling. Zhou et al.

(2016) applied BIM for safety monitoring in the Xu Huaiyan Bridge project, creating a multi-layer system for mixed data storage, modelling, and visualisation, and Zhang et al. (2023) developed a BIM-based platform for Jingxiong Bridge construction management, integrating big data, IoT, and cloud storage to optimise resource allocation and collaboration. However, in both cases, the models are limited to construction phases and focus on bridge infrastructures.

Zhou et al. (2021) used BIM for construction management of the Zhuhai Dahengqinshan No. 1 tunnel, developing a 3D geological and tunnel BIM model for collision detection and 4D progress simulation. Li et al. (2023) automated parametric modelling for rock tunnels in Revit, enabling real-time updates, and established a BIM platform for stakeholder collaboration in Laoying Tunnel (China). Huang et al. (2022) introduced a BIM workflow for object modelling, data exchange, and improved visualisation, enhancing design efficiency and decision-making through automated data retrieval and parametric instantiation. However, despite addressing tunnel infrastructure, these works target design and construction stages rather than structural monitoring and maintenance.

3.3. Infrastructure Maintenance and Rehabilitation

Maintenance is crucial for preventing technical and structural issues that compromise infrastructure operation, longevity, and safety (IAM and BSI, 2008). However, BIM applications for railway infrastructure maintenance remain limited (Xu *et al.*, 2020), partly due to information transfer limitations (Wang and Zhang, 2021). Among the few examples are Yu et al. (2021) digital twin-based decision analysis framework for tunnel operation and maintenance, incorporating an extended COBie standard for data organisation, semantic mapping for ontological expression, and rule-based semantic reasoning for tunnel twin data analysis; Foria et al. (2023) railway tunnel risk assessment method for two Italian railway tunnels, integrating laser scanning, thermal imaging, visual inspections, and ground penetration radar to create digital twins mapping structural defects and supporting maintenance and construction works; Kim et al. (2023) high-resolution digital twin from 2D panoramic images and point cloud data for Korean railway infrastructure maintenance and operation; and Wang and Zhang (2021) BIM platform based on point cloud technology to enhance data integration, retrieval, and management in underground rail transit projects.

3.4. Anomalies Characterisation and Visualisation

Timely anomaly detection, monitoring, and treatment are crucial for effective structural health maintenance (Hu *et al.*, 2019; Lu *et al.*, 2020; Machado and Futai, 2024). BIM can enhance maintenance efficiency and effectiveness by representing structural anomalies, supporting real-time visualisation of inspection data and the planning of inspection and reinforcement routines. However, BIM applications for anomaly representation remain limited. Among the few examples is Lu et al. (2020) Digital Twinning platform based on an extended IFC4 file, including operation and maintenance requirements, such as diagnostic data on asset operational condition. Besides supporting anomaly detection and decision-making, the study does not target railway infrastructures or the representation of anomalies in BIM. Similarly, Hu et al. (2019) proposed an IFC-based tunnel defect diagnosis system that integrates heterogeneous data, such as defect characteristics, location, images, and monitoring data, within a 3D model displaying defect distribution and risk levels through colour coding, along with quantitative trends and observation points markers. However, despite aiding lifecycle assessment, the system relies on single-source data and does not represent defects' geometric characteristics.

Chow et al. (2021) introduced a framework linking defect locations in BIM models to inspection reports, combining defect detection from concrete structure images and LiDAR data. However, the proposal targets buildings rather than tunnels and only identifies two defect types without modelling their position, severity, or shape. Catigbac et al. (2023) proposed a method integrating laser scanning, thermal imaging, and ground-penetrating radar to enable data-driven inspection, digitalisation, and diagnosis of underground transport infrastructures, culminating in a BIM-based digital twin. However, the method lacks a fully standardised data scheme for tunnel components, relies on specific software that may limit broader integration, and does not directly model defects in BIM, instead linking them externally. Zhu et al. (2024) created a data-driven framework for real-time tunnel inspection and maintenance using laser scanning and ground-penetrating radar, applying risk-based colour-coding to defect-related parameters. However, despite improving risk assessment and maintenance, the models do not represent defects' geometry, origin, or material. Lastly, Machado and Futai (2024) proposed a digital twin for inspection data management and tunnel intervention prediction, mapping and classifying defects using a 2D grid system and supporting real-time data visualisation. However, only anomaly severity is represented in BIM, with important details, such as shape, extent, and origin, conveyed via attached photographs and tables.

3.5. SUMMARY

Current studies reveal limitations in scan-to-BIM automation, data integration, standardisation, lifecycle management, and the representation of maintenance-related anomalies, particularly in the context of tunnel infrastructure. Although existing research demonstrates the potential of BIM and digitalisation technologies across design and construction phases, few contributions address the operational integration of heterogeneous inspection data to support long-term monitoring and maintenance activities.

In parallel, several studies have proposed high-level digital twin frameworks for infrastructure and construction asset management, emphasising aspects such as semantic integration, system validation, scalability, and lifecycle governance (Boje *et al.*, 2020). While these frameworks provide important conceptual foundations, they often remain abstract or operate at organisational or network scales, with limited focus on the operational integration of heterogeneous inspection data into object-based BIM environments.

This research addresses these gaps with an integrated, BIM-based workflow that combines algorithmic modelling, standardised schemes, and digital twinning to enable structured multi-source data management and enhanced decision-making in tunnel monitoring and maintenance contexts. By focusing on inspection-driven data structuring and practical implementation, the study complements existing framework-level research while contributing with operational artefacts that support more informed and efficient infrastructure asset management.

4. Data Systematization and Standardization

This step entailed analysing, cleaning, and systematising IP's datasets to generate data-rich as-is models. Due to the limited collaboration timeframe, a sample of 79 tunnels was selected. Essential tunnel elements and relationships were structured using the Portuguese SECClasS (Sustainability Enhanced Construction Classification System) system and the IFC4 ADD2 TC1 scheme, ensuring interoperability, data consistency, and BIM integration (Lu *et al.*, 2020). Industry standards, including EN 17412-1 for defining Levels of Information Need and ISO 19650 for lifecycle management were also adopted.

The modelling process was structured into four levels (0 to 3) of increasing detail to test applicability across different requirements and illustrate potential real-world benefits of these models for infrastructure management. While Level 0 only displays the tunnel location, terrain characteristics, and volume (e.g., for GIS integration), Levels 1-3 enable progressively richer structural data visualization, from anomaly representation to detailed geometry suitable for structural rehabilitation. Due to the absence of standardised PDTs for railway tunnel data in Portugal, templates for key components, such as linings, ballast, rails, and anomalies, were created based on EN ISO 23387 and EN ISO 23386. PDTs are structured digital formats that systematically capture and organise essential construction product data, including performance metrics and environmental declarations, ensuring consistent information exchange across project phases (Sibaii *et al.*, 2022).

Building on previous research (Sibaii *et al.*, 2020, 2022; El Sibaii *et al.*, 2023), the process entailed:

1. **Data collection** from European norms (e.g., EN 13674-1 for rails), IFC property sets, manufacturers, and expert input.
2. **Normalisation** to eliminate redundancies and inconsistencies.
3. **Property selection and categorisation** based on EN ISO 23387 guidelines (Table I).

4. **Attribute definition** for each property per EN ISO 23386, linking properties to other data dictionaries like IFC and facilitating their lifecycle management and updating within PDTs as standards evolve (Sibaii *et al.*, 2022).
5. **Master Data Template creation** for universal construction properties, which is available at https://pdts.pt

Table I. Part of the Rail PDT normalisation matrix (green: chosen properties; red: discarded properties)

EN13674-1	IFC	Expert feedback	Properties
	PositionInTrack		PositionInTrack
	TechnicalStandard		TechnicalStandard
	RailDeliveryState		RailDeliveryState
	RailCondition		RailCondition
		Rail Length	Rail Length
		Description	Description
Hydrogen content		Levels of hydrogen	HydrogenContent
Total oxygen		Levels of oxygen	TotalOxygen
Decarburisation		Decarburisation	Decarburisation
Hardness (HBW)		Hardness	Hardness
Tensile strength		Tensile resistance	TensileStrength

5. Data-to-BIM Methodology

This step entailed converting tunnel data into BIM models with varying granularity levels.

5.1. Point Cloud to Surface Algorithm

To convert tunnel laser-scanning data into surfaces, the team used Khepri (Sammer *et al.*, 2019), a parametric modelling library compatible with CAD and BIM tools. A custom algorithm was developed to process tunnel point clouds into surfaces of varying geometric detail. The only exception is Level 0, where the tunnel volume is generated through a Dynamo that extracts the tunnel cross-section from floor plans and alignment from topographic surveys, extruding the former along the latter to create the generic tunnel volume.

Upon receiving laser-scanning data and the modelling level (1 to 3), the algorithm performs the following steps:

1. Point cloud conversion into spatial locations.
2. Clustering locations into profiles by position (**Figure 1**), with spacing defined by the modelling level: wider at Level 1 and progressively narrower at Levels 2 and 3.
3. Profile cleaning and sequentially sorting (bottom-left to bottom-right).
4. Profile simplification based on modelling level (**Figure 2**): at Level 1, only essential points are retained to approximate tunnel shape and uniformised through equally spaced points; at Levels 2 and 3, additional

filtering is applied to ensure uniform point density, with users controlling both minimum and maximum point distances and maximum number of profile points.

5. Point matrix generation, with the number of lines and columns matching the number of profiles and points, respectively.
6. Surface generation (Figure 3).

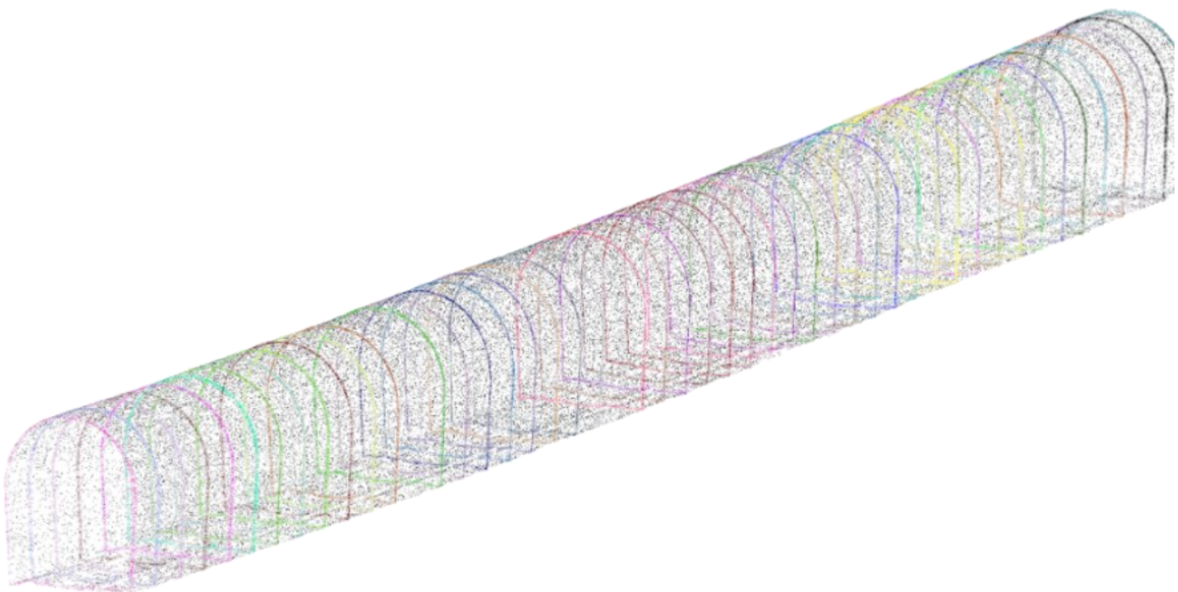


Figure 1. Clustering tunnel laser-scanning data into point profiles (Source(s): Authors' own work).

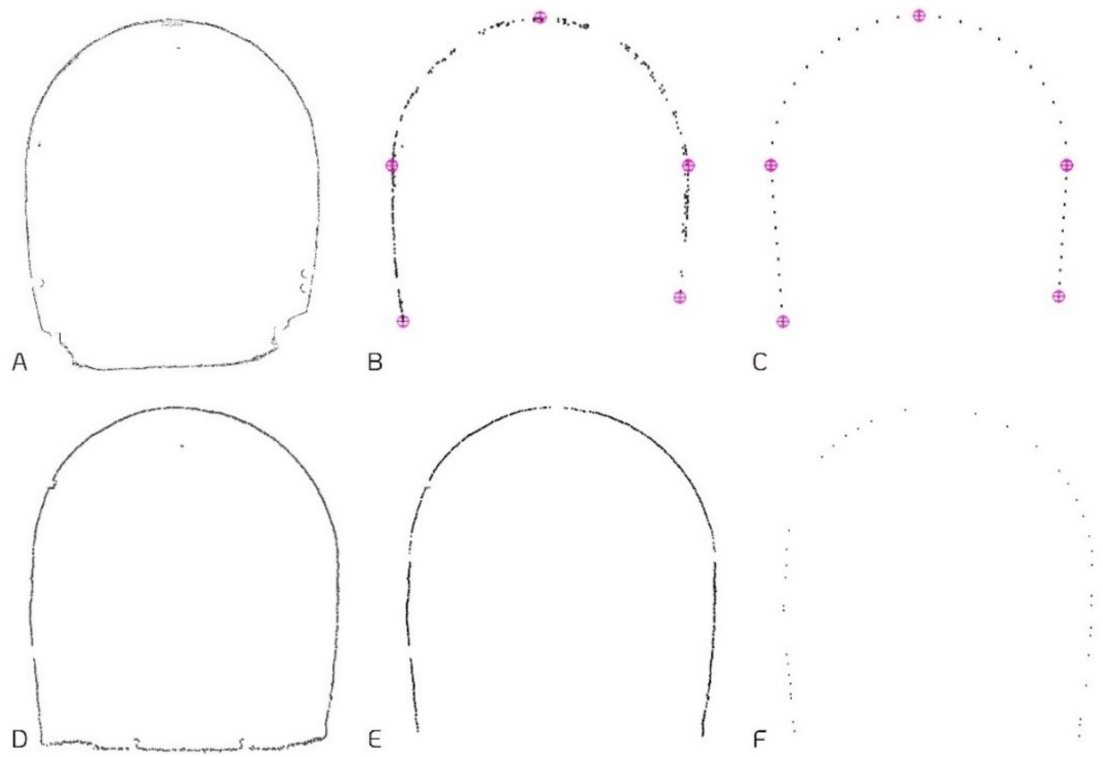


Figure 2. Level 1: the profile (A) is simplified into tunnel main points (B), between which equidistant points are calculated (C); Levels 2 and 3: the profile (D) is filtered to remove duplicates/outliers (E) and to match the minimum/maximum distances and/or maximum number of profile points (F) (Source(s): Authors' own work).

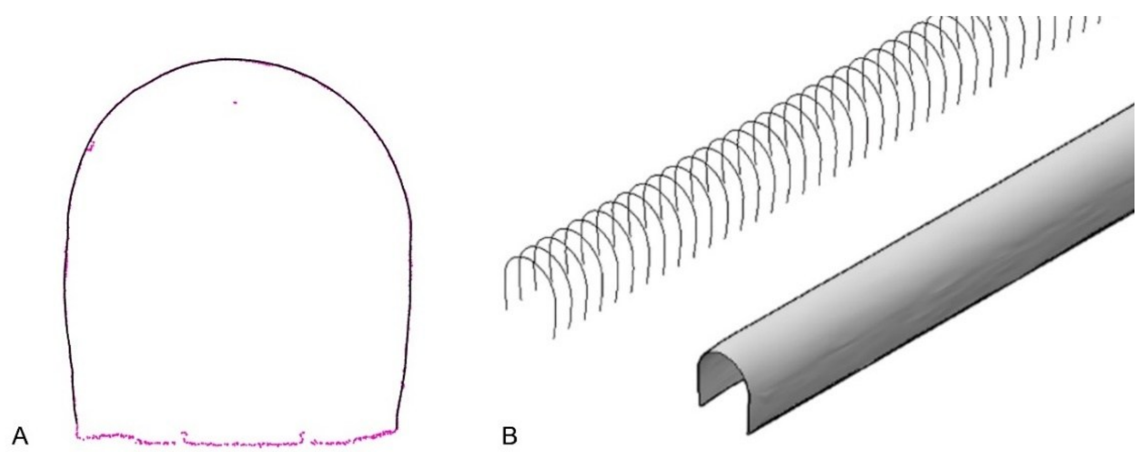


Figure 3. A. Original profile (pink dots) and the curve obtained after its filtering (black); B. Point profiles converted into curves (left), whose interpolation generates the tunnel surface (right) (Source(s): Authors' own work).

Another custom algorithm was developed to support structural calculations. Based on the given matrix and tunnel structural data, the algorithm:

1. Restructures the matrix into rectangular grid cells (Figure 4.A).
2. Creates a parallel grid based on tunnel thickness (Figure 4.B).

3. Calculates the intermediate grid between both (Figure 4.C).

Another algorithm was implemented to store grid data for structural calculations into two formats: Listing point indexes (IDs) and XYZ values (Figure 4.D) or organising IDs by grid cell (Figure 4.E).

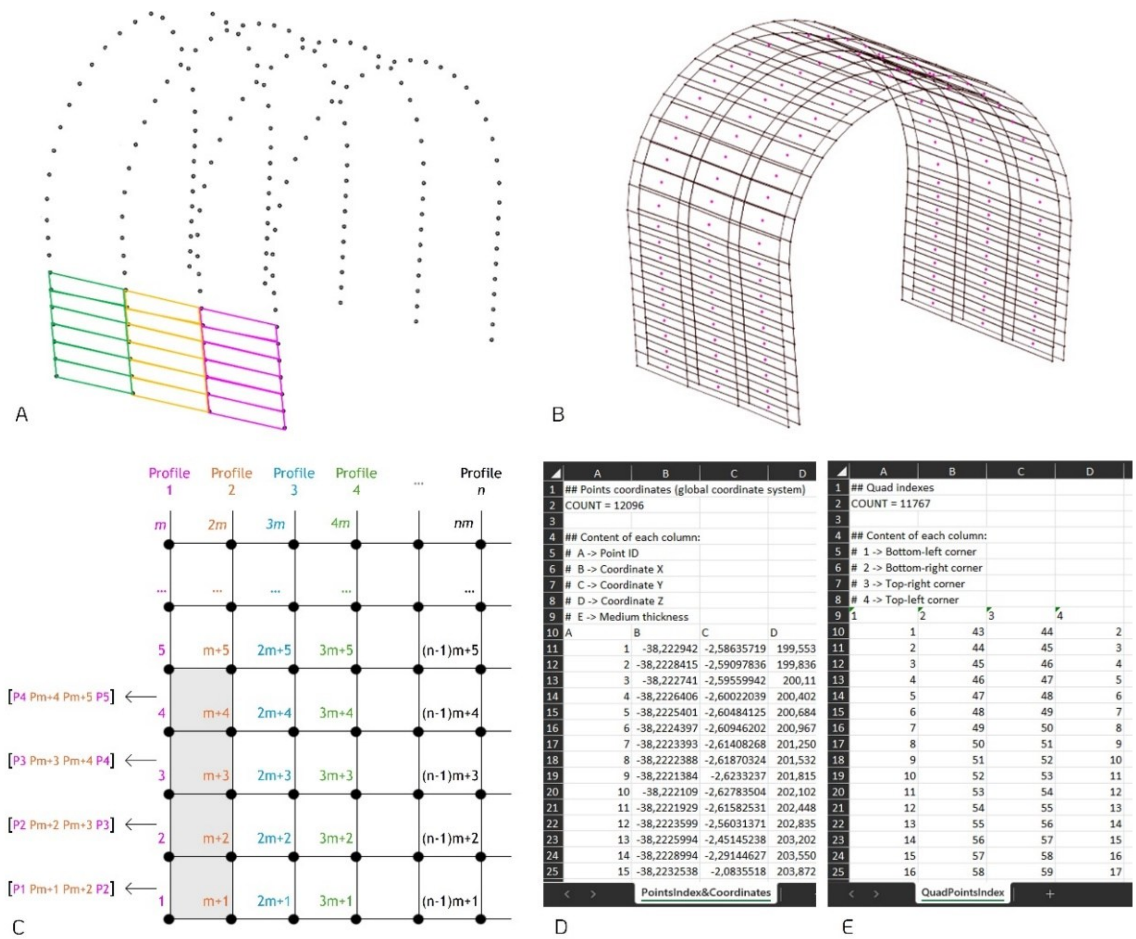
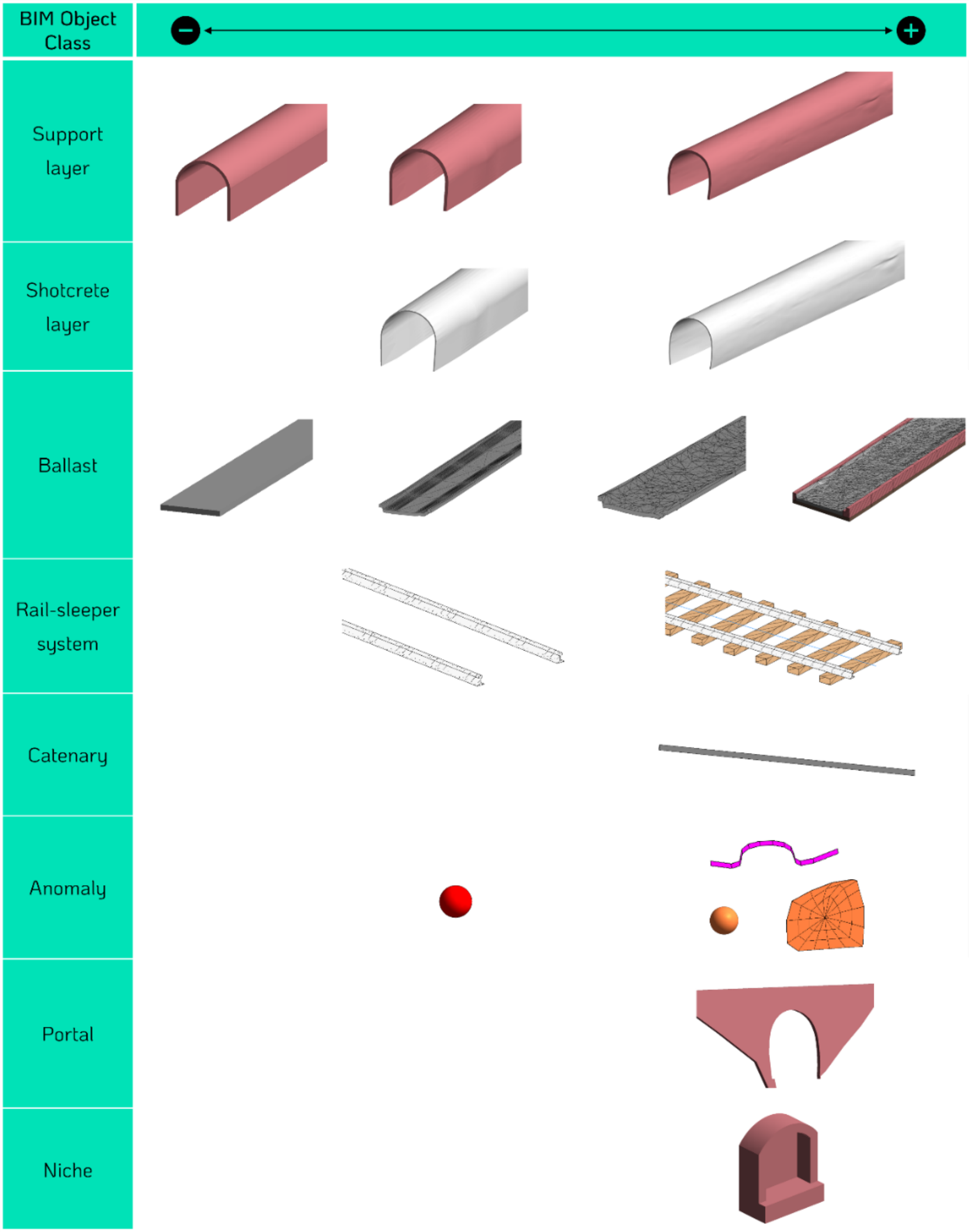


Figure 4. A. Rearranging profiles into rectangular grids; B. Calculating inner and outer grids' intermediate points (pink dots); C. Organising intermediate points into sets of four; D-E. Storing intermediate points by ID and XYZ values (D) and by grid cell (E) (Source(s): Authors' own work).

5.2. DIGITAL REPRESENTATION OF RAILWAY TUNNELS

Alongside data systematisation and manipulation, BIM object classes were created to digitally represent railway tunnel elements (Table II). Object class parameters depended on the available information and the structural importance of the represented elements. A balance was struck between the modelling level and structural relevance: elements with greater impact on structural performance were assigned more data and geometric detail. As shown in Table II, structurally significant elements like tunnel support layers, shotcrete layers, and anomalies feature more granular geometries than components with minimal or no structural role, like tunnel rails and ballast.

Table II. BIM objects for railway tunnel elements in different modelling levels.



Object classes such as tunnel support layers, shotcrete layers, and anomalies were instantiated through Dynamo scripts. When provided with information about the element—ranging from 3D surfaces to numerical data and

DWG drawings—these scripts automatically generate the corresponding BIM class, embedding the specified data and modelling level. For example, to create the tunnel support layer, the script uses the parametric surface from the previous step and its physical characteristics (e.g., materials and thickness), generating a data-rich 3D element aligned with the input surface's modelling level and information provided.

Anomaly instantiation follows a similar approach, relying on inspection data, which is provided in both numerical format (e.g., defect type, location, condition, and dimensions) and geometric format (anomaly contour). Based on these inputs, the Dynamo script instantiates the anomaly object class that best matches the defects, with a level of detail aligned to the tunnel support layer's modelling level. Figure 5 shows three object classes created for anomalies—punctual, linear, and surface—which differ in shape, associated information (e.g., material type, identification date, and condition), and colour, which indicates the defect origin and material (e.g., blue represents altered joints, red symbolizes masonry elements, orange indicates infiltrations, and pink represents structural damage).

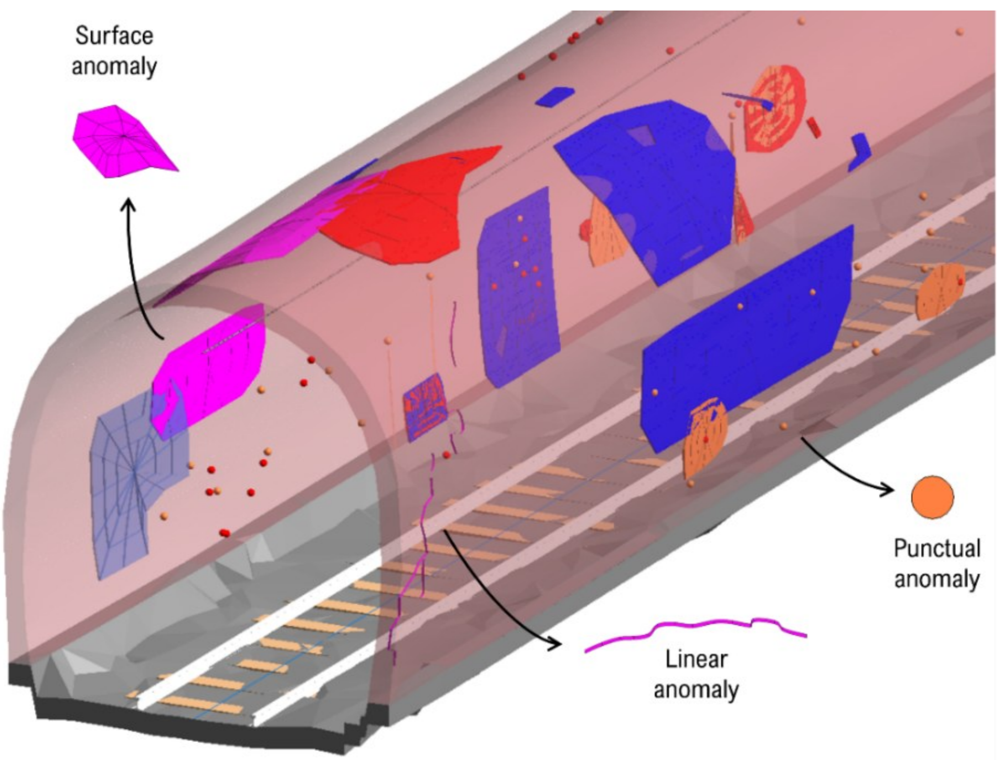


Figure 5. BIM representation of three anomaly types (punctual, linear, and surface) with different origins and materials: altered joints (blue), altered masonry elements (red), infiltrations (orange), and structural damage (pink) (Source(s): Authors' own work).

Figure 6 illustrates the instantiation of tunnel anomalies across different modelling levels. In model C (Level 1), anomalies are shown as equally sized spheres, serving primarily as location markers, whereas in model D (Level

2), they are depicted with distinct geometries and semantics, offering a more accurate and detailed representation. Figure 7 shows one railway tunnel from Level 0 to Level 2, highlighting progressive variations in geometric detail. Regardless of the modelling level, both modelled and unmodelled anomalies are recorded to ensure process accuracy and enable completeness verification.

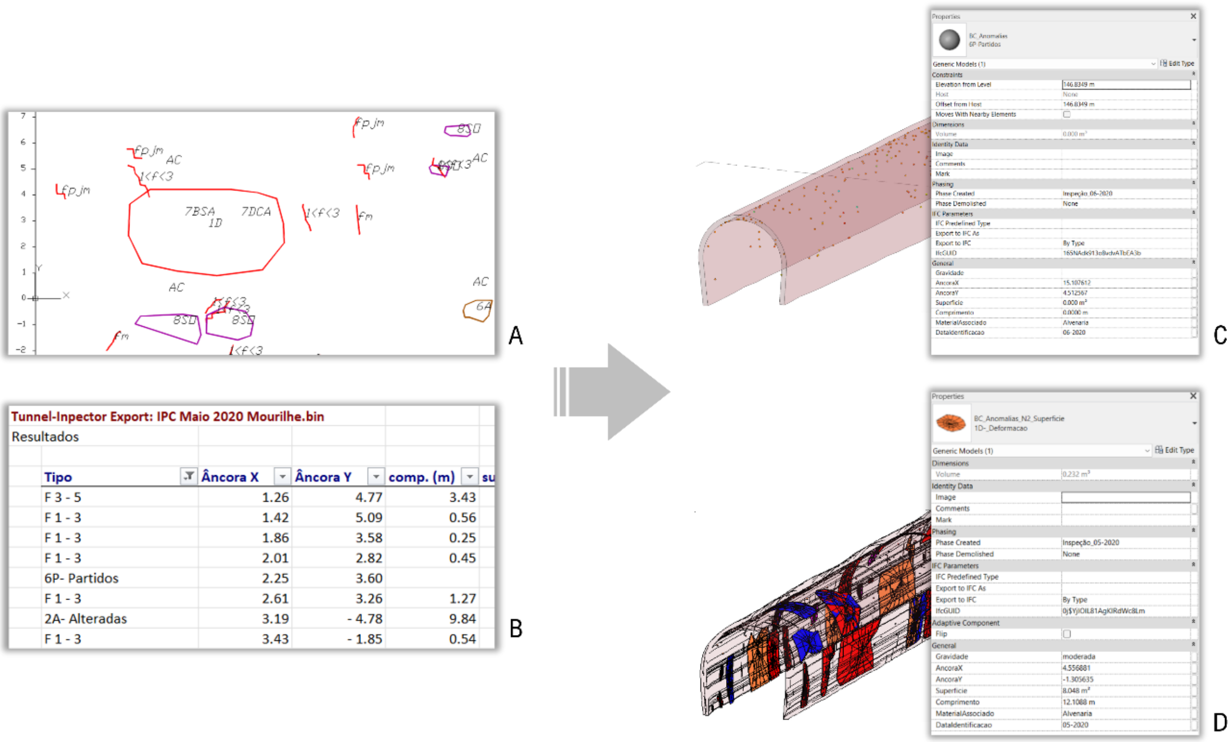


Figure 6. Left. Inspection data on anomaly geometry (A) and characteristics (B). Right: BIM object instantiation for different anomaly types in modelling levels 1 (C) and 2 (D) (Source(s): Authors' own work).

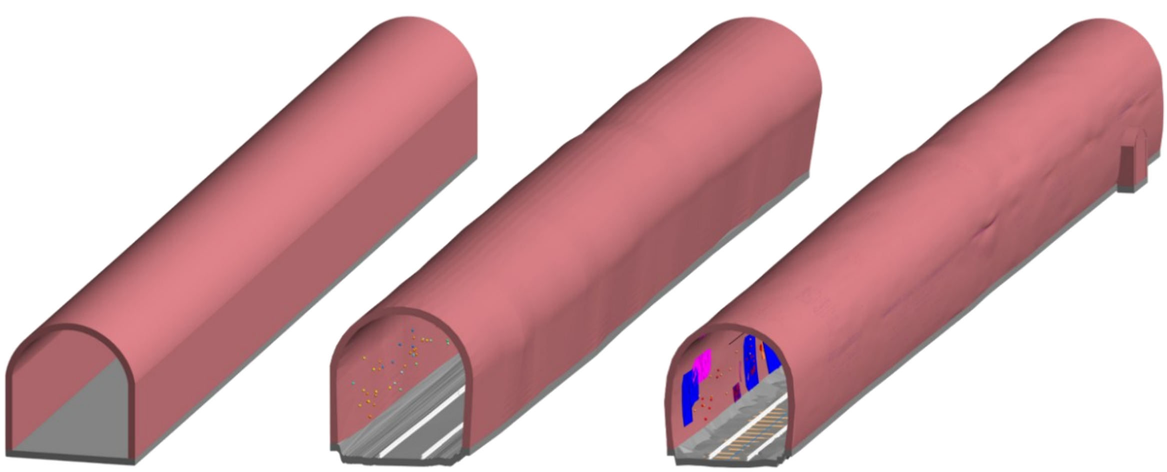


Figure 7. Left to right: A railway tunnel in levels 0, with its structure simplified; and 1 and 2, with its structure, anomalies, and railway track with increasing rigour (Source(s): Authors' own work).

6. PLATFORM CREATION AND APPLICATION

The last step entailed defining the digital platform architecture, establishing data flows, and creating a UI to improve access and visualisation of the model repository by professionals with varying expertise (Figure 8.A). The platform was designed to integrate heterogeneous data sources, including geometric surveys, anomaly mapping from inspection activities, and administrative attributes such as tunnel name and operational context, within a unified environment. By selecting a tunnel from the catalogue, users can access detailed information such as tunnel location, length, and railway line (Figure 8.B), and inspection data, including detected anomalies with corresponding dates (Figure 8.C). Tunnel models can also be opened directly within the BIM environment (Figure 8.D), enabling navigation, inspection, or modification, with automatic synchronisation ensuring that updates are available to all users.

The platform was implemented in the IP's modelling environment (Autodesk Revit) through a custom C# plugin built using the Windows Presentation Foundation framework, enabling stakeholders to access IP's tunnel catalogue and retrieve task-specific information, while preserving operational independence from Revit and ensuring consistent company branding.

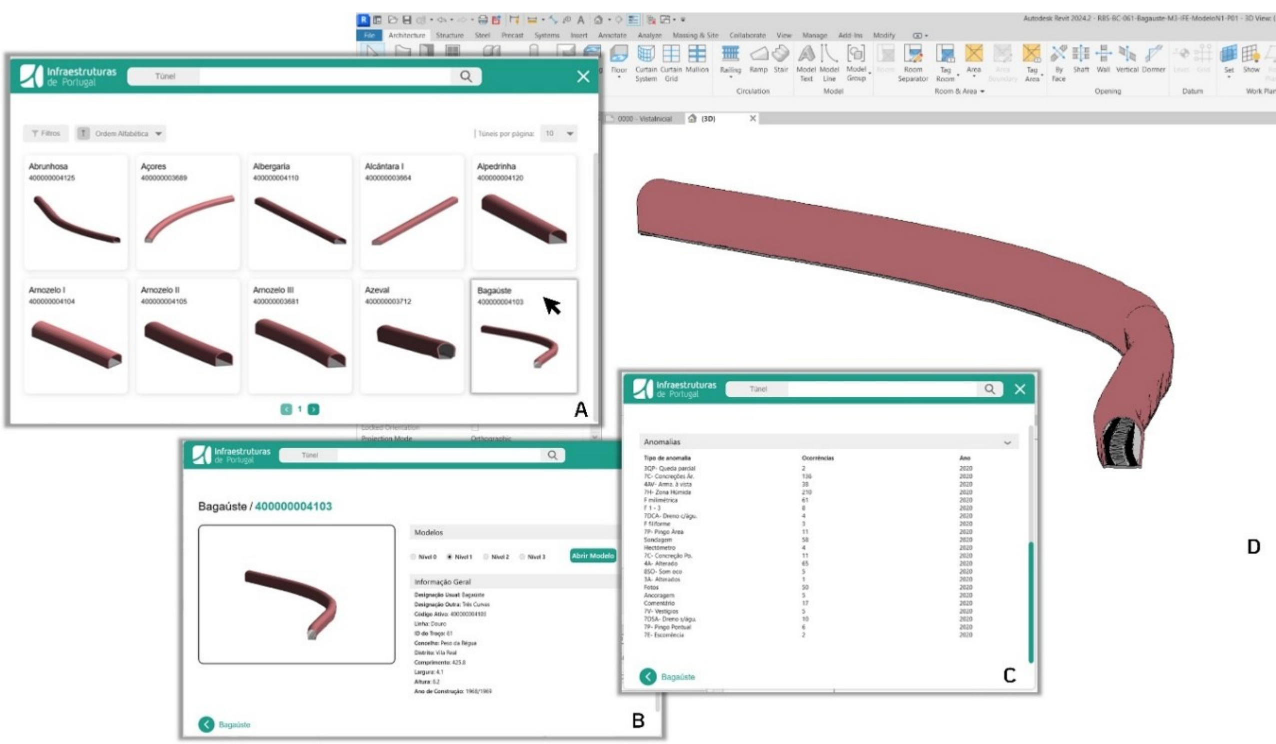


Figure 8. Menu listing IP's railway tunnels (A), whose selection shows additional information (B and C) and provides access to the BIM model (D) (Source(s): Authors' own work).

7. Research Outcomes

The research introduces a novel approach to tunnel data management by addressing the lack of standardisation and automation in existing frameworks. It combines algorithmic as-is modelling, standardised PDTs, and lifecycle integration, enabling efficient, interoperable, and continuously updatable tunnel representations. This work advances the development of digital twins by defining information requirements, data schemas, and scalable solutions for the geometric representation of tunnels, infrastructure objects, and anomalies. The approach goes beyond prior solutions by integrating multi-source data, real-time updating, and structural maintenance within a single BIM environment.

Its feasibility was demonstrated on IP's railway network, where dispersed and heterogeneous datasets, including point clouds, tabular databases, and inspection records, were consolidated into a unified repository of 79 as-is models. These models incorporated and characterised tunnel physical elements, such as structural layers, ballast, and niches, and anomalies based on these data, enabling centralised management of geometric, numerical, and condition information. This unified framework supports real-time synchronisation, ensuring that updates such as worsening, improvement, or resolution of anomalies are consistently reflected across the repository.

Nevertheless, performance limitations emerged when processing large point cloud datasets, particularly for long tunnels. This often required segmentation into smaller sections, resulting in accurate but fragmented models with occasional discontinuities that demanded additional coordination effort. While multi-source integration and automated anomaly updating were successfully achieved, full automation remained incomplete, as object classes like rail-sleeper systems, portals, catenaries, niches, and surrounding terrain still required manual modelling.

8. Discussion

The research delivered contributions that go beyond the project, including:

- Lifecycle guidelines for systematising and coordinating tunnel data across design, construction, monitoring, and maintenance stages, enhancing interoperability and collaboration.
- Standardised PDTs and BIM object classes for railway tunnel components, improving uniformity and consistency across as-is modelling workflows. These datasets are openly available through the Portuguese PDT platform, which soon will be migrated to the international BuildingSMART data dictionary, further increasing interoperability, scalability and data transferability.
- Algorithmic digital twinning strategies enabling multi-source integration, automation of as-is modelling, and continuous updating.

- A collaborative digital platform that supports lifecycle tunnel maintenance by integrating BIM models with monitoring, inspection, and maintenance data.

These contributions have broader relevance, impacting domains like:

- Structural monitoring and maintenance: The digital models consolidate essential tunnel information, including physical characteristics, anomalies, and scheduled interventions, enhancing understanding of tunnel integrity and informing maintenance planning. Additionally, models are dynamically updated with inspection and repair data, reflecting changes in tunnel condition, scheduled actions, and repair/reinforcement progress, thus enabling teams to adjust interventions promptly and efficiently. However, workflow effectiveness outside specific environments (e.g., Revit/Dynamo), and compared to traditional methods, remains untested, limiting broader applicability and measurable efficiency gains.
- Assets integration: The approach supports dynamic asset management through a centralised data structure, improving coordination. However, for large data volumes or restricted-access information, a federated data model may be preferable.
- BIM-based data synchronisation and visualisation: Automated classification, generation, and modification of anomalies enhance synchronisation, accuracy, collaboration, and decision-making. While the approach relies on IP-specific standards (e.g. SECClasS) and external tools that may limit application in other contexts, the use of data dictionaries aligned with EN ISO 23386/23387 demonstrates that generalisation is viable, with scalability and adaptation achievable through the systematic mapping of new scenarios onto open, standardised services such as the buildingSMART Data Dictionary. However, as no assessment was conducted beyond this project, broader generalisation cannot yet be guaranteed.

Despite its achievements, several constraints affect research maturity and scalability, with the short four-month collaboration limiting further refinement, particularly regarding:

- Data-to-BIM algorithms performance: processing large laser-scan datasets required point-cloud segmentation and additional coordination effort, resulting in accurate but discontinuous BIM models.
- Incomplete as-is modelling automation: transitions between modeling steps (e.g. from point-cloud selection to surface generation and BIM object instantiation) still require user intervention, and key tunnel elements, like rail-sleeper systems, ballast, portals, catenaries, niches, and surrounding terrain, are mostly manually modelled, increasing effort, error proneness, and dependence on user expertise in both modelling and programming environments.
- Tool dependency: Reliance on specific software (e.g., Revit/Dynamo) restricts accessibility and broader application, requiring adoption and familiarization with these tools.

- Lack of validation: No quantitative assessment (e.g., processing time, accuracy, or cost-benefit) or user evaluation was conducted, leaving practical effectiveness only partially verified.

Future work will address these limitations, focusing on:

- Improving algorithm efficiency, scalability, and robustness to handle large datasets without segmentation/discontinuities.
- Expanding automation to cover a wider range of tunnel elements.
- Extending compatibility to additional tools and IFC standards to broaden accessibility and interoperability.
- Enriching models with asset management data such as warranties, manufacturer details, acquisition dates, and costs.
- Conducting structured end-user evaluations and benchmarking against traditional methods to measure performance in terms of accuracy, processing time, and cost-benefit.

9. Conclusions

This research demonstrates the development and application of a data-to-BIM workflow to enhance railway tunnel structural monitoring and maintenance for *Infraestruturas de Portugal* (IP). A methodology was implemented to improve lifecycle coordination, visualisation, and maintenance planning, integrating inspection data into BIM and creating a digital platform hosting structured, data-rich 3D tunnel models.

The approach highlights digital twining potential for real-time, data-driven maintenance and informed decision-making, combining algorithmic as-is modelling, standardised PDTs, multi-source data integration, real-time updates, and lifecycle maintenance within a unified BIM environment. While developed for IP, adaptation to other tunnels is possible, though tool dependencies and context-specific standards may require adjustments.

Practical implications include the timely detection of structural issues, automatic classification of inspection data, and intuitive visualisation of tunnel conditions. The framework supports phased digital twin implementation, enabling models to reflect anomalies and interventions at varying levels of geometric and informational detail, while ensuring consistency and interoperability.

Research contributions include guidelines for systematising tunnel data, standardised PDTs and BIM object classes, algorithmic strategies for digital twinning, and a collaborative BIM-based platform for lifecycle maintenance. These enhance model consistency, data integration, and operational coordination, supporting scalable solutions for other infrastructure assets.

Among the research limitations are the data-to-BIM algorithms limited performance, the incomplete as-is modelling automation, tool dependency and need for specialised skills, and absence of quantitative evaluation metrics.

Future work will focus on improving algorithm efficiency, automating additional tunnel elements, expanding platform compatibility, enriching asset data, and conducting structured evaluations to quantify performance, usability, and operational impact.

Acknowledgements

This study is a part of the I&DT project in co-promotion with companies ''RoboShot@FRC - Robotized system for the shotcrete of optimized fibre reinforced concrete in railway tunnels'', Co-promotion project number 47075, call 17/SI/2019. It was co-funded by the PRR - Recovery and Resilience Plan and the European Union - www.recuperarportugal.gov.pt (PRR - Investment RE-C05-i02: Interface Mission - CoLAB) and financially supported by national funds of *Fundação para a Ciência e a Tecnologia, I.P.* (FCT) under projects UID/50021/2025 (DOI: https://doi.org/10.54499/UID/50021/2025) and UID/PRR/50021/2025 (DOI: https://doi.org/10.54499/UID/PRR/50021/2025) under the INESC ID – *Instituto de Engenharia de Sistemas e Computadores: Investigação e Desenvolvimento*; UIDB/04708/2020 (DOI:10.54499/UIDB/04708/2020) under the CONSTRUCT - *Instituto de I&D em Estruturas e Construções*; UID/04029/2025 (https://doi.org/10.54499/UID/04029/2025) and UID/PRR/04029/2025 (https://doi.org/10.54499/UID/PRR/04029/2025) under the R&D Unit Institute for Sustainability and Innovation in Structural Engineering (ISISE); and LA/P/0112/2020 under the Associate Laboratory Advanced Production and Intelligent Systems ARISE. It was also financed by national funds through FCT and Massachusetts Institute of Technology - MIT-Portugal Program under grant agreement MPP2030-FCT-2022 attributed to the 8th author. The financial aid of the project REV@Construction is also gratefully acknowledged.

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