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# Integrated workflow with mobile mapping survey and BIM approach to digitalize subway infrastructures

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**Abstract**

The planning and management of underground public transport is a central challenge for industrialized countries. Since an increasing number of human activities is polarized in metropolitan areas, the effort put into the digitalization for management of the underground lifelines is growing. This paper presents an innovative methodology (SCANtoBIM) to carry out digitization, inspection, and diagnostics of existing underground tunnels to obtain a digital model without disruptions. The multi-dimensional survey system (ARCHITA) allows for collecting data about the tunnel geometry, structural, and functional conditions. Data digitalization and analysis give as-built CAD models and Building Information Models (BIMs). Within the framework of the Management and Identification of the Risk for Existing Tunnels, the proposed process helps the infrastructure manager during the facility service life. The workflow for the digitalization and diagnosis from mobile mapping data has been implemented to obtain a BIM model representing more than 40 km-long metro tunnels.

*Keywords:* Building Information Modeling; digital twin; Scan-to-BIM; Mobile Mapping; subway; tunnel.

## 1. Introduction

Urban transportation systems play a pivotal role in commercial, emergency (e.g., pandemic breakout, climate changes), and touristic purposes (Corazza et al., 2021; Moretti and Loprencipe, 2018). Modern society cannot give up the public transportation advantages that interest 4 main topics (Beirão and Sarsfield Cabral, 2007):

- air pollution: less fuel burned means better air quality for cities that integrate public transit (Titos et al., 2015);

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- road congestion: the more people travel on public transport systems, the fewer private vehicles cause traffic externalities on urban roads (Beaudoin et al., 2017);
- direct and indirect costs: public transport is cheaper than private transport (Lunke et al., 2021);
- safety: statistical data demonstrate that the most dangerous vehicles are private ones (e.g., motorcycles and cars) (Friman et al., 2020).

In metropolitan areas, the “nucleated dispersion” led to new suburban centres being connected by public transport systems: underground services meet the needs of polycentric metropolises and satisfy the modern sustainable mobility trends (Galiano et al., 2021). High standards of efficiency and safety should be maintained: to achieve this goal digital tools to manage infrastructure are essential. They are compliant with the Italian standard UNI 10838 (Ente Nazionale Normazione, 1999) about programming, design, implementation, and management of plants. Therefore, this approach leads to Building Information Modeling (BIM), a complex system of procedures and technologies to manage building processes (Cheng et al., 2016). Earlier approaches to BIM mainly focused on the advantages in the design phase; recently the applications took into account economic and environmental benefits and burdens during the exercise and management phases of the civil works (D’Amico et al., 2020). BIM could summarize geometrical information, time-related data, cost analysis, environmental analyses, and maintenance information (Biancardo et al., 2021). The works are represented by digital formats through object-based modeling and information is shared during the overall facility service life: “intelligent” objects containing detailed information are modifying the construction process (Wu et al., 2019). BIM covers different sectors of the construction industry: the interoperability of models and generated data requires specialized software to facilitate the exchange and sharing of data (Turk, 2020). For this purpose, buildingSMART developed the Industry Foundation Classes (IFC) system (Plume and Mitchell, 2007): it permits standardizing the modeling of construction works (Marmo et al., 2020). Many researchers proposed specific schemes for infrastructures (Biancardo et al., 2020); buildingSMART has set up many projects (e.g, OpenInfra) to obtain models for infrastructures based on the IFC system (Kolli et al., 2018). However, the use of BIM in infrastructure, sometimes called I-BIM (Infrastructure - Building Information Modeling), is not as widespread although its use could be strategic (Abbondati et al., 2020). Cho et al. (2012) proposed a holistic BIM library system to manage geometric data, properties, and information related to the efficiency of calculations in tunnel excavation. Yabuki (2010) dealt with methods to implement BIM in the transport infrastructure sector.

The application of digital twins to railways is more complex than to other transport infrastructures due to the heterogeneity of the components to be modeled (Cantisani et al., 2022; Leone et al., 2017): architectural and structural systems, line MEP (street, bridges, and tunnels) (Bensalah et al., 2019). So far, no specific standards have been proposed for railway works. However, the railway components cannot be represented using the models to date available: in the literature, some studies tried to implement BIM in tunnels. Yabuki (2008) and Yabuki et al. (2013) developed a tunnel model compliant with the IFC scheme. Borrmann and Jubierre (2013) proposed a method to generate multi-scale models; Borrmann et al. (2017) worked on the integration of the IFC-based multi-scale model and a CityGML (Kolbe, 2009) model. Digital twin models of tunnels, as for other lifelines, are structured by constraining semantic and geometric information to the axis line: based on the IFC standard, Amann et al. (2017) proposed a model that supports data from axis line models and tunnel excavation models.

This paper presents a methodology to carry out digitization, inspection, and diagnostics of underground transport systems to obtain a digital model of the work. It aims to fill and implement the information of the as-built model through a process called SCANtoBIM (Fantini, 2017; Justo et al., 2021). Reality-based information defines a BIM model to be used by the infrastructure manager during the facility service life. To achieve this goal, the authors defined a BIM model to represent and manage the entire subway along more than 40 km-long metro tunnels. The proposed process SCANtoBIM shall be integrated into the Management and Identification of the Risk for Existing Tunnels (MIRET) platform to process survey-inspection data. In the MIRET approach, the ARCHITA phases can be repeated to update data through different time steps.

## 2. Data and methods

The process SCANtoBIM allows inspection, digitalization, and diagnosis of infrastructures and underground transport in six steps (Figure 1):

- STEP 0: *Survey & Inspection (S&I)* with a multi-dimensional mobile mapping system (ARCHITA) to carry out a non-destructive investigation technique. It allows for collecting data from on-site surveys (e.g. point clouds, thermal and HD images) about the tunnel geometry, structural, and functional conditions. Pegasus Manager allows obtaining the point cloud (Leica Pegasus:Manager, 2022);
- STEP 1: *Digitalization (DI)* of the geometric survey to obtain a three-dimensional (3D) CAD or IFC model using the software AutoCAD (Autodesk, 2022), GEDO Scan Office 2.0 (Software Trimble GEDO Office, 2022), and 3DReshaper (3DReshaper Accueil, 2022);
- STEP 2: *Defect Analysis (DA)* from high-definition linear photos and thermal photos to map and digitalize the defects in a CAD environment. Defects are identified, catalogued, and validated through the processing software Tunnel Review. Data processing of linear and thermal images allows a statistical analysis of the observed defects and the assessment of objective indexes;
- STEP 3: *Data processing* (*GP*) allows reconstruction of the overall environment using all data from the previous steps and the software CIVIL 3D (Autodesk, 2022);
- STEP 4: *Drawings* (*DW*) gives technical documents representing the three-dimensional CAD environment using the software CIVIL 3D (Autodesk, 2022). The obtained model contains all the information about the layout (e.g., plan, elevation, cross-section, boundary shape, and technical documents);
- STEP 5: *Processing of the BIM model* (*PB*) is the final step of the proposed process: the BIM model is reached as soon as its elements are turned into IFC objects because they have an open format. In this step the software CIVIL 3D, Revit (Autodesk, 2022), and Solibri (Solibri, 2022) are used.

All the steps depend on ARCHITA, a multi-dimensional mobile mapping system consisting of (Figure 1) survey sensors (i.e., laser scanner to acquire a 3D point cloud; linear cameras to take high-resolution photos of the tunnel lining, detecting the components and their condition; thermal cameras to detect and double-check defects on the lining; ground penetrating radars (GPRs) to survey the ballast thickness, condition and humidity, the lining thickness, and the void between soil and lining) and positioning sensors (i.e., Global Positioning System (GPS), Inertial Measurement Unit (IMU), and odometer).

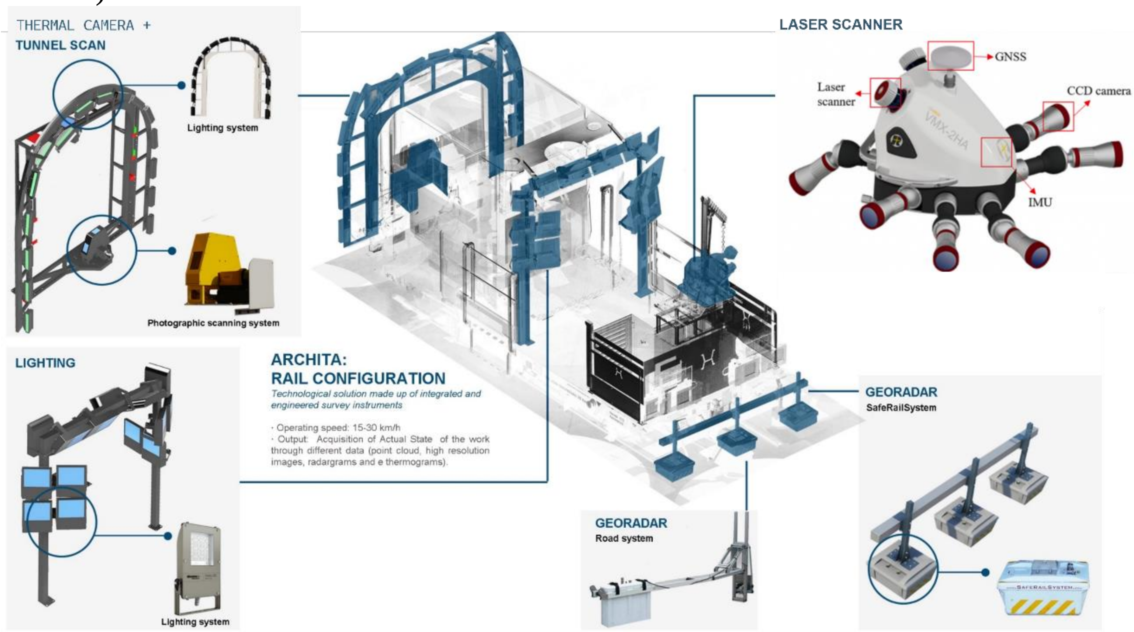


Figure 1: ARCHITA configuration.

ARCHITA uses the GNSS+IMU sensors to calculate the travel trajectory in a predefined reference system: the precision of the system depends on the positioning precision of the GNSS system. ARCHITA moves at 15-30 km/h, minimizing the impact on existing lines with shortstop of the traffic and without disconnection of the railway electrical tension. All the tools are integrated and connected to digitalize the collected data. ARCHITA is equipped with:

- Laser Scanner (Leica Pegasus:Two), in configuration with 8 digital cameras, 1 IMU inertial platform, 2 profilers, 2 GPS antennas, 1 optical odometer, and 4 thermal imaging cameras. The two profilers, arranged at 30° and 60° to the axis of the binary track, allow a reduction of the “shadows”;
- Ground Penetrating Radar with 3 radar antennas having 400 MHz central frequency;
- Ground Penetrating Radar with 1 radar antenna having 600 MHz central frequency;
- 3 high-resolution linear cameras, 1 profiler Z + F 9012, and a lighting system composed of 16 LED lights, on a steel structure aligned with the cameras.

Data from the geometric survey are used to obtain a 3D CAD model or IFC model. Given the point cloud, GEDO Scan Office 2.0 (2022) returns 3D polylines of the railway track (Software Trimble GEDO Office, 2022) and the 3D Reshaper software (3DReshaper Accueil, 2022) returns mesh from the point cloud and 3D polylines from the elements along the investigated underground line. The defect identification required a defect library to be used: an ad hoc library has been implemented considering the heterogeneity of construction methods and technologies throughout the metro history. The defined defect categories depend on the lining material: for masonry lining, longitudinal crack, transversal crack, diagonals crack, cracks network, wet surface and leakages, loss of material in the joints, detachment, deformation, moss/plants presence, and efflorescence; for concrete lining, longitudinal crack, transversal crack, diagonals crack, cracks network, wet surface and leakage, detachment, deterioration, pop-out, corrosion and exposure of rebars.

In the third step, CAD software allows surface identification and modelers creation to obtain the geometrical output. The level of geometries (LOG), details (LOD), and information (LOI) are established according to the study and/or the design phase. In the GP step, the digital twin and the defects detection are combined in a Common Data Environment (CDE) that is propaedeutic for the BIM model. The drawing phase allows obtaining tracking of tracks, line plan, line profiles, and cross-sections with and without the loading gauge (Loprencipe et al., 2018). Finally, the step of BIM processing gives a 3D solid creation to obtain the IFC model of the tunnels. The geometric model is integrated with the images from the Tunnel Scan system consisting of 3 high-resolution linear cameras. The instrument allows the acquisition of high-resolution images to carry out a precise and repeatable analysis of the condition of the investigated infrastructure (Di Mascio et al., 2014).

The thermal imaging cameras used in SCANtoBIM are integrated with the mobile survey system Leica Pegasus:Two. They are 4 thermographic cameras with 640x512 pixel resolution each and lenses that offer a 90° x 70° field of view. The combination of the 4 cameras allows a full 360° ring to cover the entire image of the tunnel surface. Each thermal camera has a 70° amplitude to have enough coverage between sets of consecutive images.

## 3. Results and discussion

In this study, ARCHITA surveyed two metro lines. The STEP 0 of SCANtoBIM permitted to obtain the point cloud in .las format, high-resolution images, and thermal images. In STEP 1 (digitalization) GEDO Scan Office 2.0 and 3D Reshaper allowed processing of the point cloud (Figure 2 to 4) and extracting a sequence of sections, with a pitch of 9 m in straight and 3 m in curves to improve and optimize the information (Figure 5).

Figure 2: Point Cloud of metro line processed in 3DReshaper.

Figure 3: Point Cloud of Metro Station in 3DReshaper.

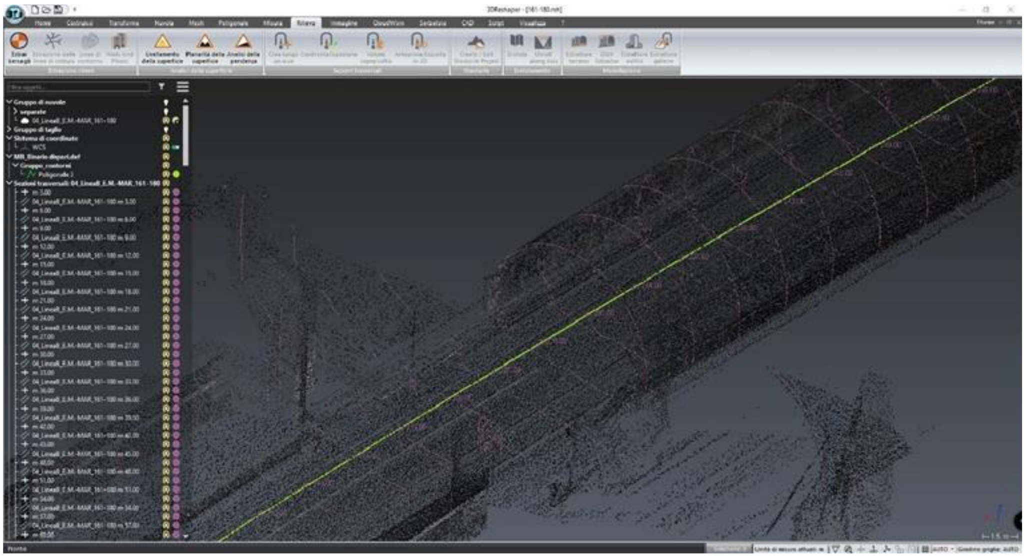

Figure 4: Point Cloud of the metro line in 3DReshaper.

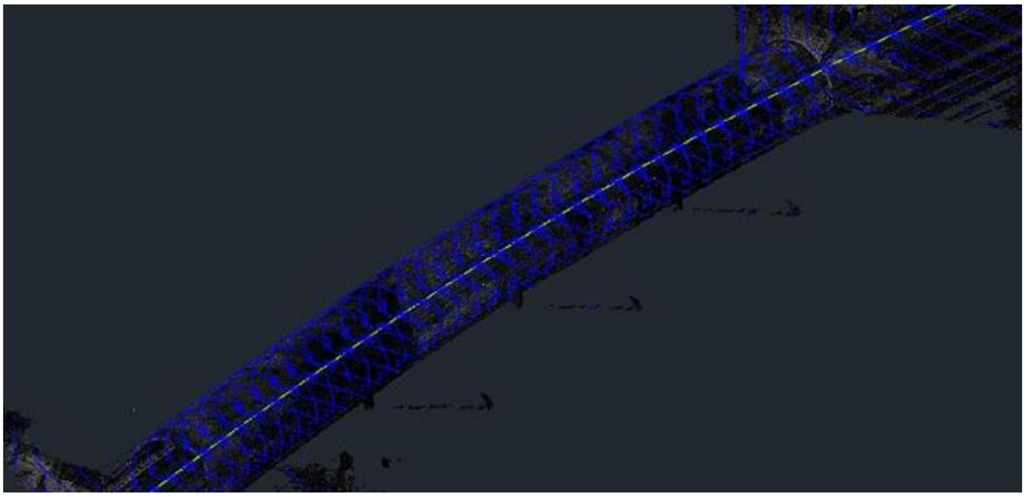

Figure 5: Progressive sections on the point cloud in 3DReshaper.

Moreover, the high-resolution photographic survey from Tunnel Scan was used to identify lining defects. Their detection is downstream of data processing which allows overlapping of the geometry of the tunnel from the integrated laser scanner on the images from the linear cameras. Such images have a longitudinal resolution greater than 1 mm and a transversal resolution greater than 1 mm.

During the post-processing phase, the acquired data are referred to the real progressive of the railway line, thus allowing a precise location of the detected defects (Figure 6). For each defect, its location, areal or linear development, and category have been recorded according to the defined defect library.

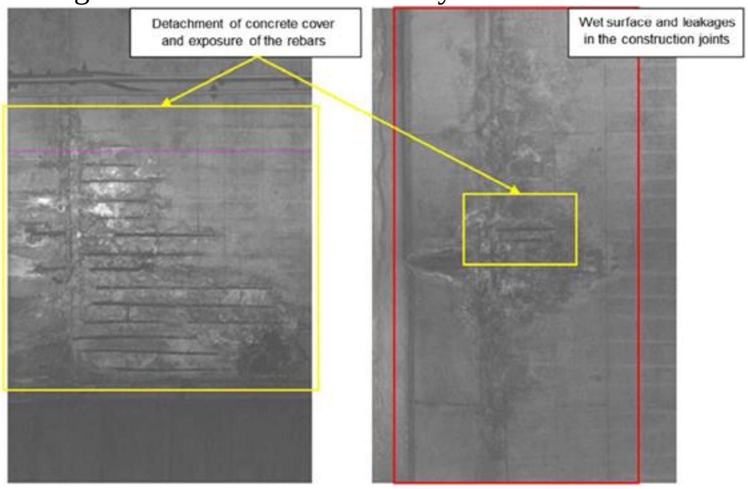


Figure 6: Example of defects: Detachment of concrete cover and exposure of the rebars (yellow) and Wet surface and leakages in the construction joints (red).

The georeferenced digital radiometric images from the thermographic survey (Loprencipe et al., 2018) were directly synchronized with the cloud of points obtained from the laser scanner. High-resolution linear images and thermal images allowed evaluation of the tunnel condition and digitalization of its defects (Figure 7 and Figure 8).

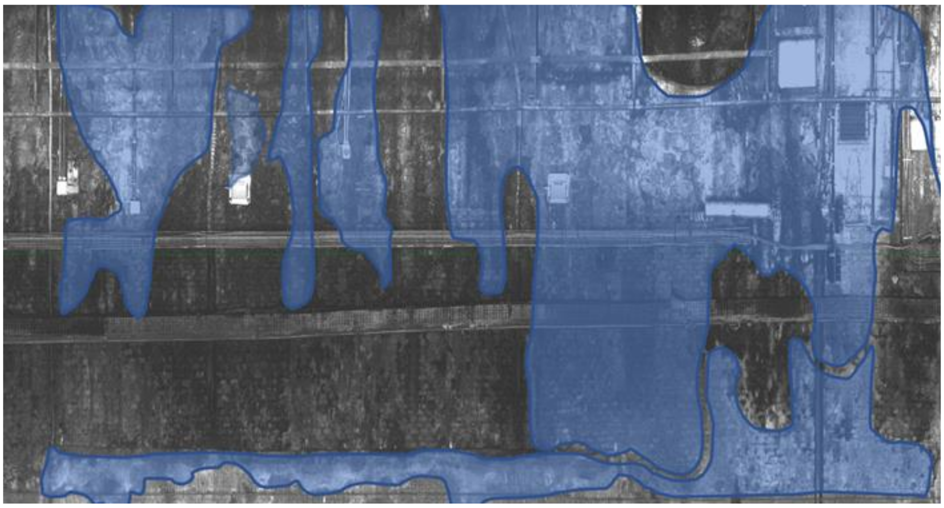

Figure 7: Detected water defects (blue area).

Figure 8 a and b compare HD-resolution and thermal images for defect detection: the blue areas in the thermal image match the areas in the HD image where water defects have been identified. Thermal surface temperatures in Figure 8b range between 9 °C (blue color) and 20 °C (red color).

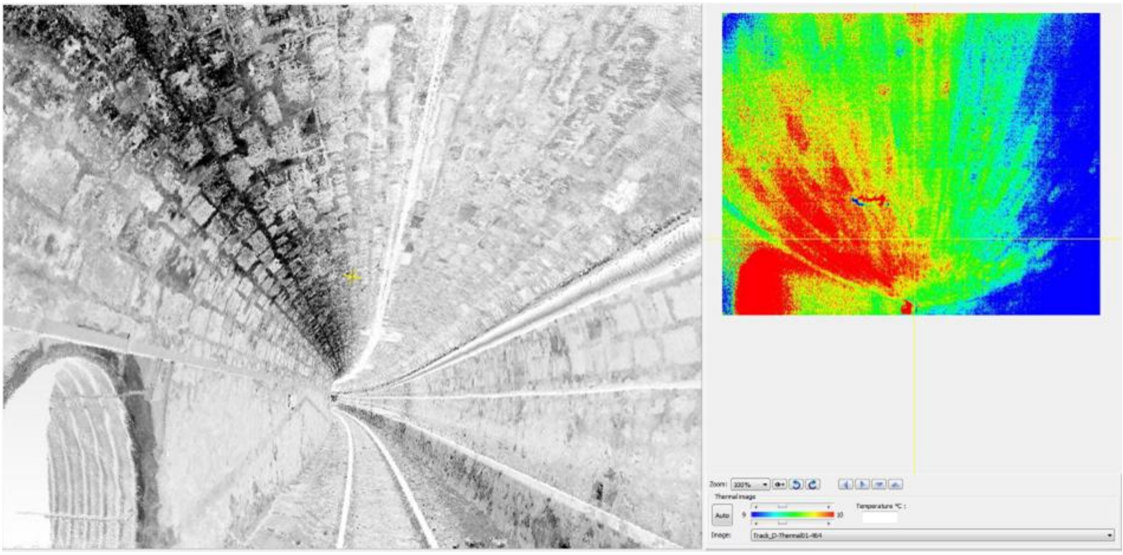

Figure 8: Comparison of a) HD-resolution images and b) thermal images for defect detection.

For each tunnel, graphical drawings and summary tables provided the defects mapping (Figure 9). The tunnel lining is represented with details about the progressive, the track position (i.e., even or odd), and its elements (e.g., piers and cap). All defects are divided into categories and other significant elements or previous works on the tunnel lining are pointed out (e.g., ribs, sealing, and painting).

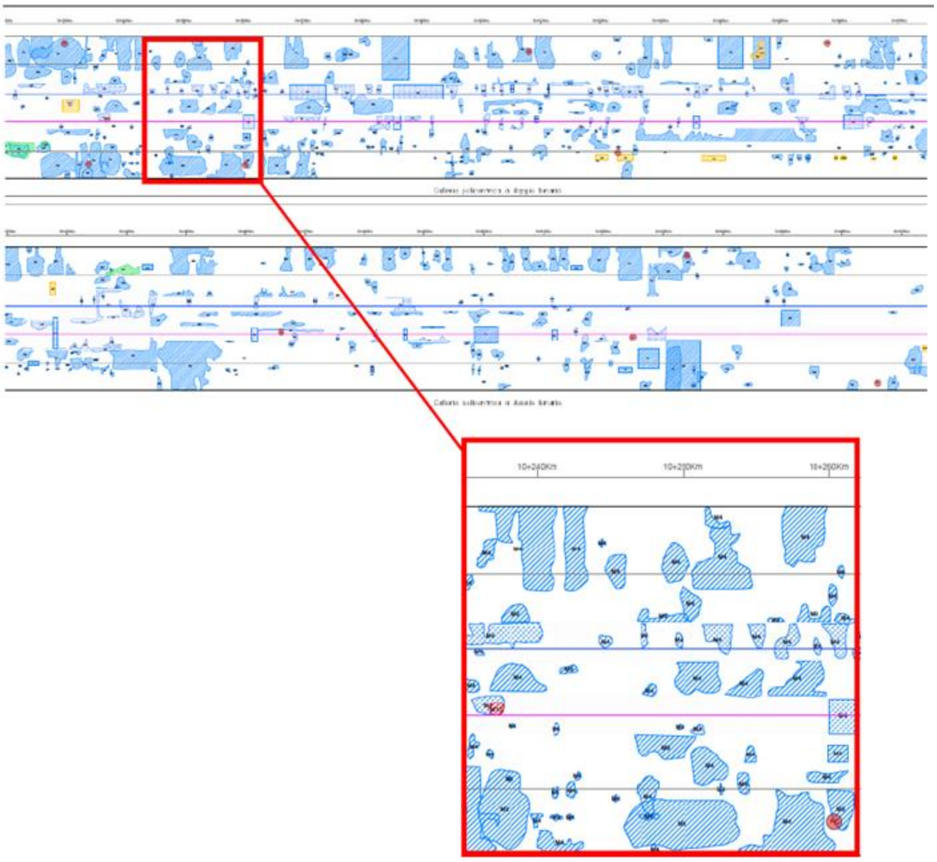

Figure 9: Example Defect Map.

The software Civil 3D, GEDO Scan Office 2.0, and 3DReshaper allowed digitalization of the overall geometry of the infrastructure including rail and fastenings (i.e., sleepers), tunnel lining, station structure, platforms, and walkways (Figures 10 to 12).

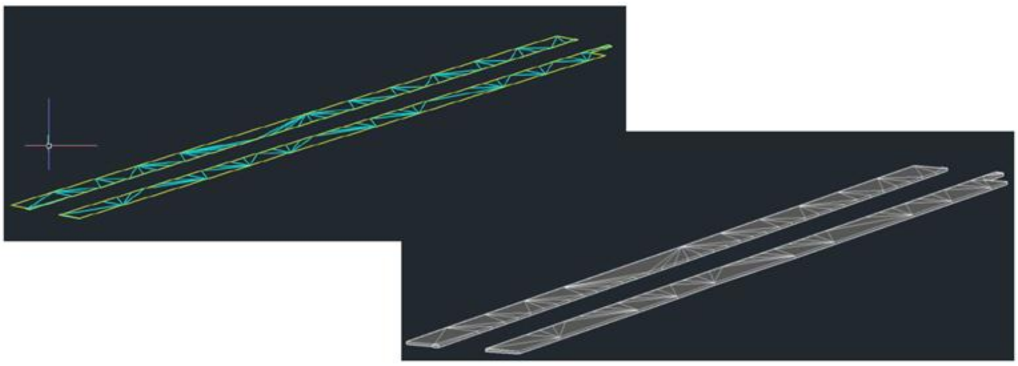

Figure 10: Surface and 3D solid of the platform obtained in Civil 3D.

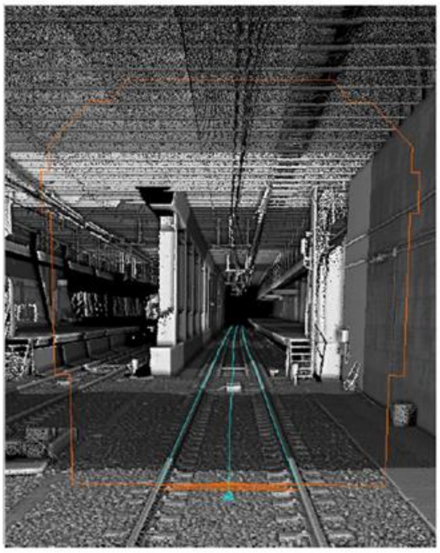

Figure 11: Overlay of the design gauge on a cross-section in 3DReshaper.

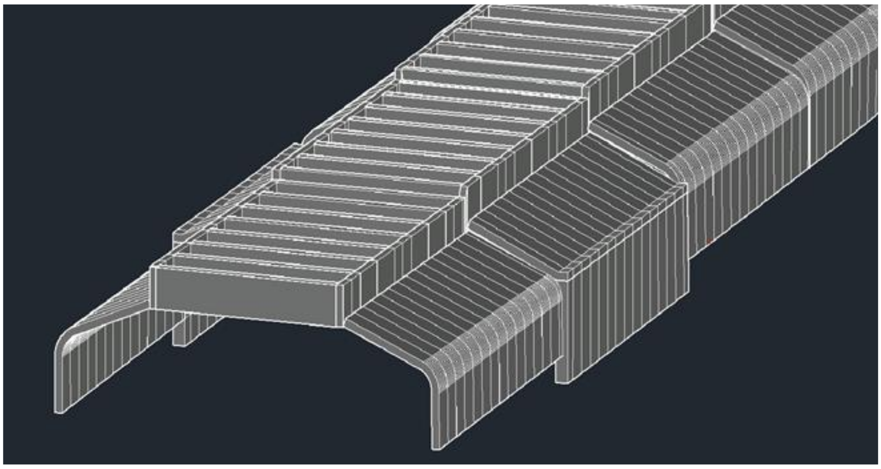

Figure 12: Solid 3D extracted in Civil 3D.

Given the extracted 3D solid (Figure 12), horizontal and vertical alignment, and tunnel cross-sections have been reconstructed (Figure 13).

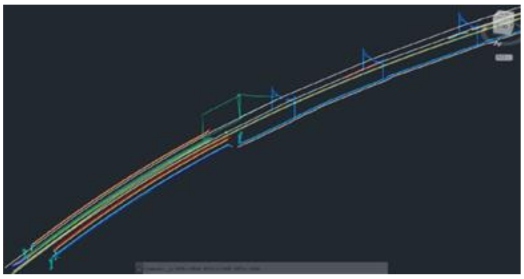

Figure 13: Solid 3D extracted in Civil 3D.

In the last phase, all the obtained information was collected in a single 3D model by REVIT. In this study, two different parameter groups were defined based on the available information: Family Parameters and Shared Parameters. They permitted to store and communicate current and future data to manage the infrastructure. Family parameters are specific to the project and therefore cannot be shared externally; shared parameters can be used in multiple families and projects, and are stored on .txt text files. Figure 14 shows an example of the defined parametric elements: rails, coupling elements, sleepers, shelters, coverings, quays, piers, and ballast.

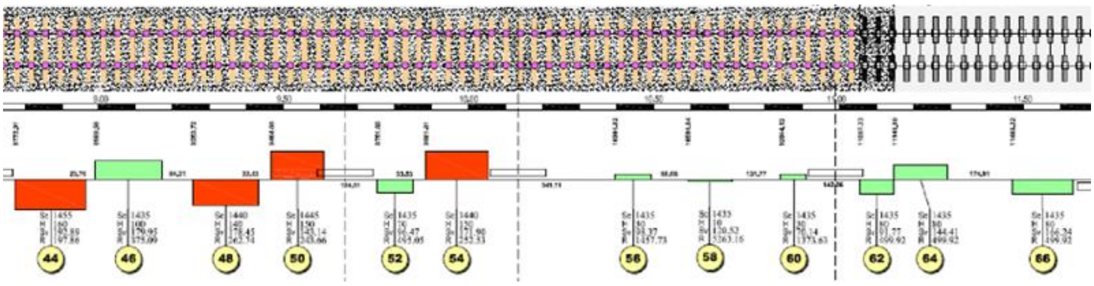

Figure 14: Scheme of the railway superstructure.

In this digital twin model, three projects were distinguished:

- switches and crossings (i.e., tracks, sleepers, ballasts, and coupling elements) (example of tracks in Figure 15);
- civil works (i.e., beams, cladding, shelters, docks, and quays);
- systems (i.e., cable ducts, ventilation pipes, and electric traction).

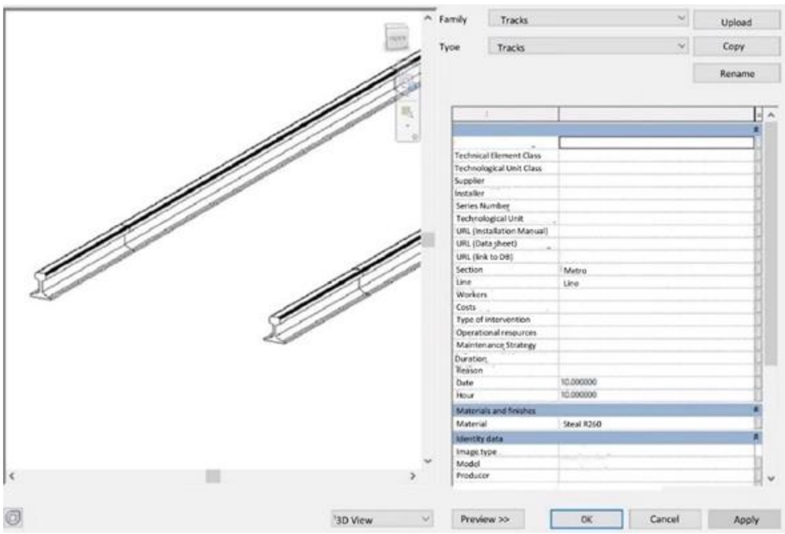


Figure 15: Tracks properties (switches and crossings).

For each line section, an abacus (Table 1) provided information about the family, material, model, producer, and quantity (imported from the bill of quantity) of the elements. Such information can be updated in real-time. Using the abacus, it is possible to display data of the surveyed line in tabular format, which can be exported in a .xls file.

Table 1: Station abacus.

| *Section* | *Family* | *Material* | *Model* | *Quantity* | *Producer* |
|---|---|---|---|---|---|
| 1 | Beams_transverse | Concrete | 30x150 | 349.35 $m^2$ | Civil works producer |
| 2 | Beams_longitudinal | Concrete | 30x151 | 131.01 $m^2$ | Civil works producer |
| 3 | Piers | Concrete | | 744.18 $m^2$ | Civil works producer |
| 4 | Docks | Concrete | | 415.12 $m^2$ | Civil works producer |
| 5 | Ballast | Crushed stone | | 240.84 $m^2$ | Ballast producer |
| 6 | Organs | Q235 | Vossioh SKL 12 | 5.55 $m^2$ | Organs producer |
| | Crossbar | Oak wood | 250x25x15 | 156.29 $m^2$ | Crossbar producer |
| 7 | Tracks | Steel R260 | 50ES (UNI50) | 4.15 $m^2$ | Tracks producer |
| 8 | Channel_Blue | PVC | Cable tray 30x7 | 3.24 $m^2$ | System producer |
| 9 | Channel_Skyblue | PVC | Cable tray 40x10 | 6.13 $m^2$ | System producer |
| 10 | Channel_Red | PVC | Cable tray 20x10 | 4.31 $m^2$ | System producer |
| 11 | Channel_Yellow | PVC | Cable tray 70x40 | 4.30 $m^2$ | System producer |
| 12 | Channle_Purple | PVC | Cable tray 30x10 | 4.67 $m^2$ | System producer |
| 13 | Channle_Pink | PVC | Cable tray 40x7 | 4.32 $m^2$ | System producer |

Finally, the BIM model was turned into IFC objects to take into account both geometry and attributes. However, the IFC format does not preserve the concept of a set of component parameters, or Revit families. Indeed, after export properties and values are retained (exported) but they shall not affect geometry. The reliability of this format is a critical issue for digital twin models: it has been widely used in construction works and industry, but some difficulties are in the infrastructure sector. Therefore, the IFC standard shall be used to develop infrastructure elements through construction components (e.g., IfcColumn for bridge piers, or IfcWall for road safety barriers). However, the IFC scheme currently in use (i.e., IFC4) implies difficulties because the semantic information and functions of building elements do not match those of infrastructures. Each type of infrastructure needs a "data scheme" to represent in a standardized way the component-based information and ensure interoperability. The extension of IFC Alignment has been added in the preliminary version of IFC4x1, and IFC5 to introduce IFC extensions for roads, bridges, and tunnels. In this study the authors used the software Solibri (Solibri, 2022) to import data from Revit (Autodesk, 2022): Figure 16 and Figure 17 show the final model imported in Solibri: in Figure 17 all the colored elements above and below the platform are wireways. They have different colors because they have different functions within the infrastructure; purple elements with a brown background are tracks. In Figure 17 grey elements are the wireways and purple elements with a brown background are the tracks.

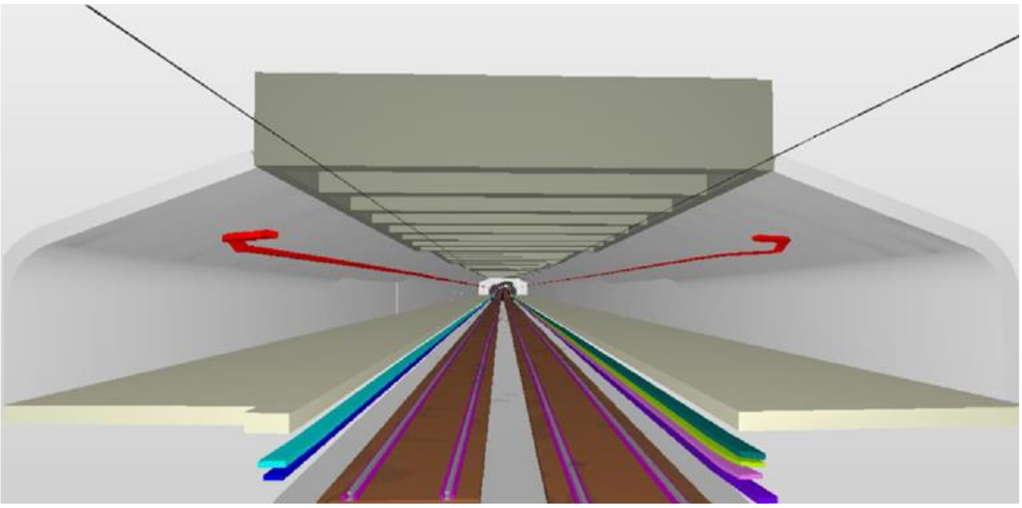

Figure 16: 3D model of a station on Solibri.

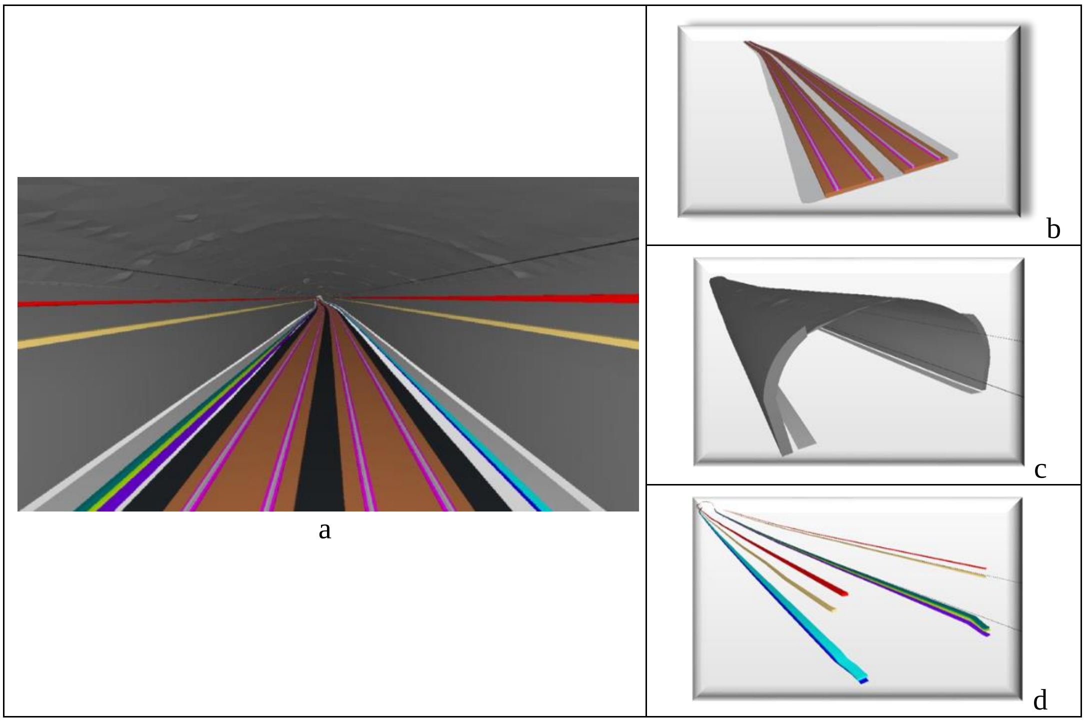


Figure 17: 3D model of a tunnel track on Solibri; a) overall model; b) rails, fasteners, and sleepers; c) civil works; d) lifelines and systems.

## 4. Conclusions

Transport infrastructures are large-scale works that require the investment of huge capital and complex relationships between stakeholders. For this reason, it is necessary to manage them in an integrated way. Underground infrastructures are a major transport system that ensures public transport sustainability balancing the often-conflicting objectives of stakeholders. Multidimensional information should be considered to manage a facility during its service life to optimize geometric, operational, environmental, and economic variables that affect the examined scenario. In general, today all information regarding existing infrastructures is often fragmented and incongruent due to traditional methods of data collection and management. According to European regulations, several dimensions should be considered to manage a facility. Consequently, to optimize the management plans of existing subway lines a multidimensional mobile mapping is proposed and implemented in this study. The SCANtoBIM innovative methodology starts from survey and inspection activities along a tunnel to collect geometrical and functional data using a laser scanner, linear and thermal cameras. The point cloud from the geometric survey permits to obtain a 3D CAD model, while the images permit to map and digitalize defects in the tunnel lining. The equipment ARCHITA ensures automation and process repeatability of the process to monitor over time the infrastructure condition and schedule maintenance works. The digital twin and its detected defects form a common data environment: the BIM model contributes to optimize the management process.

The potential of the proposed methodology relies on the objective and comparable data that are obtained by full automatic Scan-to-BIM procedures. The results contribute to the integrated platform to manage and identify critical conditions in existing or new tunnels. In the examined case study, the digitalization of the subway infrastructure gave a final model in Solibri that is useful for managing the lifeline. The model is a huge and organized archive of data relevant to the infrastructure: its large investment in both time and resources is balanced by its efficiency to improve decision-making processes during the entire life cycle of the construction. Further research should focus on the integration and recognition of defects and objects. Moreover, the integration of the entire process in the BIM environment and IFC format is not automatic, but it is necessary to extend the potential of BIM to tunnel infrastructures.

BIM models are useful to manage construction and maintenance works: during operation, the twin digital is ready for new S&I phases to update the condition indexes. Monitoring allows a dynamic database and assessment of the structures to identify the best option from different perspectives. Operational, economic, and environmental outputs highlight the need for a multidisciplinary study, to balance the often-conflicting objectives of tunnel managers, users, and citizens. The results allow a more objective and dynamic diagnostic, maintenance and risk assessment to manage existing tunnels.

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