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Innovative pavement safety assessment through integrated BIM and AR visualization

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Effective management and maintenance of pavement structures require accurate and comprehensive information on both surface and subsurface conditions to prevent risks of structural collapse. Recent advances in technologies, such as Ground Penetrating Radar (GPR) and Structural Health Monitoring (SHM), combined with Building Information Modelling (BIM), provide new opportunities to gather, integrate, and analyze all these data. The use of these leading approaches allows engineers to make informed decisions throughout the lifecycle of structures, improving efficiency, sustainability, and data-driven asset management, while also enhancing safety and reliability assessment of pavements. This contribution presents an innovative approach for the advanced documentation and deterioration assessment of a flexible pavement structure. A Trace-to-IFC methodology was employed to represent asphalt layer thickness using GPR and TLS (Terrestrial Laser Scanning) data in BIM environments, the OpenBIM IFC (Industry Foundation Classes) standard was adopted to ensure interoperability and data exchange. Then, IFC-BIM models were exported to KMZ and FBX formats respectively, allowing visualization of all integrated data through Augmented Reality (AR) devices, thus enabling real-time visualization of the models and semantic information such as layer thickness. This AR-based representation offers a complementary view to the demonstrated significant value as a decision-making tool for the maintenance and rehabilitation of pavements by retaining both geometric and semantic information across different BIM and GIS (Geographic Information System) platforms.

Keywords: Building Information Modelling, Augmented Reality, IFC, visualization tool, Pavement Management System.

1. Introduction

Road safety is a major global concern that largely depends on the condition and quality of pavements. Well-designed and properly maintained pavements not only protect the lives of road users but also facilitate efficient maintenance management. The deterioration of pavement conditions in urban areas can result from flooding caused by inadequate stormwater drainage systems, malfunctioning subsurface drainage, or the formation of surface cracks due to excessive axle loads, among other factors (Kamal and Bas 2021).

These surface defects, such as cracks and potholes, represent a significant cause of traffic accidents, as they reduce tire-pavement friction or induce dangerous deviations in vehicle trajectory, potentially leading to loss of control (Bella et al.

2012). Implementation of an effective Pavement Management System (PMS) that integrates both surface and subsurface information prevents structural failures and enables efficient maintenance planning.

The integration of non-destructive testing (NDT) techniques into Building Information Modelling (BIM) environments has emerged as a promising approach for managing large datasets from pavement inspections (D'Amico et al. 2022). Innovative NDT technologies such as Ground Penetrating Radar (GPR) allow mapping of subsurface characteristics using electromagnetic waves, providing high-precision, real-time information without excavation (Fernandes and Pais 2017; Elseicy et al. 2022; Lahouar and Al-Qadi 2008).

Applying BIM methodology to road infrastructure enables detailed representation of pavement structures and ensures interoperability through open standards such as Industry Foundation Classes (IFC) (Hadjar et al. 2025; Arif E Bakhtiar et al. 2025). Methods such as Trace-to-IFC (Solla et al. 2025) allow modelling of asphalt layers using data from GPR and Terrestrial Laser Scanning (TLS). The OpenBIM IFC standard provides an open and structured framework for the digital representation of construction and infrastructure projects, supporting detailed descriptions of horizontal infrastructure elements by incorporating geometric, material, and functional information for each component. The release of IFC 4.3 introduced specific entities that facilitate precise documentation of pavements and related structures, enhancing multidisciplinary collaboration (Bellon et al. 2025; Ait-Lamallam et al. 2021; Galasso et al. 2025). Furthermore, this standard promotes data consistency and integrity, enabling more efficient, sustainable, and information-driven asset management throughout the infrastructure lifecycle.

BIM has become a cornerstone technology in the digital transformation of the construction and infrastructure management sectors. BIM implementation integrates all project information into a single digital model throughout the entire lifecycle, from design and construction to operation and maintenance. This approach fosters interdisciplinary collaboration, optimizes time and resources, and enhances decision-making through national strategies and regulatory frameworks. Spain´s BIM Plan approved in 2023, establishes a roadmap for the progressive implementation of this methodology in public procurement between 2024 and 2030. Similarly, other European countries such as Germany and Finland have introduced policies that encourage their use in public infrastructure projects, supporting a more efficient, transparent and sustainable construction model. BIM models can also be exported to other formats, enabling the visualization of geometric and semantic information through Augmented Reality (AR) devices (Hsieh et al. 2023; Baubriaud et al. 2025; Ic 2025).

AR has become a highly valuable tool in engineering and the Architecture, Engineering, Construction, and Facility Management (AEC-FM) industry due to its ability to overlay digital information onto real-world environments (Moradi and Assaf 2022; May et al. 2022). AR integration with BIM models allows three-dimensional visualization of pavement structures and conditions directly on-site, facilitating the interpretation of data obtained through GPR and TLS. This combination provides an interactive representation that assists field technicians in identifying deterioration areas, verifying layer thicknesses, and planning maintenance operations with greater accuracy. Moreover, the use of smart glasses or AR headsets enables on-site inspections with immediate access to BIM-based information, improving decision-making and reducing errors.

Thus, the combination of GPR, TLS, BIM and AR support advanced documentation and assessment of pavement deterioration while providing effective tools for decision-making during the maintenance and rehabilitation of road infrastructure, aligning with a data-driven asset management approach.

Within this framework, this paper aims to provide a new AR visualization tool for documenting and analyzing pavement structures through the combined use of non-destructive testing data and BIM-based environments.

2. Materials and Methods

2.1. *Pavement Structure and Study Area*

The case study described in this article concerns the urban road adjacent to the Faculty of Forest Engineering at A Xunqueira University Campus in Pontevedra, part of the University of Vigo. The section experiences high levels of heavy traffic and is classified according to Spanish regulations (Ministerio de Transportes y Movilidad Sostenible, n.d.) as category T41, with an average daily traffic volume ranging from 25 to 50 heavy vehicles. The pavement structure consists of two main layers of hot-mix asphalt: a surface layer approximately 4 cm thick and an intermediate layer around 6 cm thick, both engineered to resist traffic-induced stresses and local environmental conditions. Figure 1 shows the exact location of the analyzed section within the university campus. The selected area offers convenient accessibility and exemplifies typical traffic and pavement structure conditions characteristic of urban university environments.

Fig. 1. Pavement location at A Xunqueira (Galicia).

2.2. *Data sources*

The proposed methodology relies on complementary data sources capable of describing both the surface and subsurface pavement structure. The following subsections describe the data acquisition and processing procedures for each method, prior to their integration into the BIM and AR environments.

2.2.1. *Ground Penetrating Radar*

The pavement was surveyed using a ProEx GPR system equipped with 2.3 GHz ground-coupled antennas. Data collection was performed with a trace interval of 2 cm for both antennas, using a total time window of 11 ns (376 samples per trace). Six longitudinal 2D profiles were recorded simultaneously across the road width. The antenna assembly was mounted on a survey cart fitted with an odometer wheel to ensure accurate trace spacing and measure profile lengths. A Stonex S900S RTK GPS was integrated with the GPR system to capture precise geospatial coordinates, allowing correct georeferencing of the acquired point cloud along the roadway.

GPR data processing was conducted with ReflexW software following a standard workflow: time-zero correction, gain adjustment, dewow filtering, background removal, and bandpass filtering. To extract asphalt layer information, the reflections corresponding to surface and intermediate interfaces were firstly identified on the B-scan profiles (Fig. 2). For each horizontal position (trace) the vertical depth was derived using the total time (ns) when the echo was registered and a propagation velocity of 11.5 cm/ns. Next, the resulting data from each profile was exported as ASCII files and then combined with the GPS coordinates into a comma-separated CSV format, producing a georeferenced GPR point cloud suitable for integration into BIM environments.

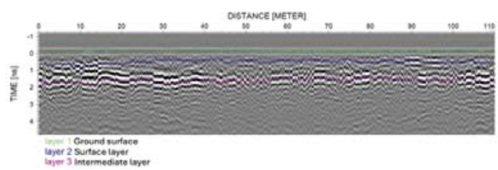

Fig. 2. Interpretation of asphalt layers from GPR data.

2.2.2. *Terrestrial Laser Scanning*

To complement the characterization of the study section, terrestrial laser scanning data were employed, obtained from the National Plan for Aerial Orthophotography (PNOA), a program managed by the Spanish National Geographic Institute that provides precise and up-to-date geospatial information (PNOA, n.d.). The LiDAR point cloud corresponding to the analyzed area was downloaded, offering detailed information on the topography and surface geometry of both the terrain and the road infrastructure. These data allow a reliable representation of the pavement surface and its surroundings, facilitating the evaluation of the road´s planimetry and altimetry.

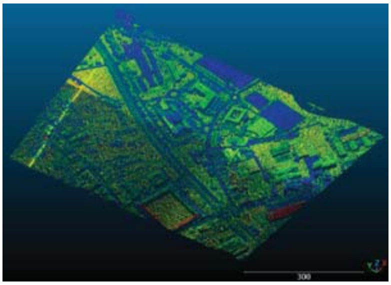

Fig. 3. PNOA LiDAR point cloud.

2.3. *Layer Extraction and BIM modelling*

Once the GPR data and the LiDAR point cloud were obtained, both datasets were integrated with the aim of generating a three-dimensional representation of the pavement structure. This integration process was carried out using Autodesk Civil 3D. First, the LiDAR point cloud was adjusted to match the dimensions of the GPR data, thereby ensuring geometric consistency between both sources. Subsequently, the "Extract Solid from Surface" tool was applied to convert the pavement surfaces into volumetric entities, representing each of the asphalt layers. These solids act as geometric objects that can be reliably transferred between modelling platforms, forming the geometric foundation for the subsequent BIM workflow.

Based on the solids generated in Civil 3D, a detailed BIM model was developed in Autodesk Revit. The imported geometry was enhanced by assigning specific parameters such as material type, layer category, and construction role, resulting in a semantically enriched model. This parametrization allows the model to include not only geometric information but also technical data relevant for future analyses and maintenance tasks. The resulting BIM model constitutes a comprehensive digital representation of the pavement structure, suitable for integration into AR environments through export to KMZ and FBX formats.

2.4. *BIM-AR visualization*

The BIM model, including material and layer information, was visualized directly in Unity using the .fbx format. To complement the 3D geometry, a point cloud representing layer thicknesses at individual locations was integrated, with data loaded from .csv or .txt files containing coordinates and corresponding thickness values. Both the BIM geometry and the point cloud were georeferenced in UTM coordinates and subsequently converted to a local coordinate system using a common reference point, ensuring accurate spatial alignment within the AR environment.

An interactive system was developed to enable the interactive measurement of pavement thicknesses. By pointing at any location in the point cloud with the MRTK Ray Interactor, a raycast detected the target point, and displayed its thickness in real time within the interface (Fig. 4). This immersive setup enables quick and precise inspection of specific points, bridging the gap between detailed digital models and on-site analysis. By combining semantic BIM data with point cloud measurements, the system provides an intuitive and informative AR experience, supporting both visualization and technical assessment of the pavement layers.

The integrated model enables analysis at different spatial scales: globally, through the continuous distribution of thickness values across the pavement, and locally, through point-based measurements that allow the identification of thickness deficiencies compromising the structural integrity of the pavement.

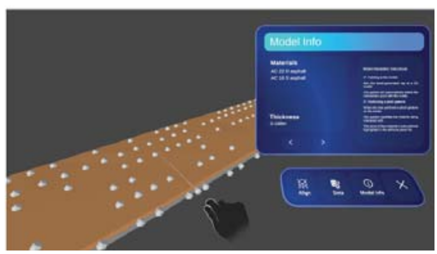

Fig. 4. BIM model in Unity.

2.5. *Interoperability*

Interoperability between different software platforms is a key aspect of the BIM workflow, ensuring that information can be seamlessly exchanged and reused across various tools. The use of the IFC format plays a central role in this process, enabling the transfer of geometric and semantic data between multiple applications. The BIM model can be integrated not only into AR visualization environments but also into platforms such as Infraworks, ArcGIS, Navisworks, Google Earth, and QGIS, using formats like IFC, SHP or KML as needed.

While these capabilities provide flexibility for various analyses and visualizations, this work focuses primarily on on-site AR visualization and the integration with Autodesk Infraworks, which is further detailed in the following results. A workflow diagram (Fig. 5) summarizes the data flow, showing how the BIM model transitions from the original creation to use within AR, as well as its potential visualization in other software platforms. This interoperability ensures that the same digital model can serve multiple purposes, from immersive inspection to broader geospatial analysis, without the need for duplicated modelling efforts.

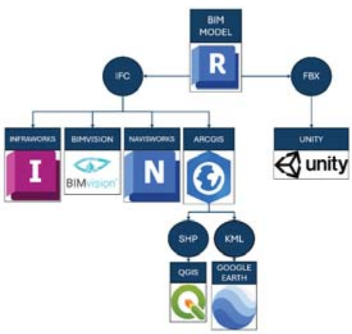

Fig. 5. BIM interoperability workflow.

3. Results and Discussion

The methodology developed in this study enabled the visualization and spatial analysis of the pavement structure through both immersive augmented reality (AR) devices and large-scale geospatial platforms. To provide a quantitative assessment of the proposed workflow, the spatial alignment accuracy between the BIM model and the real environment is supported by previous experimental results reported by the authors (Calvar et al. 2026), where control point measurements were used to evaluate AR spatial accuracy. That study reported deviations on the order of 3 cm during dynamic user movement, which is consistent with typical AR tracking performance and comparable to standard GPR-based pavement assessment practices, usually associated with uncertainties in the range of 2-5 cm. These values should be interpreted considering additional sources of uncertainty related to GPR signal interpretation and georeferencing processes, where RTK-GPS system used has an horizontal precision of 2.5mm+0.1ppm RMS.

The BIM model derived from GPR and TLS data was deployed on-site using Microsoft HoloLens 2 smart glasses, allowing real-time inspection of the pavement layers in their exact physical location. The digital reconstruction, anchored to the roadway surface, remained stable as the user moved along the inspected stretch, enabling an intuitive spatial understanding of the subsurface structure without interrupting traffic or requiring excavation. Through the MRTK Ray Interactor, technicians could select any point in the point cloud and immediately display the corresponding layer thickness, facilitating rapid identification of potential structural inconsistencies. The on-site visualization proved effective for maintenance and inspection tasks, as operators could perceive the relationship between the digital model and real-world pavement conditions in an integrated manner. Figures 6 and 7 present an example of the digital pavement layers superimposed onto their real position in the field through the HoloLens interface.

Fig. 6. AR-based visualization of GPR-derived pavement layer through HoloLens 2.

Fig. 7. AR-based visualization of GPR-derived pavement layers within the roadway context through HoloLens 2.

In addition to AR deployment, the IFC model generated from the integrated dataset was imported into Autodesk InfraWorks to assess interoperability and contextual visualization within a larger geographic environment (Fig. 8). For this purpose, a reference terrain model was created using the same coordinate system as the survey data (ETRS89/ UTM Zone 29N), ensuring initial consistency between platforms. The IFC pavement model was then inserted beneath this reference surface. Since InfraWorks locks imported objects to its geospatial database, the base topographic model cannot be repositioned; therefore, any georeferencing adjustments must be applied directly to the IFC model. During import, a vertical mismatch was observed and corrected by applying a displacement of +2.0 m in the Z direction, consistent with the adjustment previously documented for other datasets. Once corrected, the pavement geometry was accurately visualized within its urban surroundings, enabling detailed examination of the continuity of layers and comparison between the BIM reconstruction and the existing road infrastructure.

Fig. 8. IFC model visualized in InfraWorks.

The results demonstrate that IFC 4.3 provides a reliable framework for the exchange of geometric and semantic information across different software platforms. The integration of data from Civil 3D into Revit and subsequently into InfraWorks preserved both dimensional accuracy and the attribute structure of the pavement model, with only minor systematic positional adjustments required due to differences in how geospatial origins are managed among platforms. When combined with AR deployment, the workflow proves capable of supporting multiple scales of analysis: from immersive, technician-level on-site inspection to broader digital integration within city-scale geospatial contexts. Overall, the results validate the proposed workflow as an effective and interoperable approach for documenting, visualizing, and assessing road infrastructure using integrated NDT data, BIM methodologies, and AR tools.

From an engineering perspective, the results enable the interpretation of spatial variability in pavement layer thickness. Global variability is represented by the continuous distribution of thickness values derived from GPR data, while local anomalies are identified as deviations from surrounding thickness trends. These localized variations can indicate layer thickness deficiencies requiring further inspection. This information is valuable for decision-makers, as it helps identify critical sections in situ that require maintenance and supports efficient resource allocation to ensure compliance with control standards.

To support pavement assessment, the spatial distribution of GPR-derived thickness values can be translated into a decision-support layer through a simple deviation index, defined as $D_t = |t(x,y) - t_{ref}| / t_{ref}$. This index is introduced in this study as an operational criterion to support pavement assessment.

Based on D_t, three condition levels are defined: $D_t < 0.10$ (acceptable condition), $0.10 \leq D_t < 0.25$ (moderate deviation), and $D_t \geq 0.25$ (critical condition requiring maintenance). These thresholds are defined as illustrative reference values and can be adapted to specific design standards or operational requirements, enabling a direct integration of GPR results into Pavement Management Systems (PMS) for objective maintenance prioritization.

When compared with published literature, the proposed workflow demonstrates an increased level of integration and spatial consistency across multiple platforms. Typically, AR-based inspection works rely on surface models that do not explicitly incorporate subsurface information within the visualization workflow (Bavelos et al. 2024), while studies integrating GPR data with BIM environments focus on subsurface analysis within BIM-centered frameworks (Zhu et al. 2024). It should be noted that the workflow presented in this paper enables real-time, in situ interaction between geospatial information and the physical environment, supporting a more comprehensive assessment of pavement condition.

This integration maintains millimetric alignment accuracy through the use of GNSS control points, providing a measurable improvement in the coherence of multi-source pavement data across platforms. This integration incorporates subsurface GPR data, BIM-based semantic modelling, and AR visualization within a unified workflow, extending beyond approaches that docus on isolated visualization or single source data.

4. Conclusions

The results of this study show that integrating GPR and TLS based pavement models into both AR devices and large-scale platforms provides a significant improvement in the way pavement conditions can be assessed and interpreted. The ability to visualize asphalt layer thickness and subsurface geometry directly through AR smart glasses enables on-site, real-time inspection, allowing technicians to link digital information with the physical pavement environment with high spatial accuracy. At the same time, the successful integration of the IFC-based BIM model into InfraWorks and other GIS platforms confirms the robustness of the workflow in maintaining geometric alignment, semantic richness, and interoperability across different software ecosystems. This multi-platform visualization capability enhances the reliability of pavement safety assessment by offering coherent access to consistent datasets at multiple scales, from immersive field inspection to urban-context analysis, thus supporting more informed maintenance strategies and contributing to safer and more resilient road infrastructure.

Future work will expand the methodology in two directions. First, by incorporating additional NDT techniques, such as Falling Weight Deflectometer (FWD), will increase the structural detail and enrich the semantic attributes of the BIM model. Second, scaling the workflow to larger roadway networks and linking the IFC model with digital-twin platforms will enable continuous monitoring, predictive maintenance, and long-term decision support for pavement management.

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