Reconstructing existing underground service networks through BIM methodology application: a case study

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Abstract

This paper presents a methodology for the digital reconstruction and management of underground utility networks in urban environments through Building Information Modeling (BIM) integrated with UAV photogrammetry, laser scanning, and Ground Penetrating Radar (GPR). The novelty of this study lies in the structured workflow that combines international standards (ASCE/UESI/CI 38-22, PAS 128:2022) with cloud-based platforms to ensure interoperability, information quality, and traceability across the entire infrastructure lifecycle. Compared to previous studies, this work explicitly addresses uncertainty in data acquisition and demonstrates the integration of heterogeneous survey techniques within a federated BIM model. The case study at the University of Palermo validates the approach, showing improvements in accuracy, data governance, and collaborative decision-making. The contribution of this work is the establishment of a reproducible framework for Digital Twins in Smart Cities, enhancing urban planning, risk management, and sustainable infrastructure maintenance.

1. Introduction

As cities expand rapidly due to urbanization, subsurface systems like tunnels and utility networks have become critical in supporting urban functionality. These projects, much like other infrastructure developments, go through distinct phases including planning, designing, building, and ongoing operation and maintenance (Rogers et al., 2012; Wang and Yin, 2022). The main challenge addressed in this paper is the lack of standardized and reliable methods for detecting, mapping, and managing underground service networks, which often results in inaccurate data, increased risks, and higher costs during construction and maintenance.

The subsurface positioning of infrastructure inherently introduces significant technical complexity across all operational phases. Precise geolocation of underground networks is a critical prerequisite, as it facilitates the efficient design and routing of new installations, mitigates the risk of conflicts with existing systems, and serves as a reliable basis for inspection, condition monitoring, and planned maintenance activities (Sharafat et al., 2021). Accurately pinpointing the position of underground assets remains difficult because of their dense and irregular layout, combined with environmental factors like soil composition and aquatic conditions (Rogers et al., 2012; Wang and Yin, 2022). In many cases, data on underground infrastructure is still stored in paper formats or basic 2D CAD files, which limits the ability to effectively visualize and interpret the intricate network of buried utilities. Accidental damage during excavation, such as hitting a water pipe or gas line, remains a major risk that can lead to serious incidents like leaks, explosions, or fires (Feng et al., 2018). This challenge primarily arises from the unavailability of precise as-built and current-condition data, compounded by the absence of robust techniques for the reliable visualization of subsurface infrastructure (Rajadurai and Vilventhan, 2023).

During the maintenance phase, extensive manual labor is often needed to evaluate the state of infrastructure, placing workers at potential risk. Maintenance is usually reactive - performed after breakdowns occur - or follows predetermined routines based on past practices. This approach makes it difficult to avoid unexpected failures or optimize resource use effectively.

(Hao et al., 2012; Wang and Yin, 2022). The AEC sector is actively embracing digital transformation to boost efficiency and performance. In line with Industry 4.0 trends, a range of technological innovations have been introduced in construction, such as smart systems (RFID, IoT, robotics, and automation), digital modelling tools like BIM and AR/VR, and advanced computing solutions involving cloud platforms and big data analytics (Chapman et al., 2020; Huang et al., 2021; Inzerillo et al., 2023; Metje et al., 2007; Sharafat et al., 2021).

Despite growing interest in BIM and geospatial technologies, a clear research gap remains. Existing studies have focused primarily on visualization or partial datasets, without providing a comprehensive and standardized workflow that ensures both accuracy and interoperability. This paper fills this gap by proposing a structured methodology that integrates multi-source survey techniques, international standards, and cloud-based data exchange into a single federated BIM model.

The integration of BIM in the design of roads and underground utilities enables a circular and sustainable approach, where every material, piece of data, and intervention is planned to last, be traceable, and reused over time (Mantalovas et al., 2023; Vijayan et al., 2024).

The objectives of this research are to develop a reproducible workflow for integrating UAV, GPR, and laser scanning data into a BIM environment; to evaluate the accuracy and limitations of the proposed approach; and to assess the potential of this methodology to support Digital Twins and Smart Cities frameworks (Lai et al., 2025; Muchla et al., 2025).

2. Methodology

2.1 Data collection

During the construction or maintenance of new networks, there is a risk of damaging existing underground services. To mitigate these risks, it is essential to have high-quality data on the location of existing underground infrastructures, such as water and gas

pipelines, electrical cables, and telecommunication cables (Chapman et al., 2020). To improve data quality, technologies such as UAV (Unmanned Aerial Vehicle) techniques combined with Lidar and laser scanning are used for geometric detection of the infrastructure (Inzerillo et al., 2022). Information on underground services can be obtained through existing project documentation, visual analysis of surface-level service components, and techniques such as Ground Penetrating Radar (GPR) or ultrasound methods (Li et al., 2020).
The design and construction methods used in infrastructure projects have resulted in limited quality and quantity of information about underground structures. To address this, geophysical techniques such as radar or ultrasound technologies, along with visual inspection of surface-level inspection wells, are employed (Li et al., 2020). Building a BIM model requires the collection of comprehensive data on underground services, as well as detecting the infrastructure itself. Methods for obtaining information include acquiring drawings and technical documentation, historical data, on-site visits, detection of underground services through various geophysical survey methods, and excavations for position verification.

2.2 Standards and Protocols

Precise mapping of underground services can benefit from standards such as PAS 128:2022 from the British Standards Institution (BSI) or ASCE/UESI/CI 38-22 from the American Society of Civil Engineers (ASCE), which provide methodologies for detecting, verifying, and locating underground services.

2.3 BIM Integration Workflow

The adoption of BIM methodology facilitates the creation of an information database for service networks, streamlining management and design processes for designers and providing substantial support to construction companies during construction or maintenance operations involving urban service networks (Inzerillo et al., 2024). The intricate networks of underground services, especially in urban areas, are typically integrated within broader infrastructure networks. Approaches like BIM with AR and Lean have rarely been used in practice, but they can yield excellent results for relocating public services during construction or maintenance phases (Shekargoftar et al., 2022).
Despite advancements, significant uncertainty remains, especially regarding the depth of buried infrastructures. Creating a standardised system is fundamental for the implementation of BIM technologies. This requires developing a system that can follow the entire lifecycle of the infrastructure and underground services. The standard must be coordinated with the technical standards of underground engineering (Sanz-Jimeno and Álvarez-Díaz, 2023). The established BIM standard system must be comprehensive, compatible, scalable, and ensure that the shared information model can be modified, improved, and integrated (Yang et al., 2023).
To create a more comprehensive BIM model, information on soil conditions from specific maps or previous surveys can be incorporated. The BIM model encapsulates all details regarding the geometry and location of underground services, serving as a foundation for future design projects or maintenance activities and leveraging interference detection capabilities (Figure 1).
Accurate digitisation of information for creating an infrastructural BIM model that includes underground services requires detailed subdivision into the model's various components. Although the infrastructure may be managed by a single entity, urban underground service networks typically comprise individual networks owned by different entities that work autonomously and interact intermittently during design and execution phases.

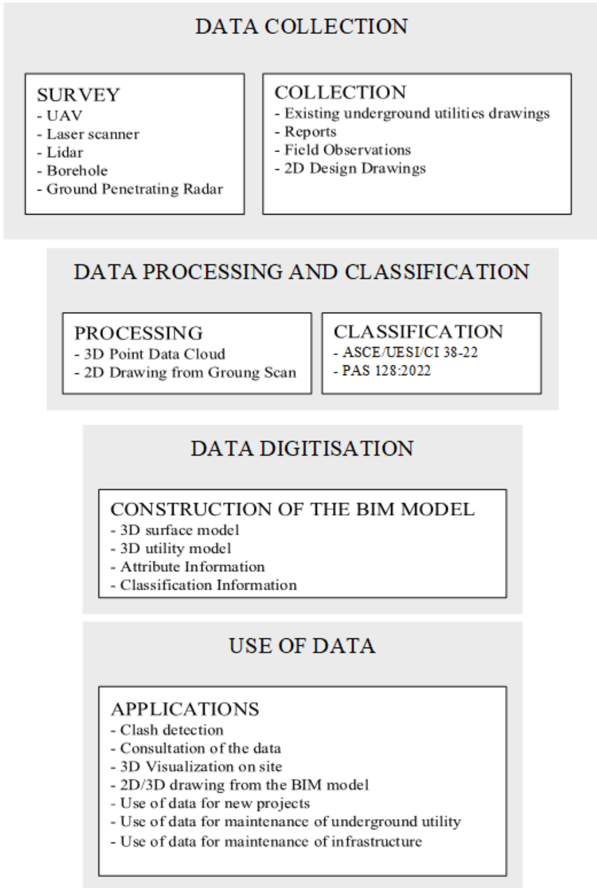

Figure 1. Methods for collecting, classifying, and utilizing data in the digitisation of existing underground services.

The application of BIM methodology promotes the digitalisation, visualisation, collaboration, and standardisation of information. Information exchange and storage among different stakeholders can be effectively carried out through the IFC format, which includes graphical, geometric, and alphanumeric information. Applying BIM to new infrastructure works allows for incremental information storage in the BIM model during design, procurement, and construction phases. The collection, digitisation, and storage of as-built information for infrastructures, including underground services, can be very useful for better maintenance management.
The open BIM approach enables stakeholders to better manage and control interventions, benefiting from an effective communication standard among the various entities involved in the lifecycle management of the work and its components. Stakeholders managing different underground service networks operate independently with their methods and software but must collaborate with external network managers to ensure efficiency and safety during all works involving underground services and infrastructure. This highlights the need for open standards to guarantee the correct transfer of information between different network managers and the infrastructure manager.

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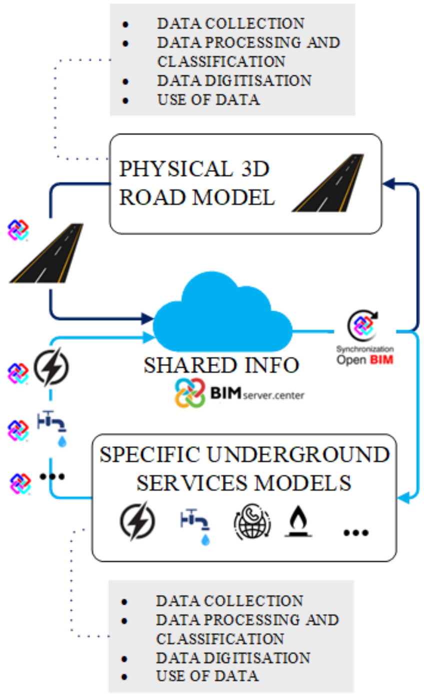

Figure 2. Proposed workflow.

A complementary workflow diagram (Figure 2) has been included to provide a clear overview of the process, from data acquisition to BIM model creation, highlighting the integration of survey techniques, standardization steps, and data sharing mechanisms. This case study proposes leveraging the potential of open BIM for sharing, storing, and using information on infrastructure works that include underground service networks. The models of different underground services have been created separately to simulate realistic information exchange between stakeholders and analyse the information flow. The BIMserver.center® cloud repository has been used for exchanging informational models in open IFC format.

3. Case study

For this case study, a small road within the campus of the University of Palermo has been selected. The data collection has been addressing various aspects. The aerial photogrammetric surveying technique using UAVs has been utilised for infrastructure mapping. Initially, point clouds have been generated to map the above-ground terrain surrounding the new site (Figure 3). Additionally, GPS station surveys have been conducted to evaluate the existing subsurface utilities, including the combined sewer system with its manholes and drains, as well as the water supply network equipped with flow regulators. The survey has been focusing exclusively on the accessible elements of the network, avoiding invasive measures.

Figure 3. Point clouds created from UAV surveys, used as the basis for terrain and infrastructure modelling.

The software Revit® has been used for constructing the BIM model of the infrastructure, starting from the point cloud modified with ReCap® (Figure 4). An initial modification of the point cloud has been necessary to remove unnecessary information or to divide the cloud into different regions, creating a more manageable reference file for the subsequent modelling phase. The primary benefit of using point cloud references for modelling has been the ability to achieve a highly accurate BIM model of the infrastructure. The Scan to BIM process has enabled the integration of all the macro-geometric information regarding the current state of infrastructure degradation into the model. Updating and comparing sequential BIM models created with Scan to BIM techniques can facilitate the mapping of areas with the most significant degradation and all the restoration interventions carried out on the infrastructure throughout its lifecycle.

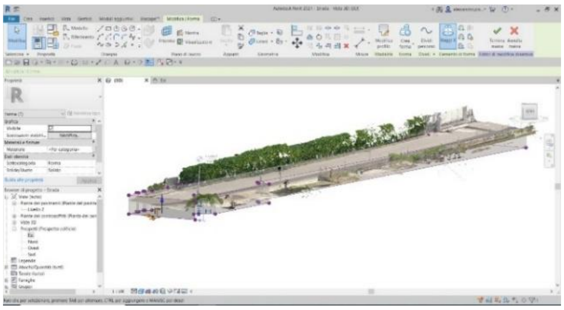

Figure 4. Point cloud import for the construction of 3D road models in Revit®.

The previous documentary information and the execution of geognostic surveys have been providing insights into the stratigraphy, allowing for the parameterisation of the BIM model of the road infrastructure and subsoil. The modelling tools available in Revit® have been effectively adapted for road infrastructure modelling, though BIM modelling of the infrastructure can also be performed with other software specifically designed for infrastructure projects. For the infrastructure modelling, specific stratigraphic families for the carriageway and pavement have been created. With Revit® 2024, it has already been possible to model the terrain as a solid, enabling the anticipation and calculation of excavation volumes. The aerial photogrammetric surveying technique with UAVs has been enhancing design efficiency by reducing errors and enabling the inclusion of various essential details for constructing the 3D model of the infrastructure (Figure 5).

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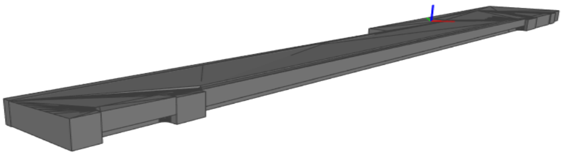

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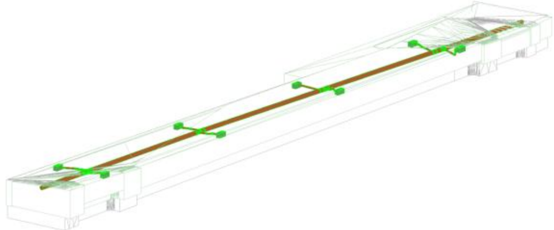
Figure 5. Overlay of the parametric road model with the point cloud in Revit® a); parametric road model created using Revit® software b); parametric model exported to IFC format viewed with BimVision® c).

The sharing of the parametric model in IFC exchange format among the managers of different networks has been eliminating all common surveying and modelling operations of the infrastructure, ensuring a single model with independent subsystems. This collaboration has been significantly reducing errors, costs, and time associated with surveying and digitalising the infrastructural components, which stakeholders would have otherwise handled independently. Each stakeholder's activities have been limited to acquiring and cataloguing data related only to their respective subsystems, leveraging their existing knowledge and expertise to digitalise this data into a specific and independent model.
The functionalities available in the BIM Authoring software Revit® have been facilitating the modelling of various urban subsystems, following the creation of specific families for the different elements constituting the systems (Figure 6).



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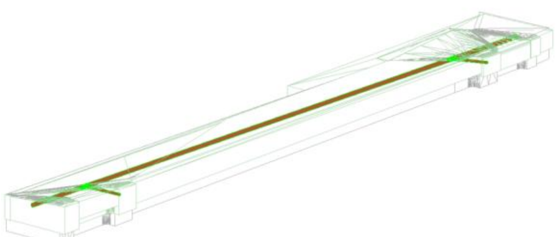

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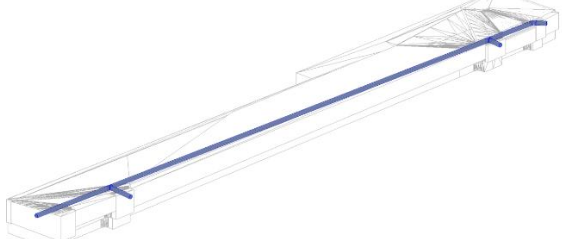

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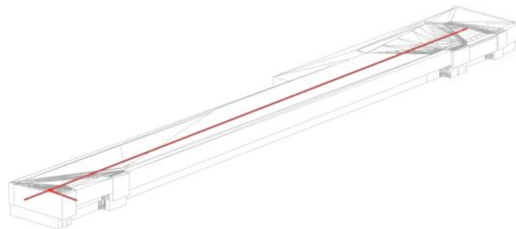

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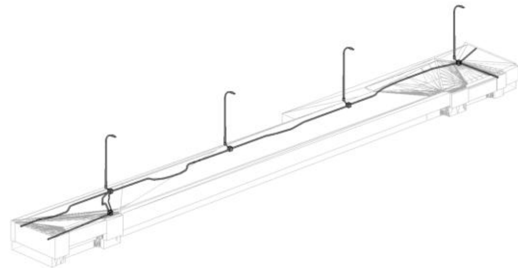
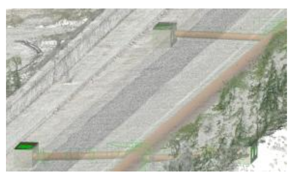


e)

Figure 6. Hydraulic system road drainage a); Wastewater system b); Hydraulic system water supply c); Methane pipeline system d); Electric system e).

Previous documentary information and non-destructive surveying techniques, including GPR, have been providing a foundation for modelling the various subsurface utility networks. The UAV aerial photogrammetric survey has been significantly simplifying the modelling of these existing systems. The overlay of the point cloud with the BIM model has been enabling the identification of all surface elements of the utility networks, ensuring precise positioning and substantial time savings in surveying operations (Figure 7).



a)

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Figure 7. Accurate positioning of elements using point cloud overlay: positioning of drainage inlets (a); positioning of pipes based on traces of previous excavations (b); positioning of manholes and lighting systems (c).

By using the "Add Insulation" command in Revit® alternatively, it has been possible to create a clearance volume around pipes as a tolerance indicator for future excavation and maintenance of the networks. The addition of a clearance volume around underground conduits can also be useful in cases where there is uncertainty about the position of an existing conduit that needs to be digitalised (Figure 8). The information about the clearance volume included in the model can be shared with other stakeholders to be considered for any future maintenance work on the underground networks.

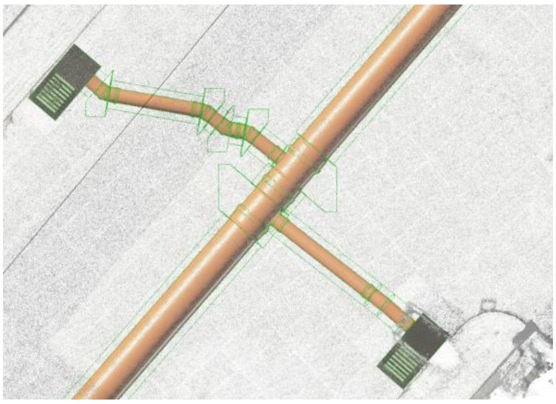

Figure 8. Insertion of clearance volumes in pipes using the "Add Insulation" command in Revit®.

Using the same principle, stakeholders have been able to use the "Zone" command in Revit® to identify areas in the model and assign specific instructions, such as no-dig zones, storing this information in the shared BIM model.

4. Results

The sharing of models via the cloud has been facilitating a smooth exchange of information. The Open BIM plug-in developed by Cype® has been streamlining the integration of Revit into the Open BIM workflow through the IFC standard, enabling direct storage and synchronization of models in the BIMserver.center® cloud. The use of the cloud has allowed the sharing of IFC models during their creation, enabling all stakeholders to overlay different networks to understand their routes in relation to each other and to verify the correct geolocation of the models (Figure 9).

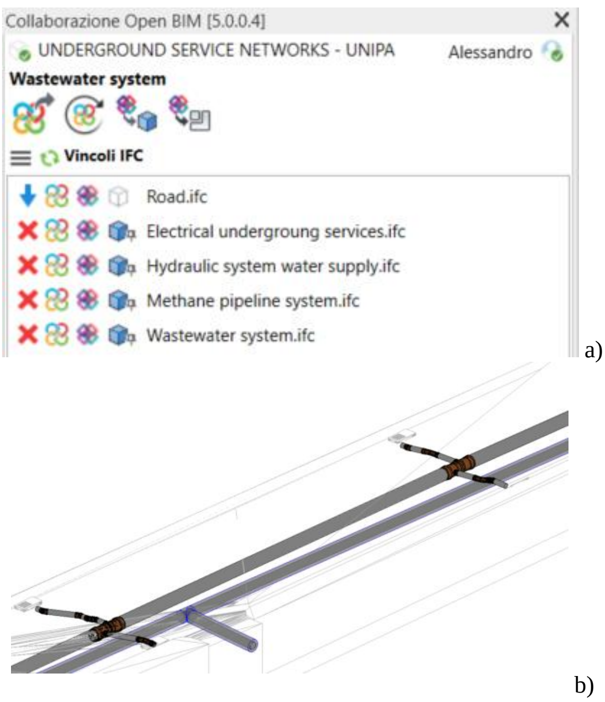

Figure 9: Interface for Open BIM collaboration in Revit® a); importing IFC models into Revit® during modelling using the Open BIM plug-in b).

For more accurate mapping of existing underground services, using standards can be very beneficial as they provide shared and validated criteria. The engineering practice of mapping underground services is known as Subsurface Utility Engineering (SUE). The SUE standard, developed by the ASCE, offers guidelines for the collection and representation of existing subsurface utility data (ASCE/UESI/CI 38-22) and additional guidelines for the recording and exchange of public utility infrastructure data (ASCE/UESI/CI 75-22).

Another applicable standard for this purpose is PAS 128:2022, developed by the British Standards Institution (BSI). These guidelines, although initially developed as project standards, can also be used by public utility owners for recording existing public services. The proposed case study has been referencing the classification from the SUE standard defined by ASCE/UESI/CI 38-22, though a similar approach could consider the PAS 128:2022 standard.

For applying SUE, it is important first to define the quality levels of the available existing subsurface utility information. The concept of quality levels arises from the understanding that reliable information on the location of underground services can sometimes be known without having any reference documents. This standard recognises four different quality levels of subsurface utility information (Table 1), which have been widely adopted and promoted by other American federal entities.

The adoption of this standard has been influencing the digitalisation of existing subsurface utilities from the initial phases of information cataloguing, which have then been digitalised into various BIM models. For each network element, appropriate textual parameters corresponding to each quality level of the available information have been created using Revit® software. This parameterisation has been enabling the mapping of various existing subsurface utilities based on the level of information knowledge. The exchange of models and the application of a common standard have also been allowing this information to be shared with all stakeholders.

Level SUE	Description of the quality level
A (QL A)	Information obtained by the actual exposure (or verification of previously exposed and surveyed utilities) of subsurface utilities, using (typically) minimally intrusive excavation equipment to determine their precise horizontal and vertical positions, as well as their other utility attributes. This information is surveyed and reduced onto plan documents. Accuracy is typically set at 15mm vertical, and to applicable horizontal survey and mapping standards.
B (QL B)	Information obtained through the application of appropriate surface geophysical methods to identify the existence and approximate horizontal position of subsurface utilities. "Quality level B" data are reproducible by surface geophysics at any point of their depiction. This information is surveyed to applicable tolerances and reduced onto plan documents.
C (QL C)	Information obtained by surveying and plotting visible above-ground utility features and by using professional judgment in correlating this information to Quality Level D information.
D (QL D)	Information derived solely from existing records or verbal recollections.

Table 1. Definition of SUE levels according to the ASCE/UESI/CI 38-22 standard (ASCE, 2022).

Using the selection options in Navisworks® software, it has been possible to obtain a comprehensive and clear mapping of all existing subsurface utilities and the corresponding quality levels of the information considered (Figure 10).

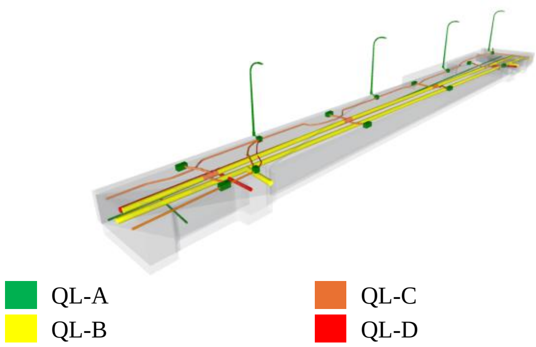

Figure 10. The ASCE/UESI/CI 38-22 standard is used to colorimetric map networks to ensure the quality of information acquired.

The creation of BIM models for various subsurface utilities and the exchange of information through the IFC standard have been enabling clash detection analyses between models developed by different managers (Figure 11). Using the IFC format has ensured a smooth transfer of information between different network managers operating with various BIM Authoring software.

The process of checking and resolving interferences has significantly improved the quality of information in the digital models managed by different stakeholders. The classification of subsurface utilities according to the ASCE/UESI/CI 38-22 standard has made it possible to resolve some interferences between different subsurface utilities. A common data quality scale has allowed all stakeholders to evaluate and adjust their systems for more accurate models. For example, accurate data was available for the methane gas line, enabling precise digitalisation of that network. For other networks, such as the water supply and sewer systems, accurate information was not always available, so their positioning was adjusted according to the quality levels of other networks. Since this involves the digitalisation of existing infrastructure, not all interferences have been resolved, as it has been challenging to define the actual location of some system parts.

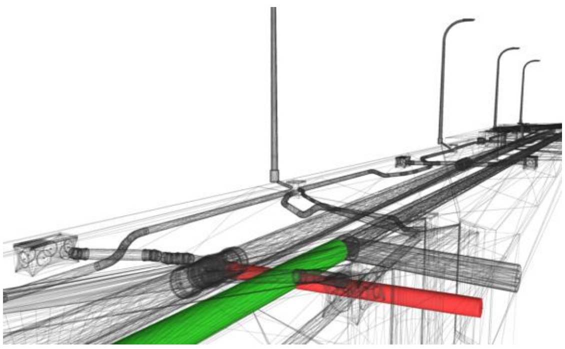

Figure 11. Clash detection performed using Navisworks® software: interference between the sewer network and the potable water supply network.

The resolution of all necessary interferences has been enabling the creation of a single federated model containing all the information on existing subsurface utilities (Figure 12). Additionally, the model has been incorporating all the information related to the quality of the digitalised data (Figure 10). Creating accurate As-Constructed or As-Built models of various underground services has been crucial, as it allows for more precise planning of subsequent maintenance activities. This approach reduces intervention costs, work execution times, potential service disruptions, and significantly increases the safety of the operators involved in maintenance tasks.

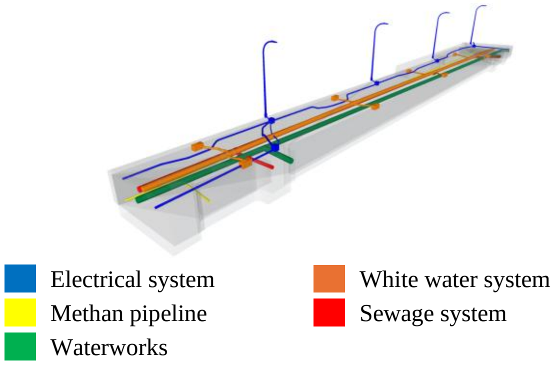

Figure 12. Colorimetric mapping of networks based on the type of subservice.

The application of BIM for creating a multidisciplinary information system for subsurface utilities has been enhancing the efficiency and quality of managing and maintaining underground pipelines. The BIM methodology has been effectively reducing errors and design costs while fostering shared knowledge among all stakeholders. This multidisciplinary approach is optimised for the management and maintenance of subsurface utilities. Developing a digitalised database of subsurface utilities has been enabling accurate simulations for new construction and network upgrades, improving intervention efficiency, reducing costs, and providing effective solutions in emergencies. The creation and continuous updating of BIM models for subsurface networks ensure data availability and usability throughout their lifecycle. Using cloud-sharing platforms facilitates the immediate transfer of information in case of an operator change and allows model viewing without specific software applications, even on mobile devices (Figure 13).

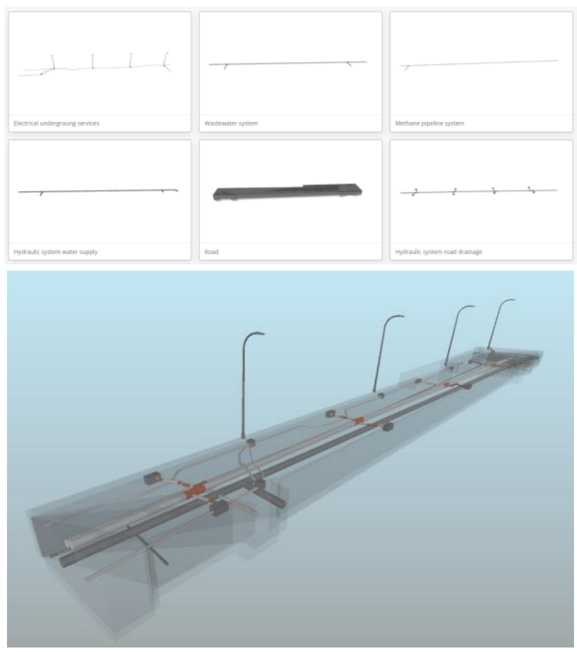
a)
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Figure 13. View of individual models uploaded to the BIMserver.center® cloud (a); visualisation of the federated model via the cloud application (b).

The use of the cloud platform has been facilitating seamless communication among all stakeholders for resolving interferences during the modelling of various subsurface networks (Figure 14). Communication via the cloud has also been enabling the sharing and archiving of all communications and updates to the models.

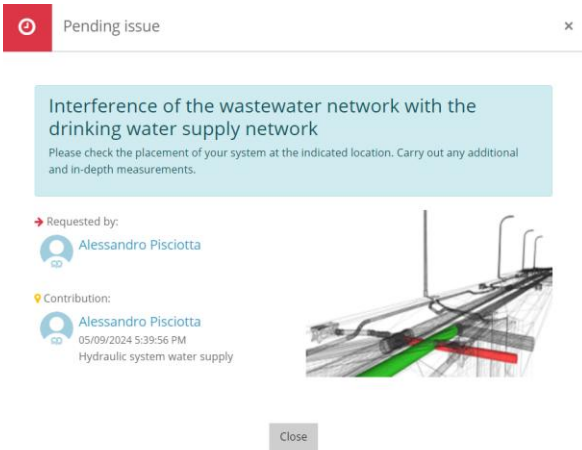

Figure 14. A cloud platform is used to manage interferences between various stakeholders through communication.

The BIM model for subsurface utilities has been integrating data related to surface constructions, soil properties, and groundwater regimes into a single model. This BIM data has been used interactively with various analysis software for risk assessment and new construction projects.

The application of BIM has been providing additional information to excavation workers. Additionally, using AR technologies, it has been possible to overlay BIM models in their actual positions, ensuring the accurate placement of subsurface utilities during maintenance or new construction activities (Figure 15).

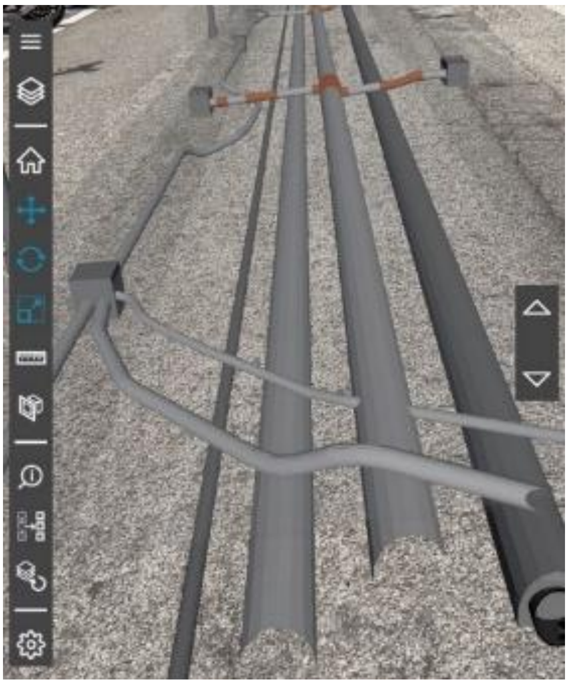

Figure 15. Smartphone BIM models overlay in their actual positions.

The proposed workflow highlights how combining UAV photogrammetry, laser scanning, and GPR within a federated BIM model can substantially enhance the precision and interoperability of subsurface utility mapping. Nonetheless, several challenges persist: the reliability of GPR outcomes is influenced by soil characteristics and moisture levels; UAV surveys depend on favorable weather and unobstructed visibility; and in some cases, direct verification of utilities was not feasible. These limitations underline the need for further methodological refinements.

Despite these issues, the workflow is shown to be transferable to larger and more complex urban scenarios, particularly when supported by cloud-based data management and open standards. The case study illustrates that structured data governance mitigates uncertainties, facilitates stakeholder collaboration, and enables more robust planning.

The findings are in line with recent studies on Digital Twins and reinforce the relevance of integrating underground utility information into Smart City frameworks (Borkowski and Olszewska, 2025; Zada et al., 2025). Beyond technical validation, this study demonstrates that federated BIM models can promote sustainable infrastructure management, strengthen public safety, and provide a foundation for long-term urban resilience (Omrany et al., 2025).

Future developments should focus on enhancing the methodology with AI-driven predictive maintenance, integration of real-time IoT sensor data, and large-scale deployment across metropolitan regions.

5. Conclusions

This case study confirms that the development of a federated BIM model for underground utilities can function as a dynamic and shareable repository of accurate information among stakeholders. The innovative contribution of this work lies in the integration of heterogeneous surveying techniques, international standards, and cloud-based collaboration into a reproducible workflow.

The main contributions are threefold improved accuracy in utility detection, structured governance and traceability of data throughout the asset lifecycle, and practical support for the implementation of Digital Twins within Smart City initiatives.

In addition to technical aspects, the results carry practical implications for municipalities, utility companies, and urban planners, enabling them to minimize risks, reduce costs and intervention times, while also improving public safety. From a policy perspective, the proposed methodology supports sustainable infrastructure governance and citizen-oriented urban services.

Future research will explore large-scale applications, integration with AI-based predictive maintenance, and the fusion of real-time sensor data to foster resilient and adaptive urban infrastructures.

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